Review:

Distributed Autonomous Robotic System Configurated with Multiple Agents and Its Cooperative Behaviors

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1. Introduction

What caused the flexibility of a manufacturing system to be regarded as important were changes in the social environment and rapid progress in production technology. Recently, however, new flexibility is sought after not only in response simply to multi-kind small-lot production but also from the standpoint of quick response to demand and fault tolerance. This is overwhelmingly larger scaled and dynamic, as compared with the flexibility discussed in the Flexible Manufacturing System, and is flexibility which allows the very structure of production facility to be re-configurated physically and logically according to situations. As a strategy for achieving this flexibility, an autonomous distribution in which a multiple number of component mechanisms (agents) are distributed functionally and are dynamically coordinated is expected to be extremely effective. As a support of this, it has been pointed out that locality is important in achieving flexibility.[1] In recent years, in particular, attempts have made actively to develop a flexible, sophisticated, holonic, autonomous, and decentralized manufacturing system. Such a system has a built-in robotic system, which is expected to play a major role in achieving dynamic flexibility. As a result, such a robotic system is also required to be organized in a manner of autonomous decentralization and to operate cooperatively with machinery and men.

This paper will discuss flexible and multi-functional robotic systems, by paying special attention to a distributed autonomy oriented robotic system configured with multiple agents. Although it is advantageous with efficiency, multi-functionality, etc., a distributed autonomy oriented robotic system has defective aspects such as optimality, coherency, synchronization, and the like. Basically, an autonomous and decentralized system has two essentially contradictory characteristics, autonomy and cooperativeness, and the biggest problem in the studies of distributed autonomous robotic systems is how to reconcile these two features. In this paper, various studies of robotic systems configured with discussed. Moreover, the paper will discuss how to operate such systems while problems are solved between agents.

2. Developmental Approaches to Distributed Autonomous Systems

The expression "distributed autonomy" has lately come to be used very frequently. Although it gives the impression of a somewhat bionic and intellectual aggregate, there are very many engineering ways in which "distributed autonomy" is treated. Even those who are conducting research on "distributed autonomy" interpret this expression in different ways, so their discussions often do not mesh.

A distributed autonomous system is defined as an "aggregate of essentially separate parts in which a part acting according to its own established criteria achieves its own goal in cooperation with other parts, thereby achieving the goal of the entire system."[2] As a representative example of studies of distributed autonomous systems, Ito and others have conducted research on the generation of a variety of periodic motion patterns by changing ways in which a multiple number of oscillators are made to cooperate, and have come up with very interesting results.[3] Such studies of distributed autonomous systems are concerned with analytical discussions on what such systems can do when different mechanisms are built into their subsystems and various inter-relationships are created between those mechanisms.

On the other hand, the development of various distributed autonomous facilities, beginning with bionic manufacturing systems,[4] has recently become active. In the field of factory automation, the concept of distributed autonomy was quickly applied to control systems for machinery.[5] Since then, facilities in which the configuration of equipments is autonomous and decentralized have appeared one after another. By using this idea, systems have been furnished with arbitrary reconfiguration and applied successfully to multi-product manufacturing, examples of which include pipeless chemical plants with mobile reactors[6] and automobile engine assembly lines using a large number of automatic guided vehicles.[7] Distributed autonomy based design concepts are extremely useful not only in production but also in maintenance. The new nuclear fuel reprocessing facilities being discussed at the Power Reactor and Nuclear Fuel Development Corporation in Japan have a modulized structure formed by a combination of a number of racks, and can easily undergo part replacement or repairing by means of a remote-control robot even at a breakdown.[8]

Those facilities do not yet have autonomy of recognizing a breakdown on their own, but high maintainability is built in based on distribution of autonomy. For the development of such distributed autonomy type facilities, an approach opposite to the above-mentioned studies is required. In other words, it is a synthetic approach of examining, when functions to be carried out by the system as a whole (production, reprocessing, etc.) are given beforehand as demanded specifications, what function each subsystem (agent) should have and what sort of cooperation should be achieved between subsystems in order to realize those given functions. Whereas an analytical approach addresses itself to simple and primitive behaviors as a whole, a synthetic approach deals with fairly realistic and high-level behaviors such as processes employed in plants.

In the studies of distributed autonomous systems, homogeneity of subsystems is focused on in some cases.9) This is not argued explicitly in studies concerning robotic systems configured with multiple agents. In many cases, though a certain degree of homogeneity in information processing ability is assumed, the premise is already set that each agent has a personality with respect to functions and characteristics and carries out a different task. When each subsystem is assigned a different task, discussions on how functions had best be distributed are necessary,10) but this depends on relations between subsystems such as whether the action of each subsystem is independent of, affected by, or subjected to other subsystems.

3. Robotic Systems Configured with Multiple Agents

The developmental research on an autonomous and decentralized robotic system composed of a group of agents having a certain degree of autonomy is included in synthetic researches according to the classifications described above.

In order to develop a robotic system which will accomplish a certain mission when the task to be performed and environments cannot be fully predicted, even in possible faulty conditions in the robot being taken into consideration, strategies of distributed autonomy must be adopted. As to robotic systems configured with multiple agents, there are a large number of research topics at different levels depending on what is regarded as an agent.

(1) When agents are processes

In creating software for high-level control of a robotic system, it sometimes happens that a multi-task operation system is used for multiple processes in parallel. One of the problems here is how to design an architecture for fairly complicated processes which is necessary for robotic systems to act intelligently. The subsumption architecture proposed by Brooks is configured as a hierarchical information processing system (in the case of a mobile robot, avoiding objects, wandering, exploring, etc.), and has a distributed autonomous structure in which processes at different levels are operated in parallel.11) When a multiple number of processes carry out different tasks, communication between processes is required so as to integrate them.

(2) When agents are processors

When a system is composed of a multiple number of CPUs, a specific process is assigned to each CPU. In the mobile robot "Yamabiko" developed at Tsukuba University, the process for each functions of the ultra sonic sensor system, vision system, locomotion control system, and map and planning system is modulized, and thus a functional distribution is achieved.12) An action program is operated by its upper module, and results of the processing between modules are transferred through a common memory called "State Information Panel". The study of sensor fusion in which results of multiple sensors are processed by different CPUs and then integrated is also regarded as a study of multiple agent systems at this level. In general, how to distribute tasks in a parallel-processing system where each agent is not assigned a certain process beforehand is a problem.

(3) When agents are actuators

Cellular Robotics13) is a field of study whose objective is to operate a multiple number of agents cooperatively which are provided with not only an information processing function but also an actuation function. Multiple agent systems at this level include such systems as distributed manipulators14),15) in which a processor is placed in the actuator of each joint, a six-legged mobile robot16) having control processor for each leg, and a fractal structure with distributed control17) in which each actuator has its own processing function. The severer the conditions of entire motions to be performed, the more cooperative control becomes necessary by such as synchronizing operations between agents.

There are also studies of self-organizing robots composed of a variety of robotic mechanisms by integrating a multiple number of component mechanisms autonomously.19)

(4) When agents are robots or equipments

As research on manipulation in which a ceratin task is to be performed by the cooperations of multiple robots or equipments, there have been reported a study of operating a specific object with multiple manipulators20) and a study of motion planning for arms operating without mutual collision.21) Besides these, there have been reported a study of coordinate control of a crane and a manipulator22) and a study of object-handling by multiple mobile robots.23) In these studies, coordinate control is focused on, and there often is a host or leader which manages and controls the entire system. However, when each agent has autonomy, namely when an agent acts based on the self-made decisions to a certain extent, a number of problems such as conflicts and deadlocks between agents must necessarily arise, so it becomes necessary to discuss how cooperative actions are to be performed. This point will be taken up in the next chapter.

4. Cooperations of Multiple Autonomous Robots

As the functions of a robot become high-leveled, its internal structure, hardware, and software become extremely complicated. When different robots have been developed by different people, it no longer is possible for anyone to integrate those robots so as to work cooperatively. There is only one way to overcome this problem, i.e. each robot developer is to build into his own robot the autonomy of managing its own action and a mechanism which enables the robot to cooperate with other robots. The problem is to come up with a general mechanism which enables a multiple number of autonomous robots to cooperate. When various robots operate in parallel, each having its own target, then such cooperations are required among robots as no interference occurs with each other (collision avoidance, etc.).

Moreover, when it is impossible for a single robot to process the tasks for achieving a common target, then cooperations are required so as for robots to help each other.

There are two strategies for getting multiple autonomous robots to cooperate. One is the strategy of building into each robot a mechanism which makes the robot to act cooperatively. Dario et al. insist that a multiple robots can be organized as a cooperative group through instinctive behaviors by reflexed movement based on sensor information assuming the personality of each robot and setting up a control mechanism similar to the subsumption architecture.[24] Also, Okuma et al. have carried out simulation of an information system for a robotic system composed of a population of robots, each furnished with a non-linear information processing system containing positive feedback.[25] These studies are attempts to create group-intelligent robotic systems similar to groups of insects like ants, and this is also referred to as swarm intelligence. As a result, it is presumed in these cases that the information processing ability or active function of each robot is limited to a considerable extent.

On the contrary, various discussions are taking place concerning information processing mechanisms for cooperative action, assuming that each individual robot is an intelligent robot. As examples treating specific problems, Takeno et al. have designed and constructed traffic rules for preventing mobile robots from colliding with each other and conducted running control for collision avoidance.[26] In addition, Kimoto et al. have created a system whereby each mobile robot learns to behave differently, with the use of neural networks.[27] On the other hand, Noreils has proposed a framework for operating multiple mobile robots in coordination by implementing a control mechanism called Multi-Robot Control Level in each robot.[28] In these studies, mechanisms for cooperation must be programmed inside the robots beforehand. As a result, they are effective in cases where it is possible to presume what type of cooperation is needed and to describe such cooperation beforehand, but they are not advantageous to flexibility in demanding for unpredictable events or dynamic requirements.

The other strategy is to achieve cooperative action based on exchanges of information, on the premise that communication is to be used aggressively as a tool for cooperation. Yuta et al. have discussed the ways for cooperation between multiple autonomous mobile robots and strategies for decision making, and proposed modest cooperation.[29] Then, as a specific example, they carried out experiments to avoid deadlocks at intersections, by utilizing communication networks between those robots, and proved the effectiveness of the modest cooperation.

Moreover, we have been conducting developmental work on an autonomous and decentralized robotic system ACTRESS (ACTor-based Robots and Equipments Synthetic System) composed of multiple mobile robots and various equipments including computers,[30] and discussed communication frameworks for cooperation.[31]

Figure 1 shows a prototype of ACTRESS; it is composed of two autonomous mobile robots, a computer for human interface, a computer for global environment management, and a wireless communication system for exchange of information between these equipments.

There still is a lot of room for consideration concerning methods of communication between autonomous robots. In methods where all the information necessary for cooperative action is transmitted actively, even information which might be utilized at some time for solving problems must constantly be transmitted, so the communication becomes heavy, and problems concerning communication load and band width arise. It is therefore considered effective to come up with a communication environment and a framework which enable exchange of information between arbitrary agents whenever the need arises. For the development of autonomous and decentralized robotic systems, communication simulation is an indispensable tool. An object oriented communication simulator has been developed with a view to verifying communication algorithms for getting multiple robots to cooperate as well as to assisting in the development of programs.[32] In this system, because each agent corresponds to an object, the state of communication can be simulated very closely. Moreover, it is possible by the use of this simulator to evaluate communication volume changes according to the form of function distribution.

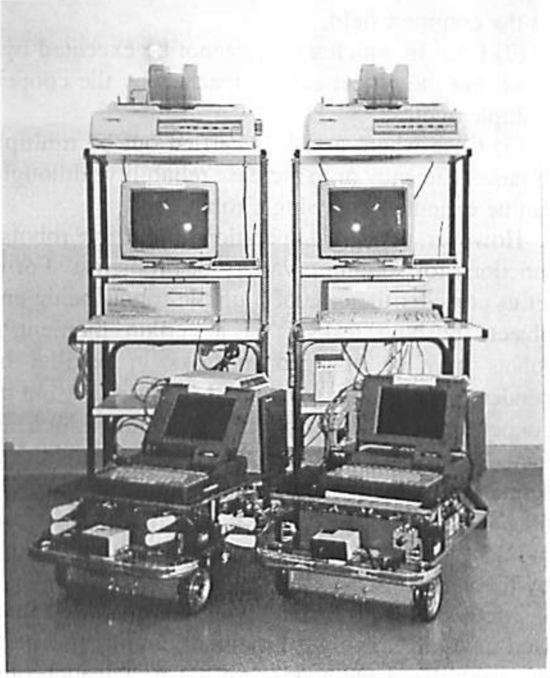

Fig. 1. Prototype system of an autonomous and decentralized robot system ACTRESS.

5. Cooperative Problem Solving in Group Autonomy Robotic Systems

Hasegawa et al. have rearranged advantages of robotic systems with group-autonomy information processing functions, composed of multiple agents, by showing actual examples such as a treasure hunt (distributed search), portable shrine shouldering (coordinated control), a bucket relay (constraint processing), players and supervisors (hierarchical management), monkey bridge, etc.[33] This shows that a group-autonomy robotic system can be configured into various forms by the way multiple agents are made to cooperate. Moreover, with respect to the way in which such cooperation is achieved, the following classification is obtained depending on the relationship between the object of each agent and that of the entire system:[34]

(1) Case where multiple robots carry out different tasks

on the common field;

(2) Case in which a task cannot be executed by a single robot, but the object can be reached by the cooperation of multiple agents;

(3) Case where a task is carried out by multiple robots to raise efficiency or to increase reliability, although the task can be executed by a single robot.

However, the actual operation of multiple robots requires functions for solving a variety of problems. For example, let us consider the case of multiple robots being engaged in objects pushing tasks. At a certain moment, multiple robots may be engaged in tasks in parallel but independently, or at other moment, they may carry out their tasks cooperatively. Some specific problems which arise here include task assignment, management of environmental information, formation of task executing groups, path planning with collision avoidance, synchronization, etc. These problems must be solved autonomously and cooperatively by the agents.

Methods for problem solving are classified into centralized methods, distributed methods, and hybrid methods. In the centralized method, there exists a leader (also called manager or coordinator) which plays a leading role in controlling the flow of information processes and judgement in problem solving, and this leader does decision making in order to derive integral solutions. There are cases where a leader is chosen from the group by negotiation according to situation, even if no leader agent has been determined beforehand. This type of strategy was applied to the method of avoiding deadlocks during locomotion of multiple mobile robots which Yuta et al. came up with.29) We have examined general methods for negotiation with a view to solving a variety of problems which multiple autonomous mobile robots face,35) developed, as an application, a path planning method for collision avoidance based on rules and communication, and succeeded in autonomous avoidance of a simple deadlock situation.36) With regard to cooperative and distributed sensing, the Distributed Vehicle Monitoring Testbed has been developed37) as a sensor network for distributed recognition of mobile objects, and Sakane et al. have proposed a distributed visual sensing system by negotiations based on contract net protocol.37) Moreover, a study has been reported concerning problem solving in task planning by multiple robots.40)

On the other hand, with respect to the distributed method, Wang et al. have examined the mutual exclusion problem and the deadlock detection problem in a distributed processing environment and presented methods for solving those problems.41) There are studies based on the assumption that cooperative actions of agents are to be executed without the use of communication in such a way that no conflict or deadlock is caused. As examples of these studies, the path planning method for collision avoidance among mobile robots42),43) and a method for planning cooperative task44) have been proposed. However, these methods have only been verified by simulation, and their applications to actual robots encounter big hurdles, since not much can be expected of recognition and sensing performance for actual robots. It therefore seems to imply that there is a limitation in how much cooperative action can actually be carried out without communication.

As for the hybrid method, Le Pape has discussed the task planning and scheduling of multiple robots.45) Here, he describes a framework for optimizing task assignments by means of each robot making up its own plan in a decentralized manner and exchanging information with the central planner and scheduler. In essence, scheduling problems are difficult to solve in a decentralized manner, since they involve very strong interdependency between agents, and so the optimization of plans in distributed systems is also difficult. In this paper, this problem is solved by combining the centralized plan and the decentralized plan. Nevertheless, in order to integrate those two plans properly, a large number of discussions are required on how much plans should be made by the centralized planning and the decentralized planning.

As a means to solving a variety of problems in autonomous and decentralized robotic systems, the application of the distributed cooperative problem solving techniques are expected. These deal with problem solving by means of loose coupling and cooperative multiple solvers (agents), and is an application study of the knowledge information processing technology called Distributed Artificial Intelligence which has been actively studied in recent years.46) Although no details are discussed here about this, methods such as the contract net,38) the multi-stage negotiation,47) and the distributed constraint satisfaction problem solving48) are useful for the planning and scheduling problems in multi-agent robotic systems. However, it is not necessarily sure that methods for distributed cooperative problem solving are useful directly for multi-agent robotic systems. This is because the structures of the problems treated are simplified in the distributed cooperative problem solving, whereas the problems robots actually face involve their share of more intricately entwined cases. The present situation is that different methods are being tried on a variety of specific examples. It is therefore expected that the accumulation of these trials and their results will be significant for future technological developments.

6. Conclusions

We have been discussing robotic systems composed of multiple agents which have been developed on the basis of the concept of distributed autonomy. The research results thus far obtained can hardly be said to be sufficient. Rather, the topic belongs to a frontier research field expected in future. As a result, to what extent the autonomous and decentralized system technology can respond to expectations as an approach to realizing flexibility will become clear as studies are advanced. There is no mistaking the fact, however, that the concept of an organization based on cooperation of multiple agents can be a new paradigm for systems which produce a variety of functions dynamically.

The concept of distributed autonomy was born with the holonic structures of living organisms as models. Moreover, the human beings, living organisms, and societies have been used as models for such theoretical systems forming bases for autonomous and decentralized systems as synergetics49) and dissipative structure,50) or for neural network technology by which a large number of application systems have been developed, or for the genetic algorithm (GA)51) which has begun to draw attention in recent years. In particular, the genetic algorithm is a method for solving optimization problems in parallel and in a decentralized manner which initates the evolution of living organisms, and is expected as a method for dealing with optimality that has been lacking in autonomous and decentralized systems. There are a lot of points yet to be clarified concerning the extremely high-level adaptability which living organisms have, while further analysis of their adaptability will give a great impetus to a breakthrough for post-mechatronics.

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