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Paper:

Elemental Technologies for Collective Robots

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The research on distributed autonomous robotic systems which has been carried out in RIKEN results in a conclusion that development of new elemental technologies is essential for realization of an collective robot system. In this paper, the required elemental technologies in mechanisms, sensory systems, and communication systems of collective robots are mentioned, and some elemental technologies developed so far are introduced. Interaction between collective robots and their environment is discussed, and an intelligent data carrier system is introduced as an example of a new device for the interaction. Human interface for operating collective robots is also discussed, which enables cooperation between collective robots and a human operator.

Keywords: Collective robots, Mechanism, Sensor, Communication, Environment, Human interface

I. Introduction

Robot systems that consist of multiple autonomous robots, such as distributed autonomous robot systems, cellular robot systems, or multi-agent robot systems, are recently attracting attention. The objective of these robot systems is to enable multiple robots to act intelligently as a group by distributing the required functions of the system to multiple autonomous robot elements (agents) and making the elements organize themselves and cooperate with each other according to the situation, without central control mechanism. It is expected that such a system can solve technical problems of the conventional robotics stated above, permitting the realization of desired performance, such as multi-functionality, adaptability, flexibility, robustness, failure resistance, and high-speed processing. When a large number of robots is operated, it is very difficult to control all robots centrally, and it is necessary to control them by means of a distributed autonomous system.

However, most studies of collective robots discuss control systems based on simulations, with very few having realized actual robots that collectively perform intelligent behavior. It is very interesting to analyze a self-organizing or emergent behavior by means of simulations, but it is considered necessary to discuss how to realize intelligent, collective behavior using actual robots. Hence, this paper will discuss what types of elemental technologies will be required when the study targets the development of technologies that enable collective robots and humans to perform tasks cooperatively, taking into consideration the fact that actual robot agents are different from simple computer agents (**Table 1**), and will introduce some of the technologies that have already been realized by the authors.

2. Studies on Distributed Autonomous Robot Systems

As a result of our studies of distributed autonomous robot systems, a prototype of such robot systems has been developed. In the course of development, a conceptual design of distributed autonomous robot systems was conducted; functional distribution was evaluated; and the communication function between robots, the concept of coordination, and the means of resource management for resource sharing were studied. Furthermore, the methods of determining task sharing, avoiding mutual collision, conducting laterally aligned synchronous motion, and supplementing sensing functions were developed through the use of the prototype, and these methods were realized using actual robots. De-

Table 1. Computer agent and robotic agent.

	Computer agent	Robot agent
Type of processing	Information processing (logical world)	Tasks (physical world)
Input and output	Information	Information and energy
Input/output means	Communication	Communication and physical actions
Conditions of stable operation	Antinoise Reliability	Antinoise Antidisturbance Reliability
Function	Homogeneous: easy to quantify	Heterogeneous; difficult to quantify
Cooperation	Conflict resolution Distributed processing Functional distribution (static) Load distribution (homogeneous)	Conflict resolution Coordinated processing Functional distribution (dynamic) Load distribution (heterogeneous)
Interaction with external world	Few (only with other agents)	Many (with other agents and with environment and humans)

tails of these studies are presented in separate papers[1]. Finally, a package clearing task was taken up as a typical example of a general cooperative task, and a package clearing task by three autonomous three-wheel steering robots was accomplished (**Fig.1**)[2]. In this task, multiple mobile robots were required to clean up a room by pushing multiple packages to a wall; the packages were scattered around the room,and were a mixture of light and heavy packages; light packages could be cleared away by a single robot, whereas heavy ones could be cleared away only through the cooperation of multiple robots. Accomplishment of this task with actual multiple autonomous mobile robots necessitated solving individual technical problems in various aspects of the task, such as determining task sharing, organizing a team of cooperating robots to carry a heavy package, controlling the cooperation of multiple robots so that they synchronously push a package, and preventing robots from colliding with other robots. In this study, an appropriate method was developed to solve each problem, and all methods were integrated.

In the early stage of the study of distributed autonomous robot systems, primary emphasis was placed on finding what types of coordinated motion could be realized through the application of existing elemental technologies. However, with the development of the study into stages where the number of robots was increased from several to several dozens, and then to several groups of robots, it became clear that the types of tasks that could be accomplished by applying existing elemental technologies were limited. In other words, the study reached the conclusion that new elemental technologies ---mechanisms for cooperation, sensors and communication systems for cooperation, and information processing (intelligence) for cooperation--- had to be developed. **Figure 2** illustrates the information/energy flow in an autonomous robot that operates in a multirobot environment.

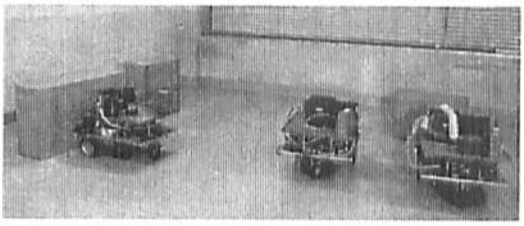

Fig. 1. Object pushing task executed by three robots.

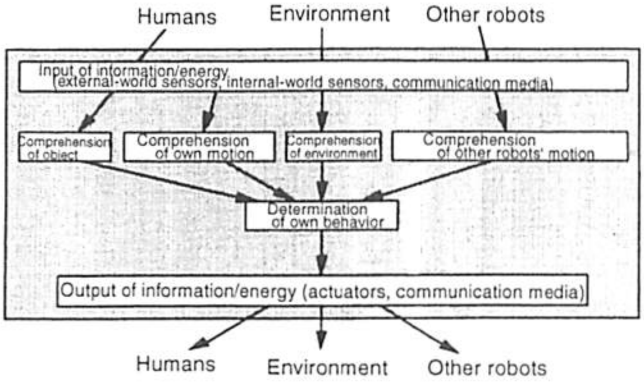

Fig. 2. Process flow in a robot in a multi-robot environment.

3. Sensors and Communication Techniques for Collective Robots

The first major problem in an multirobot environment is how to enable each robot to recognize environmental conditions. It is extremely difficult for each robot to sense, on a real-time basis, using existing technologies, where in the environment an obstacle is, where other robots are, and in what manner they are moving. The use of active sensors in a multirobot environment poses the problem of interference between multiple active signals. The use of passive image processing makes it extremely difficult to extract surrounding objects and measure their motion and also poses a problem in terms of real-time, reliable sensing. Another possible method would be to use global communication devices, such as LANs. However, it is readily anticipated that stagnation in communication will arise with increases in traffic when the number of robots increases or the traffic of communication increases.

Hence, we developed an infrared communication sensor system called "Locally Communicable Infrared Sensory System (LOCISS)" as a new sensor/ communication elemental technology for realizing cooperation[3]. This system is capable of minimizing the occurrence of interference between active infrared signals by reducing the output of infrared and limiting/localizing the reach. It is possible to enable each robot to determine whether the obstacle it approaches is a static obstacle or a robot and to identify the robot and know the manner of its movement by including, in active infrared signals, information indicating the ID and position/speed of every robot. In other words, local communication makes it possible to sense environmental conditions without burdening global communication devices. Furthermore, it is possible to detect interference when it occurs by codifying signals as redundant bit strings. Use of this system enables multiple mobile robots to avoid mutual collisions in various situations (**Fig.3**).

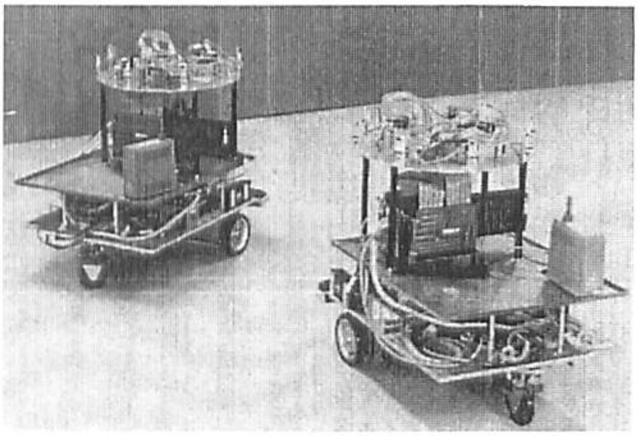

Fig. 3. Mutual collision avoidance using LOCISS.

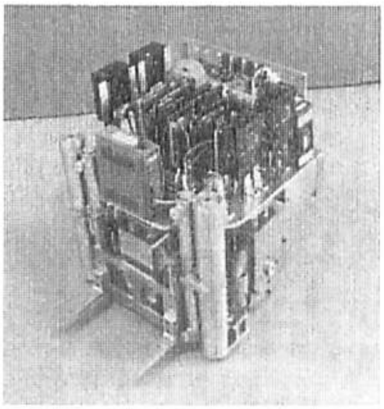

Fig. 4. An omni-directional robot.

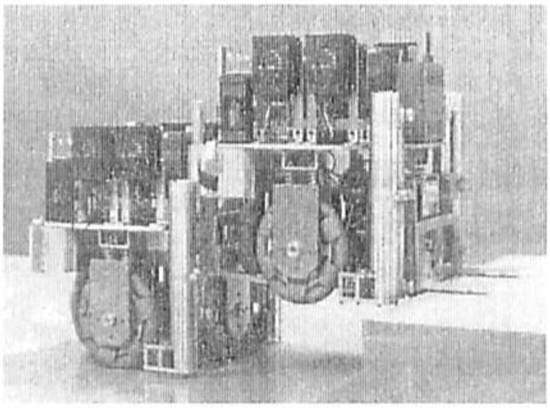

Fig. 5. Step climbing motion by mutual cooperation.

4. Mechanical Technology for Collective Robots

Nonholonomic constraint exerts critical effects on the execution of a task where multiple mobile robots mutually transport large objects. For example, the two laterally aligned robots that are going to mutually transport an object require a motion that corrects lateral lags. However, the existence of nonholonomic constraints makes it impossible to structurally compensate for lateral lags. Hence, the authors developed an omnidirectional mobile mechanism[4] as a new mechanism for realizing cooperation (**Fig.4**).

The important feature of collective robots that are required to perform coordinated motion is that each robot is equipped with flexible, excellent mobility. Use of the omnidirectional mechanism developed in this study permits robots to move in any direction without changing attitude and to turn in place. The most significant feature of this mechanism is the transmission mechanism that uses three actuators to drive the four special wheels installed on each robot. This mechanism made it possible to realize a succinct control mechanism and stable straight forward locomotion Furthermore, the mechanism made it easy to program running motions.

In the study of multiple robots, it is emphasized that the system of such robots has the advantage of permitting employment of smallrobots or microrobots. However, small robots have disadvantages: the relative size of obstacles in the environment or of the objects to be handled become large relative to robots. For example, mobile robots are occasionally unable to climb small steps or cross grooves when they are reduced in size. Hence, we want to propose the concept of mutual cooperation, which means that mutual cooperation of robots enables them to get over large obstacles. Typical examples of mutual cooperation are monkey bridges (mutual cooperation of multiple monkeys), the nesting of spinning ants (mutual cooperation of multiple ants), and circus tightrope walking (mutual cooperation of people). Mutual cooperation makes it possible to demonstrate, through the cooperation of multiple robots, functions impossible for a single robot. It is difficult for a single robot to manipulate another robot because of problems in terms of payload and balance. These problems were solved in this study through the mutual cooperation of robots using forklifts; climbing motion over a step was realized by the mutual cooperation of two omnidirectional mobile robots equipped with forklifts[5] (**Fig.5**).

5. Interaction between Collective Robots and Environment

Cooperation between collective robots, when considered from the realistic standpoint of how to develop the method of realizing it, indicates the necessity of considering interaction both between robots and between robots and their environment. The concept of "adaptability to environment" discussed in robotics implicitly meant how to make robots adapt themselves to changes in environment or to unknown environment in which they operate. In these cases, robots are "passive" to the environment. However, the observation of animals (particularly animals which form a community) enables us to see that they are actively interacting with the environment. Dogs, bears, and other animals mark (urinate) their territory. They indirectly exchange information with other dogs by leaving information in the environment and using the environment. Ants can form a path to the place where food exists by mutually reporting the location of the food by means of the pheromones they leave. Sometimes, humans also use the environment by breaking branches of trees or leaving stones in the environment as marks when they have a possibility of getting lost. Hence, we developed an intelligent data carrier (IDC) as a device for enabling robots to positively interact with the environment much like the animals in the above examples[6].

The IDC is a portable device capable of storing information. Robots are equipped with a reader/writer, with which they can read or write information in the IDC from outside, without contact, through local communication. When robots operate as a group, each robot enters the knowledge or data it obtained or the motion it performed in IDCs at the place where the entered information will become useful, so that other robots that will arrive later can utilize the information by reading the data in IDCs. In other words, use of the IDC enables robots to indirectly communicate with each other through their environment. Generally speaking, the information and knowledge that robots need in order to move can be classified into two types; one type of information lends itself to global management, and the other either lends itself to local management, such as detailed

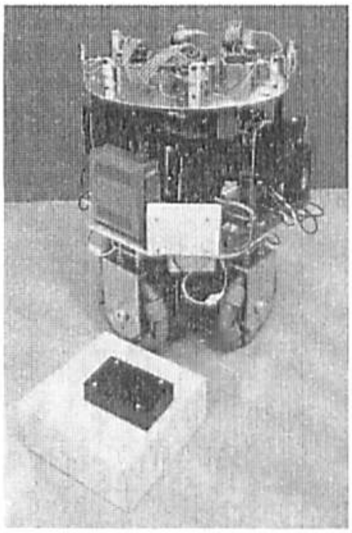

Fig. 6. A robot reading data in IDC attached on an object.

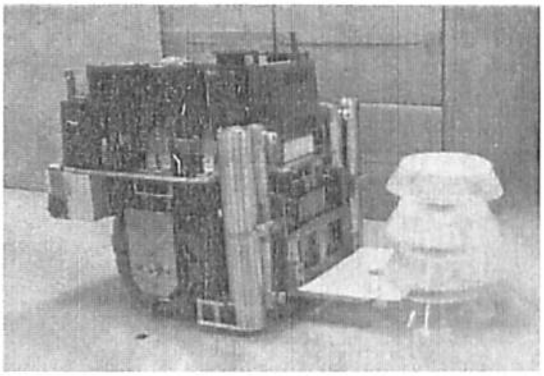

Fig. 7. A mobile robot handling IDC unit.

information that is required only locally, or does not readily permit global or central management, such as maintenance information. The IDC is effective in locally managing the latter type of information. With respect to information that is difficult to obtain through sensors, robots that approach an IDC can obtain these kind of information simply by reading information stored in the IDC without burdening the global communication system, by having the information entered in the IDC in advance (the IDC supplements the functions of sensors).

As to the means of promoting practical robot applications, one argument holds that robots should be provided with an environment in which they can move around smoothly. This concept is analogous to improving roads so that cars can run easily. However, actually preparing a special infrastructure for robots is very difficult in both economical and technical terms. The existing environment can be converted into informational infrastructure by using the IDC; for example, if information is entered in IDCs installed at places where information will become necessary later, such as on walls, floors, doors, and packages, robots can accomplish tasks flexibly, interacting with the environment. Furthermore, the IDC, because of its programmable feature, permits its use as a device of storing and providing information and as a means of converting the environment into agents. In other words, it is possible to program the function that each IDC must perform and download the program to the IDC. In termed studies ubiquitous computing (Xerox)[7] and TTT (Things that think; MIT Media Lab)[8], proposals are made on environment where people live surrounded by computers and networks. Use of the IDC permits ready realization of exactly such an environment the IDC provides the means of embodying such an environment. Furthermore, use of the IDC makes it possible to dynamically design and realize so-called affordance for making collective robots move intelligently as a group[9].

The IDC has various possible applications, e.g., prohibition of entrance into hazardous areas, security, navigation, sharing of obtained knowledge/motion, and clearing packages away. In this study, an IDC unit was developed as a package for actually executing the handling using the forklifts of omnidirectional mobile robots. Use of the IDC enables robots to perform distributed autonomous package transportation tasks. In the package transportation operation, it is difficult to centrally control all packages if packages to be handled are carried in at random, and the manner of handling varies depending on the package. However, it is possible to build a distributed system that is capable of autonomously and flexibly clearing away packages without any central control mechanism by downloading processing procedures into IDCs installed on packages and having robots that detect the IDCs read and process the program. **Figure 6** illustrates an omni-directional mobile robot reading data in an IDC placed on a package, and **Fig.7** shows another mobile robot that is handling an IDC unit with a forklift.

6. Cooperation of Collective Robots and Humans (Interface)

A key in making collective robots actually perform a task as humans intend is how humans provide robots with action objectives. The objectives must be such that humans can give them to robots according to the situation, which in turn makes it necessary for humans to know the situation where collective robots are placed. It is impossible to make collective robots do everything autonomously, because their capability is limited. Furthermore, it is necessary to take into consideration the possibilities that failure occurs. With humans, it is also impossible to completely prevent human error from occurring, even by educating and training, because the human capabilities are limited. Hence, it is considered necessary to develop a cooperative system including collective robots and humans. In the system, humans compensate for the weak point of the mechanical system, and the mechanical system compensates for the weak point of humans. In developing such a system, the interface between collective robots and humans plays an extremely important role. This interface enables humans to monitor or grasp the operation of collective robots and manipulate collective robots in various ways. Likewise, it enables collective robots to ask humans for help if they became unable to operate, e.g., (if they come to a standstill). This idea leads to the concept of the so-called R cube (R^3: Real-Time Remote Robotics)[10] in the sense that it permits the coexistence of humans and robots, i.e., the robot system is integrated into the human environment.

Simulation is very important for the interface. Because it functions as an interface not only when robots operate but also when the system is in the developmental stage, where robot programs are developed, learning by robots is simulated, system architecture is designed, or robot behaviors are evaluated. This simulation function is very helpful in supplementing real-time functions when collective robots are remotely controlled using a network (three-dimensional simulated images may be displayed as computer graphics using a model if actual images cannot be transmitted in realtime).

Humans required to remotely manipulate collective robots must be able to give commands to robots in various forms according to the situation, monitoring the collective

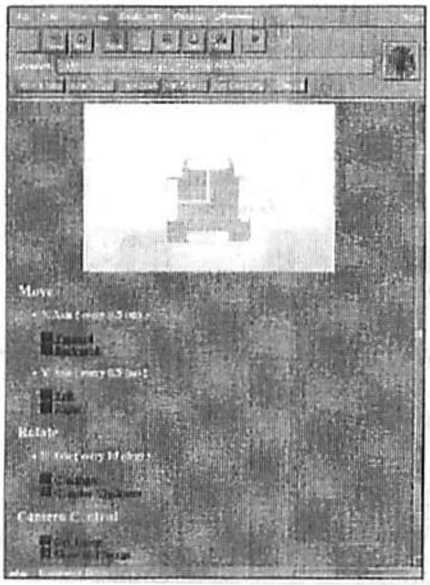

Fig. 8. WWW home page for operating robots.

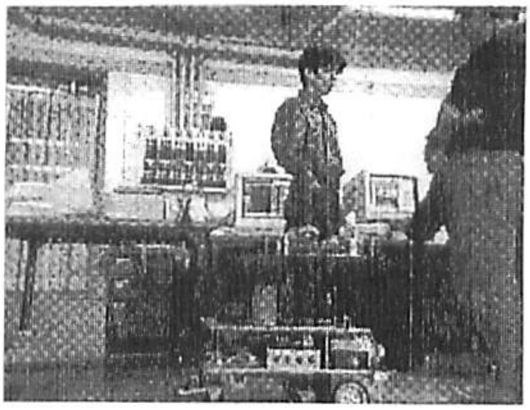

Fig. 9. Example of transmitted image.

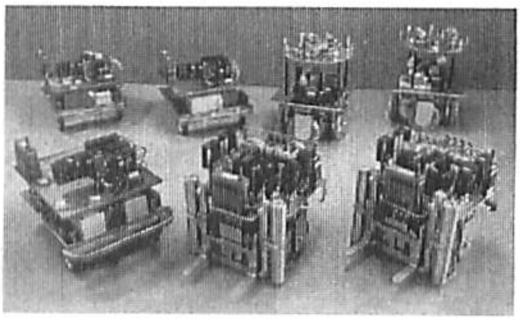

Fig. 10. Collective robots.

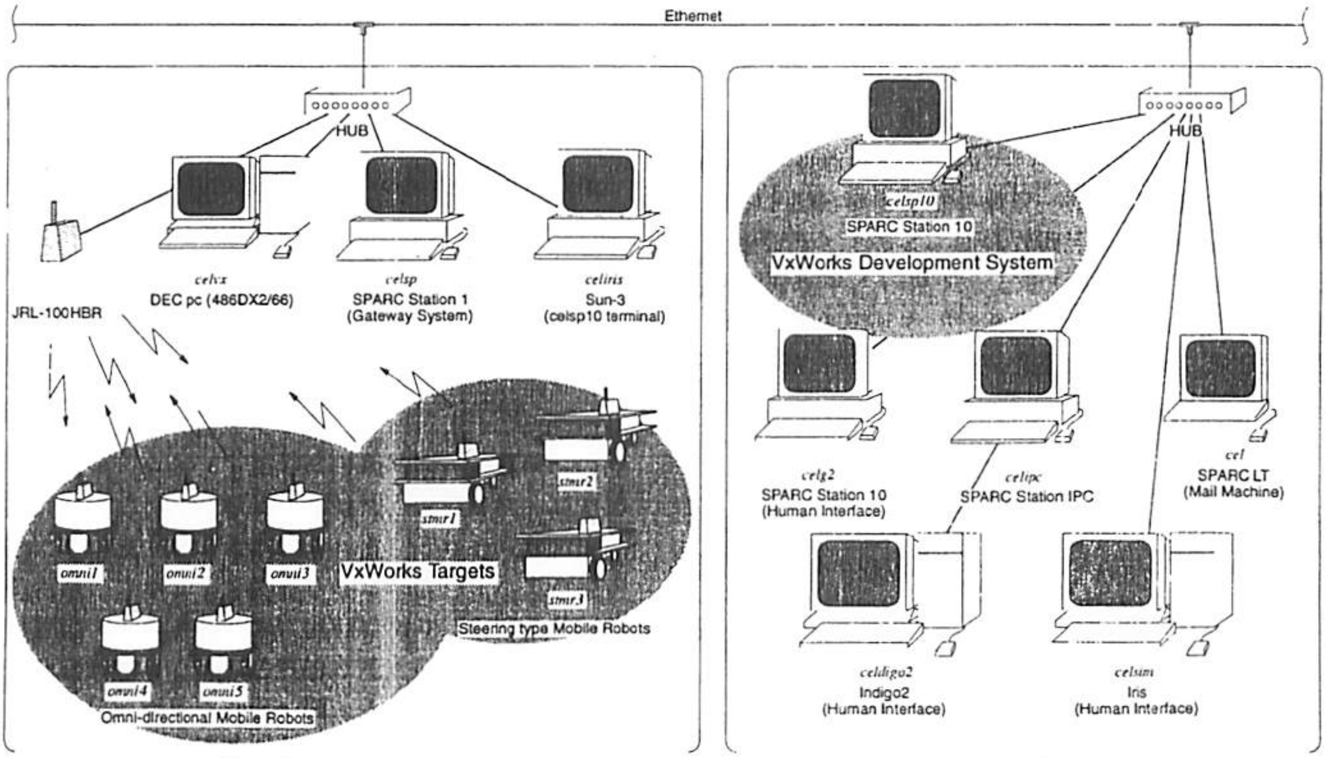

Fig. 11. System configuration.

robots behavior. We developed an interface system, targeting the realization of a system that permits humans to inspect plants in cooperation with robots manipulating. As a result, remote control of robots using an internet and remote monitoring using the visual senses of robots have been realized. **Figure 8** illustrates a home page, developed using the WWW browser, that shows a screen for remote control displaying the built robot, and **Fig.9** presents the interface screen of a computer for remote control that displays the image taken by a CCD camera on a robot.

7. Conclusion

This report described, through the development of a distributed autonomous robot system, what elemental technologies are required in order to actually develop a collective robot system and make it accomplish tasks. It discussed the interaction between collective robots and the environment, and also between collective robots and humans, and introduced the technologies that we have developed. **Figure 10** illustrates the autonomous collective robots that we developed using the elemental technologies described above. **Figure 11** presents the configuration of this collective robot system. we are currently proceeding with the development of technologies using this system in order to realize a mechanism that is capable of performing advanced coordinated motion and solving various problems.

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