Emergence in distributed autonomous robotic systems towards symbiosis engineering by using ubiquitous devices

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A device for ubiquitous computing called Intelligent Data Carrier (IDC) was developed, which enables active informational interaction between robots and its operating environment and provides the environment with intelligent information processing functionality. The concept of IDC and the developed ubiquitous devices were introduced, and its applications to efficient organization of distributed autonomous robotic systems were presented, where adaptive behaviors are expected to emerge. As a perspective of further applications of the ubiquitous device, symbiosis engineering for designing human-united artificial systems was discussed.

Introduction

Intelligent, flexible, and fault tolerant robot systems have still been demanded in various social aspects such as plant maintenance, rescue, medical, and welfare care, *etc*. In spite of research efforts for intelligent robots, a pessimistic view is taken because of the technological difficulty in realization of autonomy and unclear feasibility of application to the actual problems. On the other hand, robot tele-operation technologies have achieved great advance together with advance of IT including network technology and virtual reality. Nevertheless, in order to improve the robot operability, autonomous functionality of robots has become more important. In order to realize practical autonomy for intelligent, flexible and fault tolerant robot systems, we have developed distributed autonomous robotic systems,[1)] which are composed of multiple autonomous mobile robots, and realized various cooperative behaviors by using mutual communication. However, the adaptiveness against unexpected events such as dynamic task execution with environmental change, in unknown environment, or according to the self-function, is still insufficient and limited due to technological immatureness.

Concerning the feasibility, not only the function of mobile robots themselves but also the infrastructure for the robots should be taken into account, which corresponds to the traffic system for automobiles. By making the environment intelligent and implementing information structure in the environment, the environment as the infrastructure facilitates the robots to acquire the necessary information for autonomous action. Concerning the intelligence for adaptiveness, it is considered to emerge through interaction between the individuals and its environment in ecological psychology.[2)] In contrast to conventional robotic research where robots are passive to the environment, creatures behave with active and purposive interaction with environment, which is remarkable especially in social insects and animals. Such a bio-mimetic approach can be applied to artificial adaptive robotic system design.

Based on the consideration, we have developed a device for ubiquitous computing called Intelligent Data Carrier (IDC), which enables active informational interaction between robots and its operating environment and provides the environment with intelligent information processing functionality.[3)]

Intelligent data carrier system

The Intelligent Data Carrier (IDC) is a portable electronic data carrier device with functionality of information storage (rewritable non-volatile memory), information processing (MPU), local contactless data exchange (RF-ID week radio communication), power supply (battery - optional), and external ports (I/O interface - optional). The structure of the IDC is shown in Fig. 1. Figure 2 illustrates the concept of an IDC, which consists of a number of IDCs embedded in the environment (wall, floor, obstacles, objects, *etc*) and reader/writer devices. Each IDC manages and processes local information depending on specific place or ob-

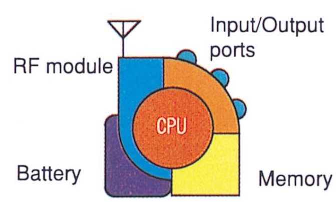

Fig. 1. Structure of IDC.

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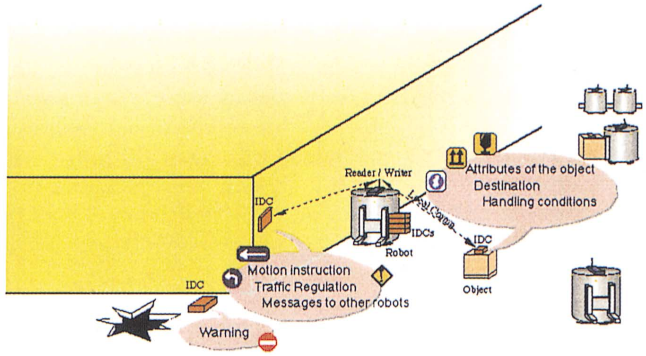

Fig. 2. Concept of IDC System.

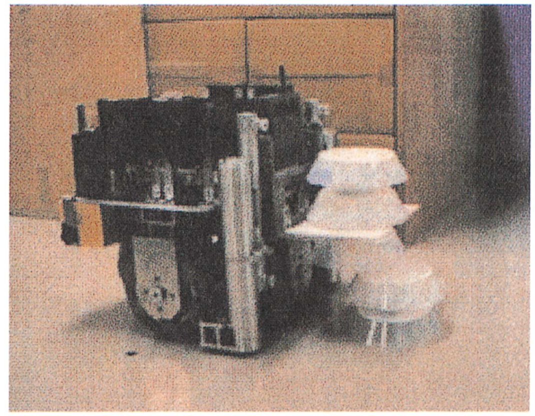

Fig. 4. IDC units handled by a robot.

jects. Robots can communicate with the IDCs via a reader/ writer device provided with each robot, and extract/add/ update the local information in IDSs through local radio communication. Or, the IDCs inform the robots of the necessary local information for navigation or task execution, and mediate the knowledge or commands stored by a robot to other robots. With these interactions, robots share knowledge via environment without mutual direct communication. Moreover, by providing each robot with a mechanism to handle the IDCs, the robot can place (or pick) IDCs, download and execute programs to construct arbitrary informational structure or distribute the mediating agents in the environment. We have developed various types of the IDC. Figure 3 and Table 1 show a photo of IDC ver. 4 and its specification respectively. IDC with mushroom-type case (called IDC unit) was also designed so that a mobile robot can handle a set of the units by a forklift, which is shown in Fig. 4. IDC system facilitates realization of a ubiquitous computing environment,[4) which makes the mobile robot operation feasible and task execution efficient and flexible. The IDC system provides not only the utility for robots as their infrastructure, but also means for emergent adaptiveness of cooperating robots constructing active and dynamic affordance. The global order of the robotic system is expected to emerge through the local interactions by using IDCs.[5)

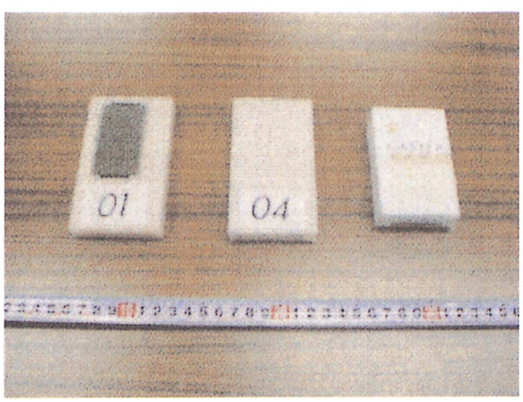

Fig. 3. Photo of IDC ver. 4.

Table 1. Specifications of IDC ver. 4.

Media	Electromagnetic wave
Size	$111 \times 63 \times 15$ [mm]
Weight	75 [g] (with battery)
Communication	RF-ID
Frequency	290, 310 [MHz]
Modulation	OOK (ON/OFF keying)
Communication rate	1200 [bps]
Communication range	< 3.0 [m]
Memory	68 [bytes]
Power source	Li-ion battery (3.6V)

Robotic applications of IDC

We applied the IDC to various robotic systems that are difficult to realize with conventional robotic technology.

(1) Distributed task management in object transportation [6)
Object transportation task is a basic robotic problem, and expected to apply to AGV, logistics, *etc.* The task is to transport multiple objects to each specific destination, which appear in arbitrary location and at random timing. Namely, the environment is dynamic. It is assumed to deal with the objects by multiple robots. It is difficult to manage the dynamic situation (dynamically appearing tasks, changing environment, operating robots) in a centralized manner. We proposed a distributed task management method in object transportation by using IDCs. The task information depending on each object can be stored in IDC attached to the object, which is destination, handling instruction, specification, required deadline, flag for processing, *etc.* The operator writes the information in the IDC on the object by RF wireless communication and puts the object anywhere anytime. The robots that wonders in the environment along predetermined or planned path and receives the response signal of any IDC attached on an object read the information inside it, and execute the specified task, namely transport the object to the specified destination. This method is very simple, flexible, and robust. By this method, the robots can deal with unexpected and dynamic task requirement, and execute the tasks efficiently without any complicated task management or global communication.

(2) Cooperative search in unknown environment [7)
In case that multiple robots operate in an unknown environment as the case of ants' foraging, the robots should search the environment as well as navigate themselves. For effective

search and navigation, it is required for each robot to utilize sensors for knowledge acquisition and share it among multiple robots. In case of large number of robots and large area of the operating environment, it is difficult to manage the acquired knowledge by each robot in a centralized or global manner. Accordingly, we applied the IDC to a cooperative search task in unknown environment in order to manage and share the knowledge in a distributed and local manner, which is acquired by each robot's search action. The method we developed is quite simple and similar to ants' procedure using chemical trails (pheromone). Assuming unknown maze-like environment operation, each robot navigates itself along a path, and when it meets a branch and cannot find any knowledge on the local environment, the robot select a path randomly. At the same time, the robot puts an IDC at the branch and writes information in it about the path it selected. If the robot meets a dead-end in the selected path, it comes back to the branch, and update the information in the IDC at the branch about the dead-end information, namely the acquired knowledge on the environment. After the operation, since the environmental knowledge is organized in the environment where local information is embedded, when another robot that has no knowledge on the environment arrives at the branch, it can extract the knowledge on the local environment, which the previous robot stored in the IDC at the environment, and select the path properly and effectively based on the knowledge. The schematic procedure is illustrated in Fig. 5. As a result of experiments, it was verified that IDC enables local environmental knowledge management and sharing for multiple robots, and is effective for their cooperative search in unknown environment.

(3) Other Robotic Applications
IDC can be utilized for other various robotic applications. We applied the IDC to landmarks for mobile robot localization,[8] which is required for navigation. IDCs for the landmarks are set in an environment, in each of which location information is stored. By recognizing the IDCs by local radio communication, reading location information stored in them, and calculating relative position based on visual information processing, each mobile robots can localize itself and compensate the positional error at every chance to meet IDCs.

IDC can be applied to role-playing by multiple robots.[9] For example, we developed a method for distributed organization

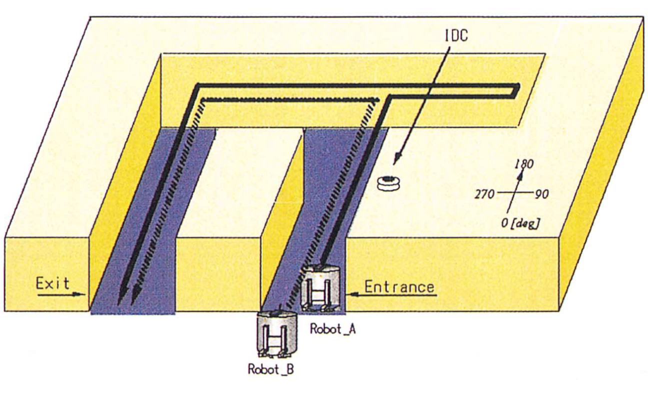

Fig. 5. Environment search using IDCs.

of task executing robots moving in an environment with obstacles and obstacle removal robots. By embedding an IDC in each obstacle, obstacle can behave as an intelligent messenger among robots. If a task-executing robot recognizes the necessity to remove an obstacle during operation, the robot can write the messages or commands to remove it in the IDC attached to the obstacle. Any obstacle removal robot that finds the IDC in which removal request is stored can deal with the obstacle based on the local message transmission via the obstacle.

In addition, as an application of the IDC to grass mowing in forestry task, we discussed a method for distributed map management including arrangement of trees, task processing procedures and their progress situation.[10] The IDC is also very effective for mobile robot teleoperation guidance. By storing local map or instruction for operation at the local place in IDCs scattered in an environment, the robot that recognizes an IDC can send the guidance information in the IDC to the remote operator. The guidance information makes the operator's remote operation easy, which is difficult for the robot to acquire by sensors or global communication.[11]

The IDC is a very convenient device for realizing ubiquitous computing environment, and efficient for developing various robotic applications, especially cooperative tasks in multi-robot environment, by enabling local and distributed information management and processing with local radio communication. This notable functionality allows each robot to construct informational structure in its operating environment and emerge adaptive behaviors.

Towards symbiosis engineering

The further application of IDCs is the *Symbiosis Engineering*, which is a new paradigm we propose to design human-united artificial systems. In contrast to the current IT (Information Technology), which is *network oriented*, namely based on the network and intelligent terminals connected to each other via the global and permanent network, a new IT based on local and temporal network or autonomous (stand-alone) functionality is required for symbiosis engineering, which we call *substance oriented* IT. The human adaptive system can be realized by applying IDC technology. We call the IDC *ubiquitous device*, which is attached to each individual and manage the personal information locally.

(1) User-adaptive system
The artificial systems including the robot systems should act up to the human intention. To enhance the human friendliness of the artificial systems, we propose to utilize the ubiquitous device as means to recognize the individuals and to equip the system with a mechanism to serve according to each individual, which is called as user-adaptive system. The personal attributes, preference, historical data, handicap, *etc.* can be stored in the personal IDC, which is carried by the person. The artificial systems provided with an equipment to read the personal data by local radio communication can be designed to behave according to the personal data. Figure 6 shows an example of user-adaptive systems, which is a guidance robot adaptive to the visitors. The robot changes the speed and judges the usage of auditorial guidance according

Fig. 6. Example of user adaptive system.

to the information (visitor's category and his/her handicap information) stored in the IDC carried by the visitor.

(2) Rescue assist system [12]
We developed a ubiquitous device for rescue assist as shown in Fig. 7. The concept of rescue assist system using the ubiquitous device is shown in Fig. 8. This device is equipped with a speaker to speak to victims and microphone to record the voices of victims. The ubiquitous device is scattered in houses or buildings, and when an earthquake destroys them, it is buried in the detritus with victims. When the device is activated from outside, this device starts autonomous action to speak to victims, record sounds, and transmit the sound data to the rescue center.

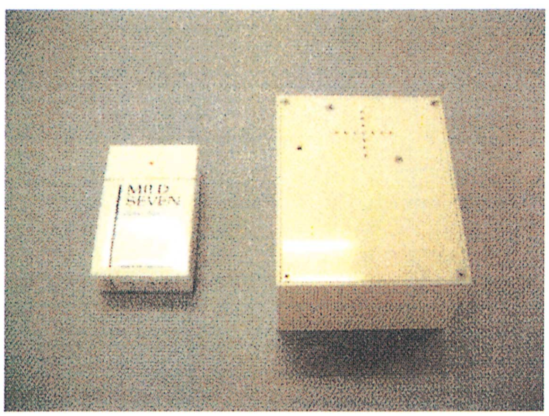

Fig. 7. Ubiquitous device for rescue.

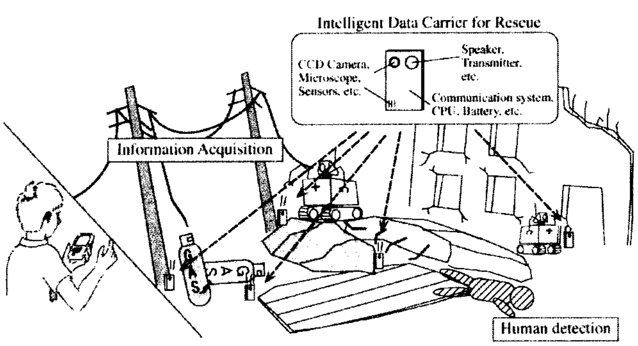

Fig. 8. Concept of rescue assist system.

(3) Individual information management system
The IDC is also very effective to manage the individuals in population. Downsizing of the device is essential to enlarge the application of the device. We have discussed an animal management system by using the newly developed micro ubiquitous devices (IDCs) as shown in Fig. 9. The individual information such as genetic or inheritance information can be stored in the device embedded to the animal. We are discussing to provide it with sensing functionality for monitoring physical conditions. This concept is extendable to human body united medical and health-care device.

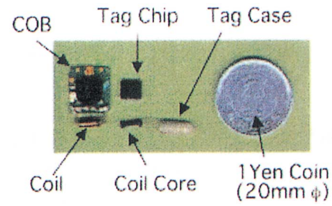

Fig. 9. Ubiquitous device for animal management.

Conclusions

In this paper, the concept of IDC and the developed ubiquitous devices were introduced, and its applications to efficient organization of distributed autonomous robotic systems were presented, where adaptive behaviors are expected to emerge. As a perspective of further applications of the ubiquitous device, symbiosis engineering for designing human-united artificial systems was discussed. Integration of the ubiquitous device with Micro-TAS technology is considered to open new breakthrough of applications.

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