ELSEVIER

Robotics and Autonomous Systems 19 (1996) 1–13

Robotics and Autonomous Systems

Co-evolution of a multiple autonomous robot system and its working environment via intelligent local information storage

Teruo Fujii [a,*], Hajime Asama [a], Thomas von Numers [b], Takanori Fujita [c], Hayato Kaetsu [a], Isao Endo [a]

[a] *Biochemical Systems Laboratory, Institute of Physical and Chemical Research (RIKEN), Saitama, Japan*
[b] *VTT Automation, Otakaari, Finland*
[c] *Department of Mechanical Engineering, Toyo University, Saitama, Japan*

Abstract

This paper proposes a new strategy of evolution and adaptation of a population of multiple autonomous mobile robots to make multi-robot systems more flexible and robust against unpredictable environmental conditions and human operator's capricious commands, and to overcome the limitation of biologically inspired techniques which need a certain degree of redundancy and diversity. The important idea of the strategy is to utilize the advantageous parallelism of the multi-robot system and immobile but portable devices (data carriers) for information storage and management. A device named IDC (Intelligent Data Carrier) is developed with a unique mushroom-like structure to be easily handled by a forklift mechanism which can be mounted on actual mobile robots. The handling method of the IDC unit, which should be essential to realization of the proposed strategy, is examined through the experiment using an omni-directional mobile robot, and the robot succeeded in placing the unit at an appropriate location. With the demonstrated handling technique, the robots can adapt and evolve as a population by accessing locally available information which is stored and processed in the IDC unit.

Keywords: Autonomous mobile robots; Multiple robots; Evolution; Adaptation; Co-evolution

1. Introduction

Multiple autonomous robot systems are among the emerging concepts to realize flexible and robust robotic systems for a wide variety of missions such as plant maintenance, warehouse operation, etc. In order to realize the system's functions as required, however, each robot in the system should be designed, organized and controlled appropriately according to the missions. Generally, one big obstacle to solve the problems, i.e., how to design, organize and control the system, is that the dimension and complexity of the system might explode as the number of robots increases. To avoid such difficulties and to reduce the number of dimensions and the degree of complexity, we have been proposing a distributed approach named "DARS: Distributed Autonomous Robotic Systems [4,18]" to make up multiple autonomous robot systems. In DARS, functions necessary to achieve the commanded goal are distributed over multiple autonomous robotic agents which behave cooperatively according to the situations appearing during the mission execution.

Several numbers of multiple autonomous robot systems have been proposed and even physically

* Corresponding authors. Tel: +81-48-467-9310; fax: +81-48-462-4658; e-mail: fujii@cel.riken.go.jp.

PII S0921-8890(96)00029-2

constructed, for example, the CEBOT of Nagoya University [9], the ACTRESS of RIKEN [5], the MAUV concept by Albus [1], etc. In MAUV system, control of the whole system is designed essentially under one unified architecture, the so-called "Hierarchical Control [2]". The control software of each vehicle is, therefore, programmed and implemented quite deliberately rather in an inflexible way. This kind of system implementation is effective for a specific objective, for which the MAUV system is developed such as anti-submarine warfare, team attack operation, etc. But even if the minimum autonomy of each vehicle is guaranteed by the implemented software, it is difficult to realize the flexibility as a whole system with this kind of predetermined approach. The CEBOT and the ACTRESS are designed as more flexible and adaptive systems and can be categorized in DARS approach. In these systems, configurations of the system such as cooperation, coordination, team organization, conflict reconciliation, etc., are determined on-line via mutual communication among the robots participating in the mission. Moreover, in the CEBOT system, the robots are able to self-organize to realize specified physical configurations in which an individual robot becomes a component of the larger structure by docking with each other.

These procedural approaches over mutual communication are proved to be really effective to utilize attractive advantages of distributed systems. But, similar to many discussions on single autonomous mobile robots, those procedures are still below the designer's prediction and expectation of the operating condition f the system. Furthermore, when we treat a large number of robots, we have to consider the high degree of complexity by which unexpected events may occur locally within the system as mentioned above. Generally such events cannot be formulated to be implemented onto the system in advance. It is, therefore, indispensable to multiple autonomous mobile robot systems to have learning and evolving strategies for on-line adjustment of their behaviors from the individual level to the global/system level in order to handle unpredictable conditions and to meet human operator's capricious and selfish commands.

In this paper, we propose a new strategy of evolution/adaptation for multiple autonomous mobile robot system utilizing immobile but portable media for local information storage and management. By the proposed strategy, the robots in the system can efficiently co-evolve/co-adapt with the working environment without consuming global communication resources. The background and the concept of the strategy are presented in the following sections. Then we introduce a new device called "Intelligent Data Carrier: IDC [22]", for realization of the proposed strategy. Finally the practical implementation along with the usage of the IDC is discussed in detail.

2. Evolution/adaptation of a robotic system

Learning and evolution are undoubtedly the concepts inspired by or originating from the behavior and the capability of living organisms. Recently, such biological essences have attracted not only biologists' but also system designers' interest including robotic engineers, computer scientists, etc. [19]. Since these essences may possibly solve the difficulties underlying the physical world which cannot be solved by conventional engineering methodologies. Most of the attractiveness of biologically inspired methods come from redundancy and diversity of the biological world. The redundancy and the diversity are meant not only in a physical form but also in reaction, decision, and control fashions of individual creatures. Unfortunately, this fact may lead to serious drawbacks of these methods because it is very difficult to realize the redundancy and the diversity in actual engineered systems. Here we are not trying to develop new techniques for learning and evolution themselves, but rather we intend to propose a new strategy to avoid such drawbacks so that available techniques, i.e., Neural Networks, Genetic Algorithms, etc., can be effectively utilized from the engineer's point of view (cf. Fig. 1).

2.1. Available techniques

A lot of methods and tools have been proposed as shown in Fig. 1 for evolution and adaptation of robotic systems and they seem to be almost established as each independent method and tool. For example, artificial neural networks, especially Back-Propagation type networks, have already been used for a long time as robotic controllers and considerable amount of advantageous usage has been reported [8,15,16], while there are still advanced research topics to reveal more

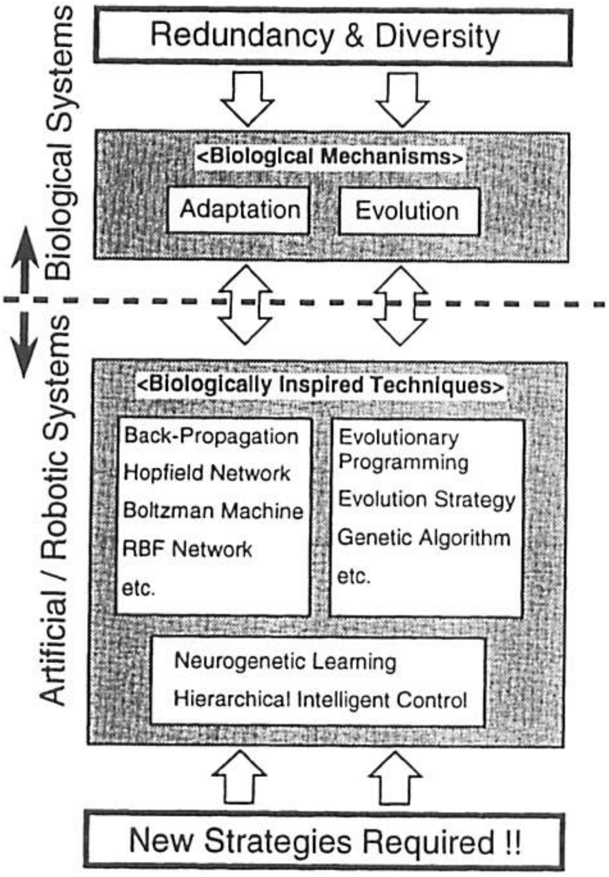


Fig. 1. The scope of this paper.

generalized characteristics of this technology [13,23] or even to refine the nervous model of living creatures [6,12]. Similarly, so-called "Evolutionary Computation [7]" represented by the Genetic Algorithm [10] has been applied to various problems as one of the quick search methods through simulated evolution of the phenotypic entities, e.g., physical robots [17,20,24].

2.2. *Limitations of implementation (drawbacks)*

When we try to implement these biologically inspired techniques onto an actual system, it is very difficult to make the system adaptive and evolutional as expected. For example, when we use an adaptive control system based on BP type neural networks to control a certain robotic system for some specific objectives, a considerable number of trials should be conducted to train the network until satisfactory performance is achieved [21]. If this training time is within an allowable range, it can be said that an efficient system has been constructed. However, the higher the system's complexity or degrees of freedom becomes, e.g., in the case of multi-robot systems, the more training time is required in general. The same problem occurs when we use evolutionary type techniques for selecting behaviors during given tasks. These are the practical aspects of the major drawbacks which usually appear when we apply biologically inspired techniques to engineered systems (cf. Fig. 2). There are many discussions for these problems [7,11,14], e.g., one typical opinion is that to overcome the problems, the networks or the chromosomes can be trained or evolved in computers using simulators and numerical models without interacting with actual environments. As tools for story telling of long history of the living creatures' adaptation and evolution, simulation-oriented techniques are quite attractive to see what happens and why it happens [14]. But from the engineer's point of view, the authors would like to claim that the problems in a physical world which are difficult to be modelled in a numerical form are just what we should use biologically inspired evolutionary/adaptive techniques for.

3. A new strategy of evolution/adaptation

Multiple autonomous mobile robot systems are potentially suitable for applying the biologically inspired methodologies. Not only because certain numbers of such systems are directly inspired by biological systems, but because the fact that there are multiple agents (robots) which can possibly provide a key to the redundancy and the diversity necessary to make truly evolutionary and adaptive systems. Namely, with multiple robots we can have the following advantageous parallelism as shown in Fig. 3;

(1) the robots can have various configurations and characteristics in their behavioral styles,
(2) the robots can be distributed spatially over the work area in attention, and
(3) the robots can be distributed temporally or sequentially into handling of the specific objects.

A new strategy of evolution and adaptation, by which a system improves its performance as a population of the member robots in principle, can be derived considering these advantages. This means that the

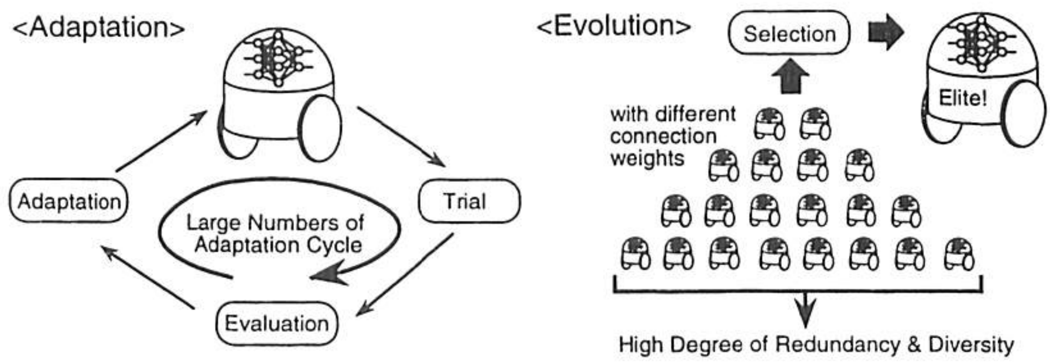


Fig. 2. Required redundancy and diversity.

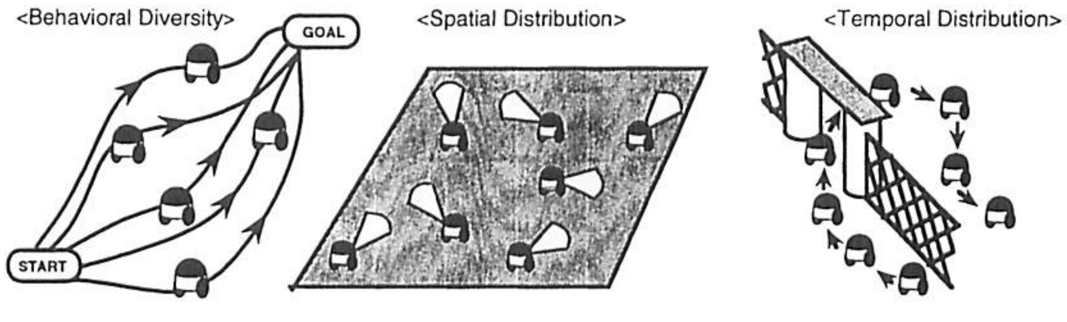


Fig. 3. Advantageous parallelisms in multiple robot system.

local inefficiency and inconvenience at the individual robot level should be permitted for the evolution at the population level.

3.1. Evolution/adaptation as a population

In a multiple autonomous mobile robot system, if the environmental information collected by each robot is accessible from all the individuals in the system, spatial distribution of the robots leads to comprehensive recognition of the working environment in a quite efficient way. The same logic can be applied to the temporal distribution of the robots, i.e. "experience". The individual robot encounters the local situations, e.g. a gate in Fig. 3, one after another in the working environment and should manage them by its own autonomous functions. But as a whole system, i.e. "the population", the system can be seen as if it experiences various situations simultaneously in the different places in the environment and each specific situation is encountered by the multiple individuals many times in a certain time span. If these experiences of the individuals are accessible from all the individual robots, we can easily make all the individuals well-experienced because all the robots in the system can learn, evolve, and adapt based on the results of plenty of trials attempted by their colleagues. Important ideas of the new strategy of evolution and adaptation described above are;

(1) evolution and adaptation can be achieved not by an individual robot but by a whole population of robots, and
(2) the experiences and information acquired by temporally and spatially distributed robots in the system are compiled as common property of the population.

3.2. Local information storage

The most natural way to realize the proposed strategy in practical is to broadcast every event experienced by the individuals over the whole system. In this case, however, sufficiently wide bandwidth should be prepared for global communication especially when the number of robots in the system is large. To overcome this kind of limitation in communication resources and to take advantage of the parallelisms in multi-robot systems, local and parallel communication media with

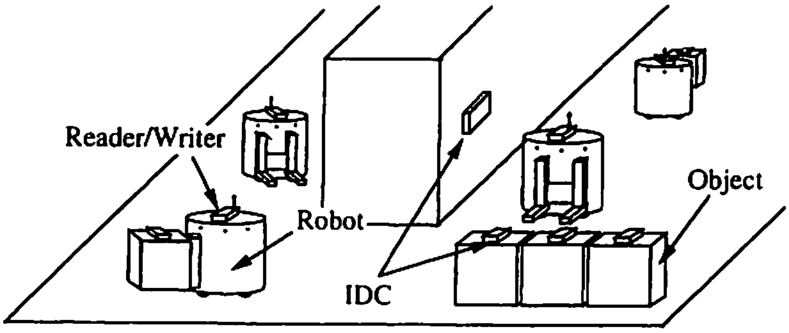


Fig. 4. The concept of the IDC system.

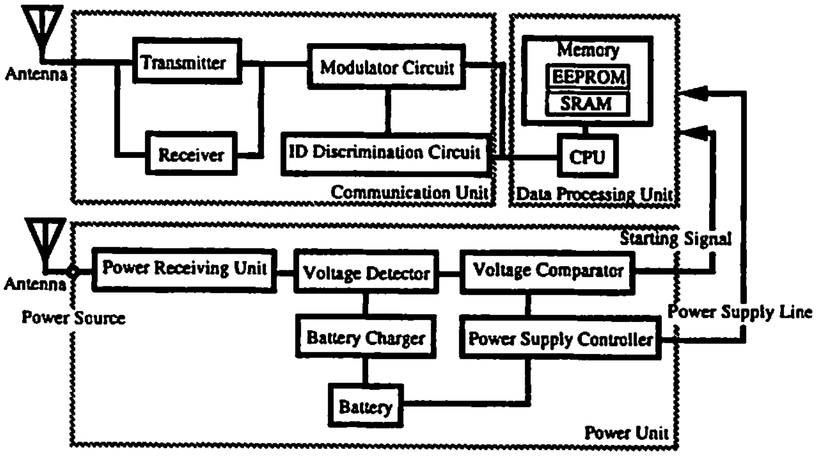


Fig. 5. Schematic circuitry of an IDC device.

limited range should be considered as a way to access to the compiled experiences. It can also be observed that acquired knowledge should be bound to the locations where the individuals encountered these specific situations.

An immobile but portable information storage with communication ability for inscription and retrieval in a limited range could be, therefore, the most effective media for compiling acquired knowledge and being attached to the specific sites and/or objects. Although environments have been treated as uncontrollable in most cases, the robots can actively reconfigure the information environment of the working place if the information storage unit can be handled by the robots.

3.3. Distributed adaptation and evolution

We can assume that behavior strategies and control signals applied to a robot for a task which is dependent on a particular location or object are memorized in an information storage unit attached to the location or object, and that the results of the task execution can be evaluated by the information processing capability of the unit or the robot itself. Based on the memorized data for every robot, which expresses what kind of strategies and/or controls the robots took against the task, and the evaluation of the strategy and/or control, adaptation and evolution processes can be executed in the information storage unit to achieve a better solution for the specific and local task. Same processes can be executed in every information storage unit attached to particular locations and objects in the working environment. Thus, thanks to the advantageous parallelism of the multi-robot system, adaptation and evolution of the population of the robots in the system can be realized in a distributed manner.

4. A Local information storage

In order to avoid excessive communication in multi-robot systems because of limited processing

Table 1
Specifications of the IDC system

Media	Electromagnetic wave
Frequency	90 MHZ
Modulation	FM
Data rate	9600 bps
Range	1 m
Intensity	< 10 mW
Power supply	DC5V

power and bandwidth of radio communication, an intelligent local communication device named "IDC: Intelligent Data Carrier" has been developed by the authors [22] to reduce the traffic for global communication by providing local communication links and local information management functions. By reading from and writing into the IDCs, the robots can use them as media for inter-robot indirect communication. Furthermore, by placing the IDCs on some specific places in the working environment, the robot can give the places necessary functions to be agents for information storage and management. Thus, besides local communication, the IDC also plays the role of an extra information storage which can be utilized in the proposed framework for adaptation and evolution of the robot system, providing robots with processed relevant information.

4.1. The IDC system

The IDC system consists of portable autonomously functioning information storages (IDCs) and reader/writer devices carried by the robots for local communication with the IDCs as shown in Fig. 4. Devices placed on robots to act as the local communication devices of the robots are termed reader/writers which play the active role in the system by initiating communication. The IDCs are usually placed in the environment or on the objects to act as local information storage. They store and process information and reply to requests from reader/writer but do not initiate a communication themselves, mainly because of energy constraints related to their self-contained function. The IDCs turn to a sleeping mode to save energy and are only woken up by a signal from a reader/writer. The schematic circuitry of the IDC is illustrated in Fig. 5, while a reader/writer has almost the same circuitry with a power line connection and

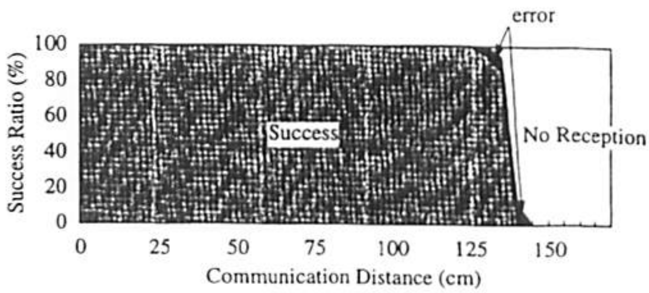


Fig. 6. Communication characteristics of the prototype IDC.

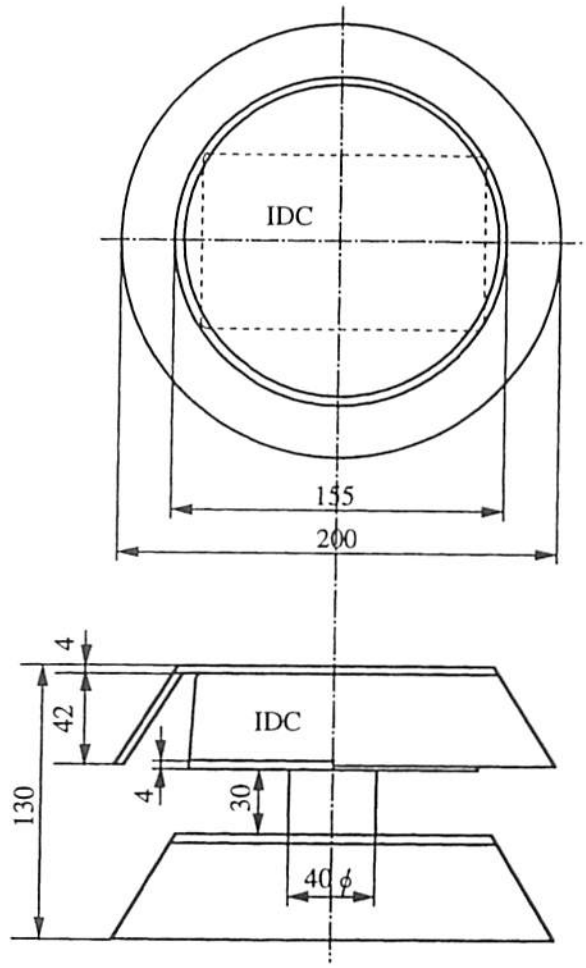


Fig. 7. Structure of the IDC unit.

a serial interface with the robot instead of the power unit of the IDC.

4.2. Specifications

The specifications of the IDC are shown in Table 1. The IDC is an application of RF-ID (Radio Frequency Identification) type low intensity electromagnetic

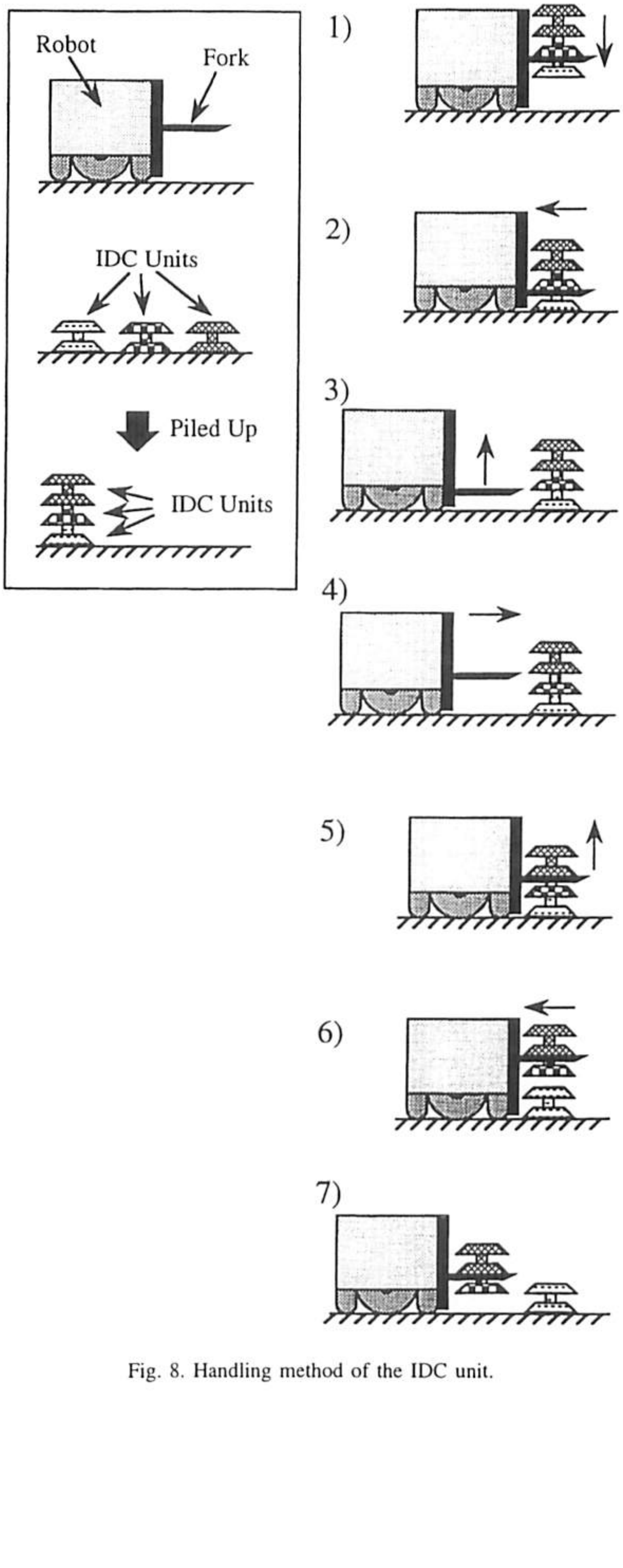


Fig. 8. Handling method of the IDC unit.

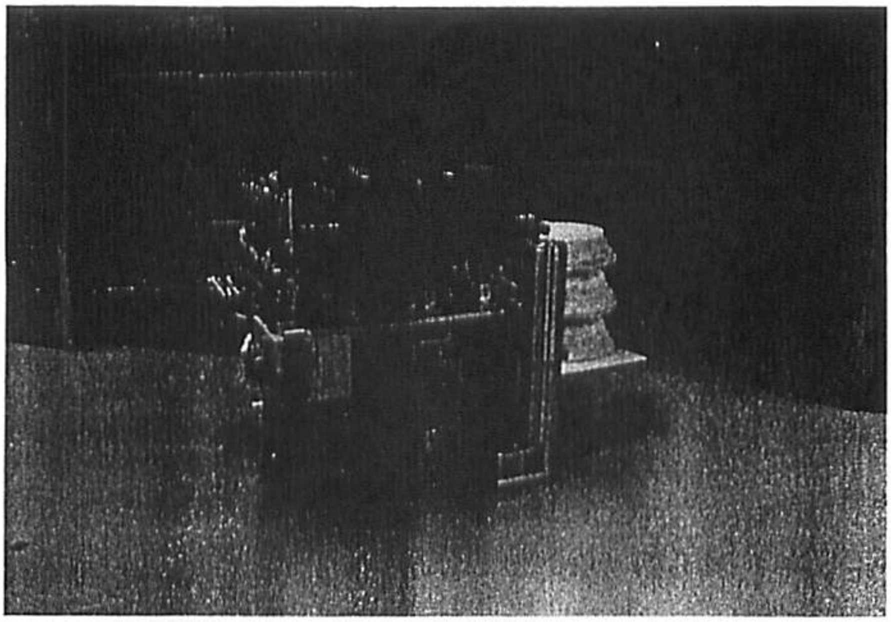


Fig. 9. The omni-directional mobile robot carrying the IDC unit.

wave transmission. Transmission frequency is 90 MHz and frequency modulation is used to achieve high reliability and minimum disturbances outside the communication range. The communication range can be adjusted through intensity adjustment in a range from 1 to 10 m, and the transmission rate is 9600 bps.

4.3. Functional properties

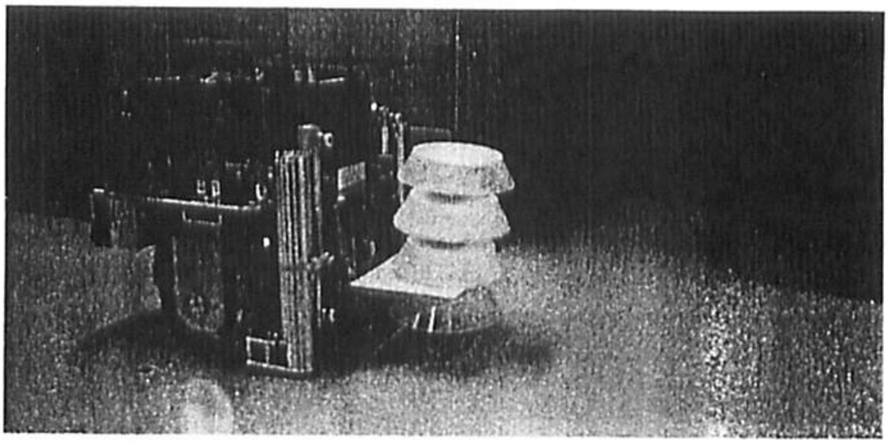
The functional properties of the first prototype IDCs have been tested in our robot testing environment. A test communication program has been conducted with the IDC device in various positions in relation to each other. The test results show consistently reliable communication within the intended communication range as shown in Fig. 6. At the outer limit of the communication range a narrow band of erroneous communication is observed, outside of which consistently no communication is received. It is verified that the developed IDC system realizes local communication without large interference with global communication.

4.4. Structure and handling

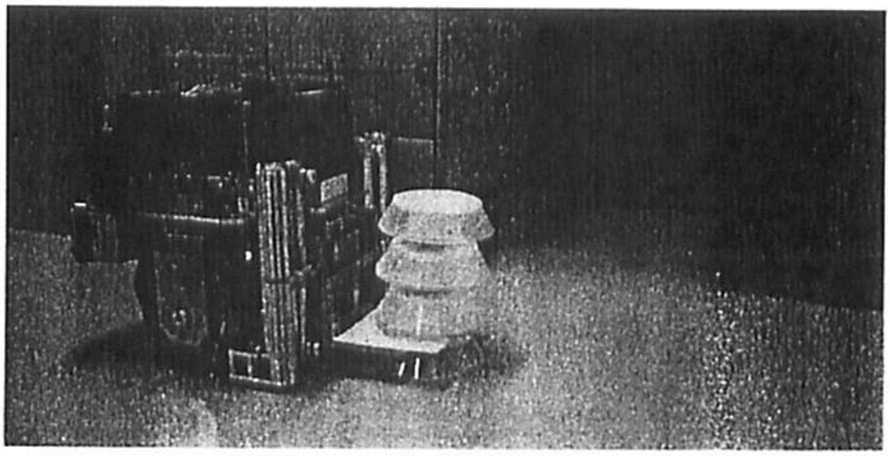
A robot system which consists of multiple autonomous omni-directional mobile robots with forklift mechanisms [3] are used as an experimental platform for the proposed strategy. In order to handle the IDC by the forklift mechanism, a mushroom-like structure is designed for the IDC packaging as shown in Fig. 7. Hereafter, the IDC with the mushroom-like package is called "the IDC unit". With this structure, the IDC units can be easily piled up and put on the floor one by one at appropriate locations. Fig. 8 shows a pick/place method of the IDC unit by a forklift mechanism mounted on a robot. To place the IDC unit on the floor, the robot should execute the sequence from (1) to (7) in the figure, and to pick up the unit, the robot should do the sequence in reverse order, i.e., from (7) to (1). The fork should be moved downward at first until the IDC unit at the bottom touches the floor ((1) and (2)). Then the robot should move backward and pull up the fork to pick the upper two units ((3) and (4)). After all, the robot moves forward to insert the fork, pull up the upper two units, and left the bottom unit on the floor ((5)–(7)).

5. Realizing the evolutionary robotic system

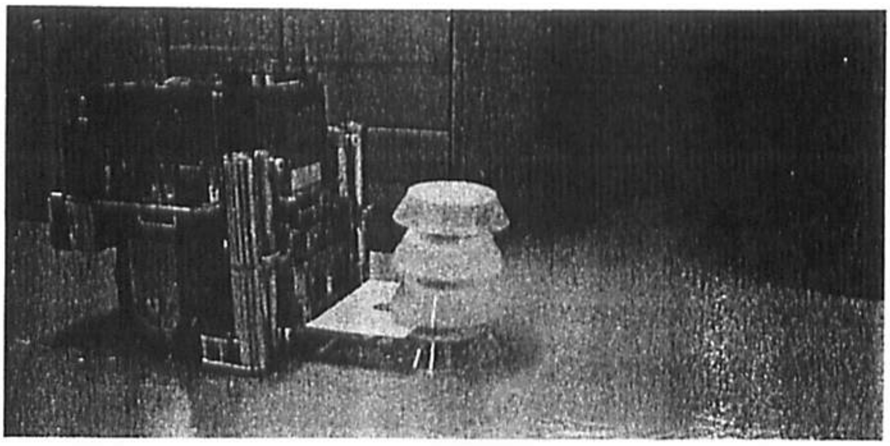
An omni-directional mobile robot [3] is used as a testbed for examining the handling method of the IDC unit which should be essential to realization of the proposed strategy for adaptation and evolution. Fig. 9 shows the omni-directional mobile robot carrying the IDC units by its forklift mechanism. The robot is de-



(1) Approach

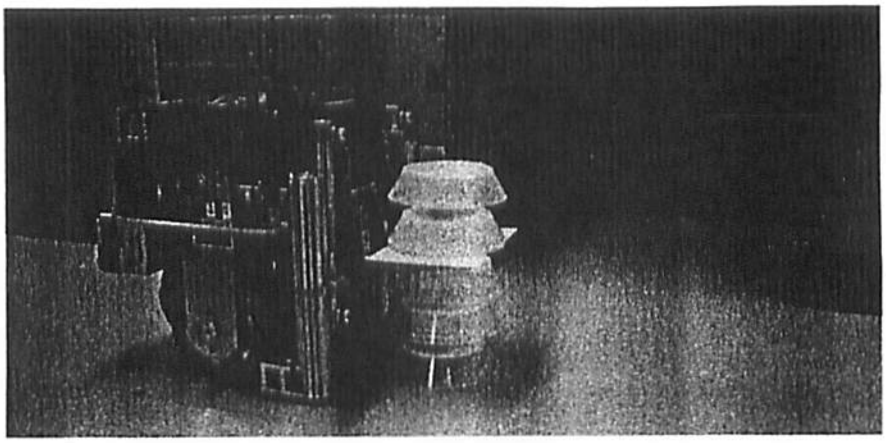


(2) Put down

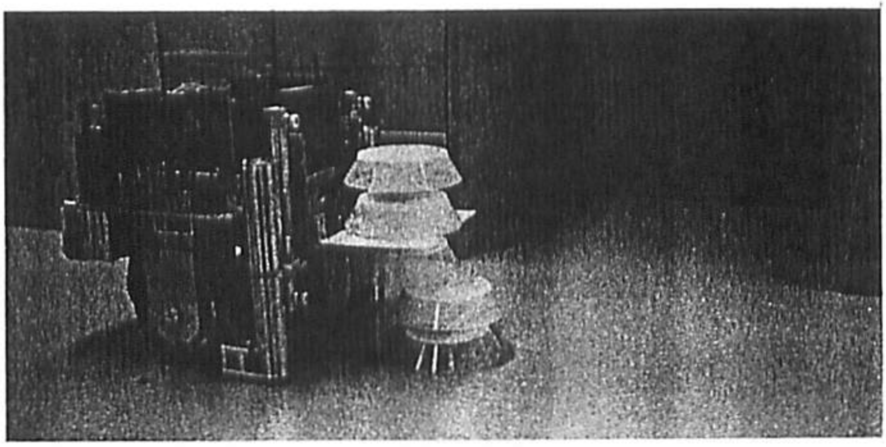


(3) Move backward

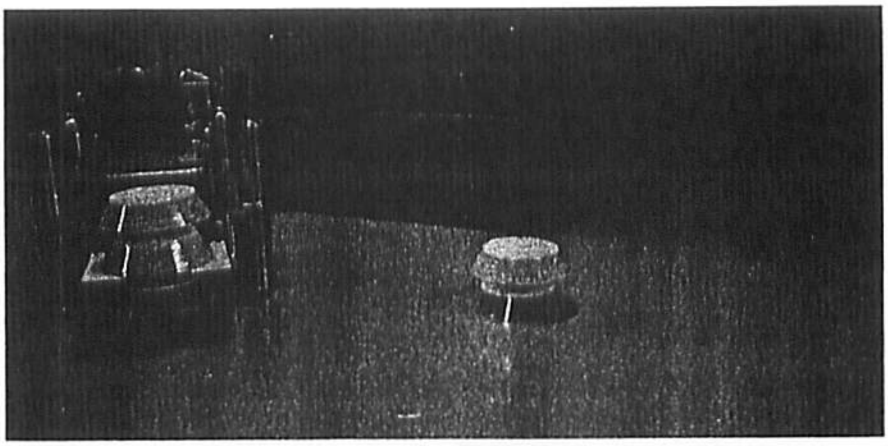
Fig. 10. (Continued)



(4) Insert and lift



(5) Pick off



(6) Leave the IDC

Fig. 10. Experimental results of IDC handling: (1) approach; (2) put down; (3) move backward; (4) insert and lift; (5) pick off; (6) leave the IDC.

signed to be a fully self-contained system, and is expected to function autonomously. The size of the robot is W: 460mm× D: 435mm× H: 480mm and the weight is approximately 45 kg.

Using the omni-directional mobile robot, the experiments were carried out to examine the proposed handling method of the IDC units as shown in Fig. 8 in a realistic condition. In the experiment, we assume a situation in which after the robot discovers a deadend pathway, it tries to place an IDC unit at corner of the pathway to let the other robots notice the fact that the deadend exists. By the placed IDC, wasteful behaviors, i.e., going into the deadend pathway, of the robots which happen to pass the corner can be avoided. The experimental result is shown in Fig. 10 as the series of photographs expressing the sequence of handling method. The robot approaches to the corner at first and the fork is moved downward until the bottom IDC touches the floor ((1) and (2)). Then, the robot goes backward (3). After the fork is moved upward and the robot moves forward, the robot picks the upper two IDC units, moves backward and goes somewhere else ((4) – (6)). The IDC is left at the corner. The handling of the IDC units is successfully conducted as shown in these photos. With the developed IDC units, the robots have become able to store location dependent and/or object dependent information into the units and put them at the sites or on the objects directly.

6. Summary

A framework of a new strategy for adaptation and evolution of the multiple autonomous mobile robots was presented to overcome major drawbacks which generally occur when applying adaptive and/or evolutionary techniques to the actual system. The most important idea of the strategy is to utilize (1) the advantageous parallelism of the multi-robot system, and (2) local information storage units with information processing and management capability. The IDC (Intelligent Data Carrier) unit was developed as a local information storage device with a unique mushroom-like structure to be easily handled by the forklift mechanism which can be mounted on the actual robot. The handling method of the IDC unit is examined through the experiment using an omnidirectional mobile robot, and the robot succeeded in placing the unit to indicate existence of the deadend to other robots. Though the adaptive and/or evolutionary methods which should be implemented onto the IDC unit for specific missions and environmental conditions should be discussed further in detail, the most essential and fundamental technique, i.e., the IDC system and its handling method, to realize the proposed strategy was established so that the robots can adapt and evolve as a population by accessing to locally available information which is stored and processed in the IDC units.

References

[1] J.S. Albus, System description and design architecture for multiple autonomous undersea vehicles, NIST Technical Note 1251 (1988).

[2] J.S. Albus and D.R. Blidberg, A control system architecture for multiple autonomous vehicles (MAUV), *Proc. Int. Symp. on Unmanned Untethered Submersible Technology*, Durham, NH (1987) 444–466.

[3] H. Asama, et al., Mutual transportation of cooperative mobile robots using forklift mechanisms, *Proc. IEEE Int. Conf. Robotics and Automation '96*, Minneapolis, MN (1996) 1754–1759.

[4] H. Asama, T. Fukuda, T. Arai and I. Endo, eds., Distributed Autonomous Robotic Systems (Springer, Berlin, 1994).

[5] H. Asama, A. Matsumoto and Y. Ishida, Design of an autonomous and distributed robot system: ACTRESS, *Proc. IEEE/RSJ Int. Workshop on Intelligent Robots and Systems*, Tsukuba, Japan (1989) 283–290.

[6] D. Bullock, J.C. Fiala and S. Grossberg, A neural model of timed response learning in the cerebellum, *Neural Networks*, 7 (6/7) (1994) 1101–1114.

[7] D.B. Fogel, *Evolutionary Computation* (IEEE Press, New-York, 1995)

[8] T. Fujii and T. Ura, Development of motion control system for AUV using neural nets, *Proc. IEEE Symp. on AUV Technology*, Washington, DC (1990) 81–86.

[9] T. Fukuda and T. Ueyama, *Cellular Robotics and Micro Robotic Systems* (World Scientific, Singapore, 1994).

[10] D.E. Goldberg, *Genetic Algorithms in Search, Optimization & Machine Learning* (Addison-Wesley, Reading, MA, 1989).

[11] K. Ishii, T. Ura and T. Fujii, A feed forward neural network for identification and adaptive control of autonomous underwater vehicles, *Proc. IEEE Int. Conf. on Neural Networks'94*, Orlando, FL (1994) 3216–3221.

[12] M. Kawato et al., Hierarchical neural network for voluntary movement with application to robotics, *IEEE Control Systems Magazine*, 8 (3) (1990) 8–16.

[13] P. Kerlirzin and P. Refregier, Theoretical investigation of the robustness of multilayer perceptrons: Analysis of the

linear case and extension to nonlinear networks, *IEEE Transactions on Neural Networks*, 6 (3) (1995) 560–571.

[14] C. Langton, Preface, *Artificial Life II* (Addison-Wesley, Reading, MA, 1992).

[15] K.S. Narendra and K. Parthasarathy, Identification and control of dynamical systems using neural networks, *IEEE Transactions on Neural Networks*, 1 (1) (1990) 4–27.

[16] D.H. Nguyen and B. Widrow, Neural networks for self-learning control systems, *IEEE Control System Magazine*, 10 (3) (1990) 18–23.

[17] S. Nolfi et al., How to evolve autonomous robots: Different approaches in evolutionary robotics, in: *Artificial Life IV* (MIT Press Cambridge, MA 1994) 190–198.

[18] *Proc. Int. Symp. on Distributed Autonomous Robotic Systems'92*, Saitama, Japan (1992).

[19] *Proc. Int. Workshop on Biologically Inspired Evolutionary Systems '95* (1995).

[20] L. Steels, Emergent functionality in robotic agents through on-line evolution, *Artificial Life IV* (MIT Press Cambridge MA 1994) 8–14.

[21] T. Suto and T. Ura, Unsupervised learning system for vehicle guidance constructed with neural network, *Proc. Int. Symp. on Unmanned Untethered Submersible Technology'91*, Durham, NH (1991) 203–212.

[22] T. von Numers et al., An intelligent data carrier system for local communication between cooperative multiple robots and environment, *Proc. 2nd IFAC Conf. on Intelligent Autonomous Vehicles'95*, Espoo, Finland (1995) 366–371.

[23] J. Wray and G.G.R. Green, Neural networks, approximation theory, and finite precision computation, *Neural Networks*, 8 (1) (1995) 31–37.

[24] J. Xiao et al., Evolutionary planner/navigator in a mobile robot environment, UNC Charlotte Technical Report 010 (1994).

Teruo Fujii received B.E., M.E. and Ph.D. degrees in Naval Architecture and Ocean Engineering from the University of Tokyo in 1988, 1990, and 1993, respectively. He served as an associate professor of Globe Engineering at the Institute of Industrial Science, University of Tokyo from 1993 to 1995. He is currently with the Biochemical Systems Laboratory at the Institute of Physical and Chemical Research (RIKEN). His research interests cover distributed autonomous robotic systems, evolutionary robotics, human–robot interaction, and ocean related robotic systems. He is a member of AAAS, IEEE, and INNS.

Hajime Asama graduated from the University of Tokyo in 1982 and received the doctor degree of engineering from the University of Tokyo in 1989. From 1986, he joined the Institute of Physical and Chemical Research (RIKEN) and he is currently a research scientist in RIKEN. His main interests are distributed autonomous robotic systems and intelligent bioprocess systems. He is a member of IEEE and the New York Academy of Science.

Thomas von Numers entered Helsinki University of Technology in 1983, where he studied manufacturing technology and manufacturing automation. From 1994 to 1995, he studied at the Institute of Physical and Chemical Research (RIKEN) as a visiting researcher. In 1995 he joined VTT Automation in Finland. His main interests are distributed autonomous robotic systems and applications of Intelligent Data Carriers in robotics.

Takanori Fujita graduated from Toyo University in 1995. He is currently a graduate student in Mechanical Engineering, studying on the topics related to Intelligent Data Carriers and their applications in distributed autonomous robotic systems toward his master's degree.

Hayato Kaetsu studied at Science University of Tokyo from 1968 to 1971. In 1971 he joined the Institute of Physical and Chemical Research (RIKEN) as an Engineer and is currently a Senior Engineer. His main interests are distributed autonomous robotic systems.

Isao Endo graduated from the University of Tokyo in 1965 and received a Doctor of Engineering degree from the University of Tokyo in 1970. He joined the Institute of Physical and Chemical Research (RIKEN) in 1970 and is currently a chief scientist at the Biochemical Systems Laboratory. Since 1989 he has been co-appointed as a visiting professor of Saitama University. In 1994 he received a Honorary Doctor of Engineering from Helsinki University of Technology. His main interests are bioprocess engineering and distributed autonomous robotic systems. He is a member of the New York Acad. Science, AIChE, ACS, Eng. Acad. Japan, etc.