A Study on Dynamically Reconfigurable Robotic Systems*
(Recognition and Communication System of Cell-Structured Robot "CEBOT")

Toshio FUKUDA**, Yoshio KAWAUCHI***,
Martin BUSS**** and Hajime ASAMA*****

The **dynamically reconfigurable robotic system** (DRRS) is a new kind of robotic system which is able to reconfigure itself to optimal structure depending on the purpose and environment. To realize this concept, we have proposed CEBOT (cellular robotics). Communication is needed in the CEBOT system as follows. When cells are separated, the communication master cell needs to know the other cell's function and positions and determine the target cell for docking. Mobile cells should be able to coordinate with other mobile cells. When cells are docked, forming cell structure/module, a master cell should control the bending joint cell and know of which cells the construction is composed. In this paper, we propose a communication protocol for both the cases with an optical sensor applicable to CEBOT. Some experimental results are shown by realizing the proposed communication method between cells.

Key Words: Robotics, Application of Control, Dynamically Reconfigurable Robotic System, Cell Structure, Self-Organizing System, Communication, Protocol, Self-Repairing Robot, Fault Tolerance

1. Introduction

The **cellular robotic system** "CEBOT" is a new kind of multiple distributed intelligent robotic system which can reconfigure both it hardware structure and software structure in order to carry out many sorts of tasks under various environments. CEBOT consists of many basic units called **"cells"**. Therefore, CEBOT is very similar to a living creature in its structure. The basic concept of CEBOT, a method of realizing automatic approach, docking, and separating, and an optimal structure planning method step have already been studied by the authors[(1)~(4)]. Each cell has one simple function, a sensor system, a communication system, a database, and a knowledge base. When many cells combine and configure a complicated structure, the cells can perform difficult tasks which a single cell cannot carry out. During task execution, each cell must communicate with others because a cell needs many kinds of data of other cells, for example, the output of a photosensor for detecting other cells, the output of the ultrasonic sensor for obstacle avoidance, and the value of position sensor for controlling

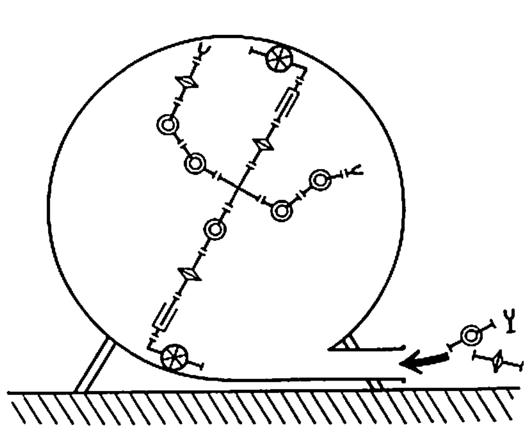


Fig. 1 Application of CEBOT inside a tank

* Received 3rd October, 1990. Paper No. 89-0345A
** Nagoya University, Department of Mechanical Engineering, Furo-cho, Chikusa-ku, Nagoya 464-01, Japan
*** Toyo Engineering Corporation, 8-1, 2-chome Akanehama, Narashino-shi, Chiba 275, Japan
**** Technical Univ. Darmstadt Schlossgraben 1, D-6100, Darmstadt, Germany
***** The Physical and Chemical Research Institute 2-1 Hirosawa, Wako-shi, Saitama 351-01, Japan

the structure. In cases in which many cells carry out a given task cooperatively, it is necessary for cells to communicate with each other. Communication is a very important problem for developing a **dynamically reconfigurable robotic system.** Thus, this paper mainly deals with the **communication of a distributed system.** In particular, the **necessity of communication and two communication protocols** for the distributed system are reported. Based on the protocols, some types of communication among cells are realized by using the **optical communication sensor** for the undocked state and the **communication bus** for the docked state.

2. Outline of CEBOT

CEBOT is a system which is constructed of autonomous components called "cells" or "modules".

A cell is an intellectual function unit which has one function and more than one connectable face.

A module is an intellectual function component which is constructed of cells and has more than one connectable face.

The cell literally corresponds to a biological cell; the module corresponds to a biological cellulation or organ which is group of cells. The cell type is shown in Table 1, and examples of cells (series II) that we fabricated are shown in Figs. 2 and 3. Figure 2 shows the cells in an undocked state, while Fig. 3 shows a constructed module of the docked cells. Every cell has eight LEDs and three photodiodes (PD 1, 2, 3) for autonomous approach and docking and three ultrasonic sensors (one transmitter, two receivers) for obstacle avoidance (see Fig. 4). The efficiency of the sensor arrangement and the experimental results of automatic approach, docking, detaching and obstacle avoidance have already been reported. Every cell has two communication systems. One is an optical rotating sensor on the front connectable face for cells in the

Table 1 Cell type

cell type	symbol
moving cell	
bending cell 1	
bending cell 2	
rotating cell	
sliding cell	

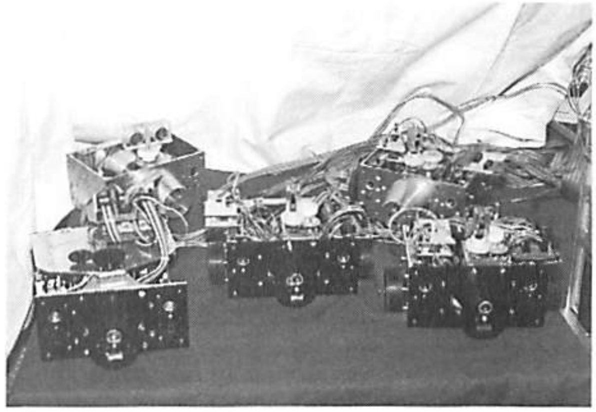


Fig. 2 Photo of CEBOT in undocked state

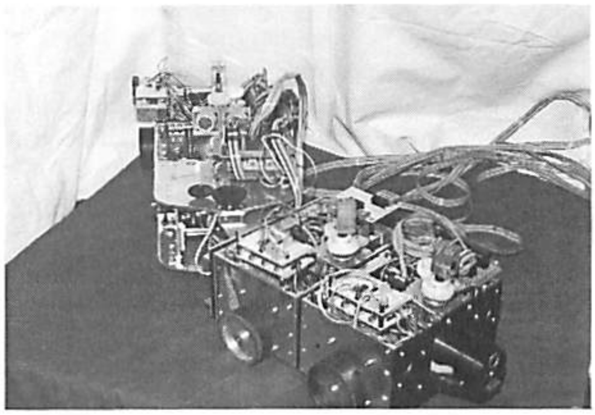
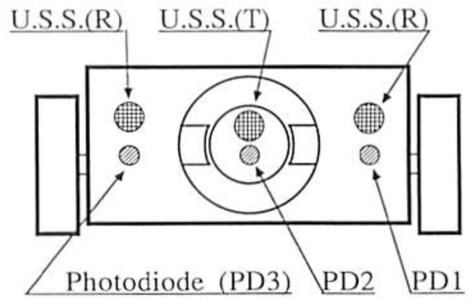
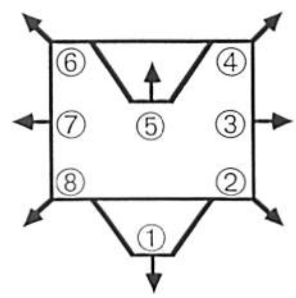


Fig. 3 Photo of CEBOT in docked state



(a) Eight LEDs for position and attitude detection



(b) Three ultrasonic sensors and photodiodes

Fig. 4 Sensor arrangement

undocked state and the other is a communication bus-line (COMBUS) for cells in the docked state. There are ten lines between the front and back faces in CEBOT and the structure COMBUS results from jointing the connectable face. A mobile cell has two pulse motors for moving, and a bending joint cell controls the bending angle by its own DC motor. The total control system of CEBOT is shown in Fig. 5.

3. Necessity of Communication between Cell

In order for a system to be autonomous, decentralized and coordinated, communication between cells is necessary. The necessity of communication under both states is shown as follows.

3.1 The necessity of communication in the undocked state

When CEBOT creates an optimal structure for a given task, CEBOT needs to communicate for the following reasons.

(1) A moving master cell must know if cells with the desired function are there.

There are various cell types (see Table 1). Therefore, a mobile cell/module must be able to recognize whether or not the cell with the desired function is there.

(2) The master cell must choose one target cell from the suitable function cells.

If there are many cells which have the desired function, a mobile cell must choose which cell to couple with.

(3) The master must measure the relative angle and distance.

After the master cell chooses the target cell, the data of the relative angle and distance between cells aid in autonomous approach and docking.

(4) Coordinated control is realized by communication.

When a mobile cell carries a large structure which cannot be carried by one cell, it can be carried by several cells.

3.2 The necessity of communication in the docked state

After CEBOT constructs the optimal structure, communication is needed for the following reasons:

(1) To control cell structure.

A moving master cell must control cell structure to execute given tasks. For example, the master cell changes the angle of the bending joint cell in the structure.

(2) For transmitting data to other cells.

When a mobile cell constructs a mobile module with other cells, the mobile cell requires data from other cells.

In the case of autonomous docking, the mobile cell requires data from the cell's photodiodes at the front of the module. In the case of obstacle avoidance, the mobile cell requires data from the ultrasonic sensors.

(3) For self-checking.

One of the features of CEBOT is fault tolerance. If a part of the module breaks down, CEBOT can maintain its functions by substituting another cell for the malfunctioning cell, so it is not necessary to change the whole system. Therefore, it is necessary to communicate in order to know of what cells the structure is composed and for self-checking.

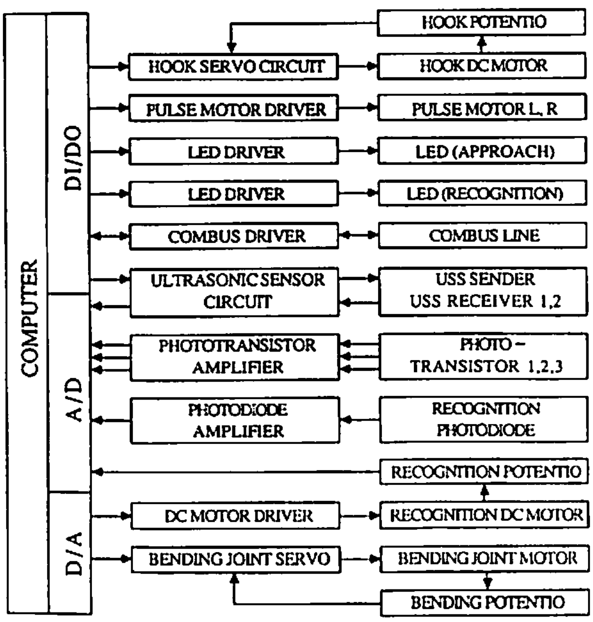


Fig. 5 Control system structure of CEBOT

4. Communication Protocol

4.1 Communication protocol in the undocked state

Communication in the undocked state is carried out by the serial 12-bit signal. The 12 bits are divided into three parts (H, M, L-Digit) of 4 bits. The meanings of function words are transmitted by H-digit, sender cell address is transmitted by the M-digit, and the L-digit indicates the receiver cell address. Also, 12 bits are sandwiched between one start bit and two stop bits (see Fig. 6). The error is checked by two methods. One, which is on the word level, involves checking whether or not both start and stop bits are received. The other, which is the communication level, involves the checking of the function word. Many controls are realized by changing the H-digit. This time, we define the function word, as shown in Table 2, in order to realize all recognition. The measuring relative angle, the (θ_1, θ_2) and distance (x) are shown in Fig. 7. Figure 8 shows the basic sequence of the communication. This communication is carried out in 6 steps as follows:

step 1: A communication master cell calls cells with desired function. Communication slave cells adjust their sensor to the communication master cell and stop rotating sensor (rough adjustment).

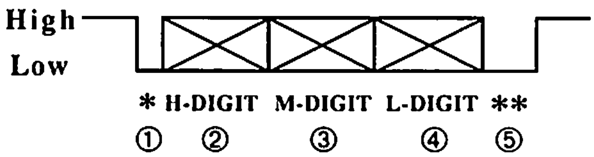
step 2: A desired function cell answers. The other cells start to rotate the sensor again.

step 3: The communication master cell selects an object cell which answers first.

Table 2 Communication sequence control scheme

step	DIGIT 1	2	3	DESCRIPTION
1	1	x	F	x calls cell with function F
2	2	y	x	one cell with function F (address=y)answers
3	3	x	y	x calls y (y stops rotation)
4	4	y	x	waiting for end of adjustment
5	5	x	y	x finishes receiver adjustment waiting for end of adjustment
6	6	data		y finishes receiver adjustment and transmits θ_2

Digit1: control function
Digit2: transmitter address
Digit3: receiver address



① Start bit,
② Data word function, H-digit
③ Transmitter address or data, M-digit
④ Receiver address or data, L-digit
⑤ Two stop bits.

Fig. 6 Serial 8-bit communication protocol

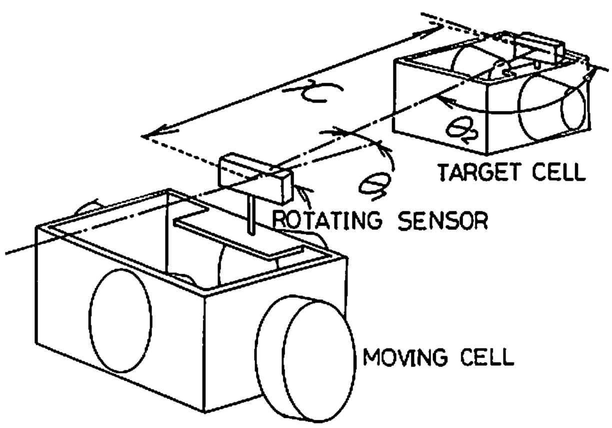


Fig. 7 Geometry of sensor and receiver

step 4: The master cell adjusts the rotating sensor to the object cell (fine adjustment).

step 5: The object cell adjusts the sensor to the master cell again (fine adjustment).

step 6: The object cell transmits relative angle data (see Fig. 7).

In all steps, if there is response in transmitting communication words during a set time, the communication sequence proceeds. However, if there is no response, it is a recognized error. The experimental results of this communication protocol are shown in section 6. 1.

4. 2 Communication protocol in the docked state

The communication in the docked state is done by parallel 8-bit signal. The 8 bits are divided into three parts, as shown in Table 3. One bit is allocated to show whether or not transmitted signals are valid, three bits show the meaning of the signals (function word) and the remaining four bits show the value related to the function word (data bit). If the "data valid" shows low, all signals are valid. Table 4 shows the relationship between the kind of function word and communication bit. As shown in Table 4, function words are composed of data, cell address and control

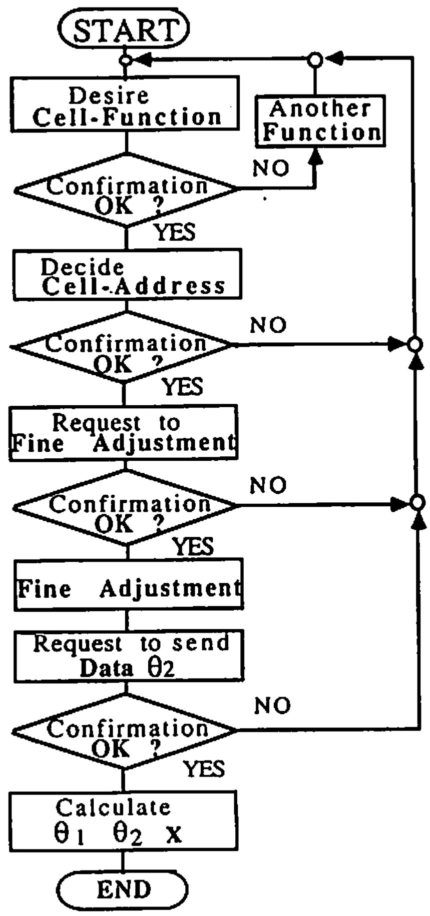


Fig. 8 Algorithm for communication in undocked state

word. The value of the sensor is shown by the function word (data). The function word (address) is used in the case of calling cells. The function word (control) shows the meaning of communication signals. It is possible to achieve many communications through the changing of meanings of control words (see Table 5). The communication is carried out in three steps (see Fig. 9). Table 6 shows an example of communication by the defined protocol. In this example, a mobile cell requests a cell which is docked on the front of the mobile cell to transmit the value of the left photodiode and the cell answers it. The experimental results are shown in section 6. 2.

Table 3 Pin assignment of the connector

Pin-No	Name	Description
1	Bit7	Data valid, activ low
8	Bit6	Bus function 2
2	Bit5	Bus function 1
9	Bit4	Bus function 0
3	Bit3	Data bit 3
10	Bit2	Data bit 2
4	Bit1	Data bit 1
11	Bit0	Data bit 0
5	GND	Signal ground
12	GND	Signal ground
6,7,		Future expansion for
13,14		power supply lines

Table 4 Bus function bit

Bit 2 1 0	Bus function, data word type
0 0 0	Data low digit
0 0 1	Data high digit
0 1 0	Address low digit
0 1 1	Address high digit
1 0 0	Control low digit
1 0 1	Control high digit
1 1 0	spare
1 1 1	bus reset

Table 5 List of control words and their function

Ctrl	Description
$0x	Confirmation from cell [x]
$10	Attention, next word is address
$11	End of Attention, next word address
$12	Check for cell malfunction
$20	Read value of left photodiode
$21	Read value of center photodiode
$22	Read value of right photodiode
$23	Read value of rotating photodiode
$24	Read obstacle sensor, left receiver
$25	Read obstacle sensor, right receiver
$3z	Read present actuator position
$4z	Change actuator to new position
	z=0 -> hook coupling mechanism
	z=1 -> joint actuator
	z=2 -> rotating sensor motor
	z=3 -> obstacle sensor, sender
	z=4 -> LEDs for attitude finding

5. Communication method

On the basis of the protocol shown in section 4, a signal is transmitted by the following methods.

5.1 Communication method under separated state

The communication is realized by rotating the communication sensor (see Fig. 10). It is controlled by a DC motor, and it has one LED (infrared type) for the transmitter and one photodiode for the receiver. The example of a rotating sensor is shown in Fig. 11. A pulse is produced when LED is turned on and off by DI/DO. The photodiode receives and amplifies the

Table 6 Example of transfer sequence

Cycle No.	sender M	sender S	Data	Type	Description
0	●		$1	Ctrl-H	Attention followed by an
1	●		$0	Ctrl-L	address word (control $10)
2	●		$M	Addr-H	M: address of master cell
3	●		$S	Addr-L	S: address of slave cell
4		●	$0	Ctrl-H	Confirmation by
5		●	$S	Ctrl-L	slave cell S
6	●		$2	Ctrl-H	Photodiode PD1 data
7	●		$0	Ctrl-L	request (control $20)
8		●	$M	Data-H	Slave cell S sends 16-bit
9		●	$N	Data-L	photodiode value
10		●	$N	Data-H	M: most, N:next, L:least
11		●	$L	Data-L	significant digit
12	●		$1	Ctrl-H	Master cell M sends End
13	●		$1	Ctrl-L	of attention to slave (ctrl $11)
14	●		$M	Addr-H	M: address of master cell
15	●		$S	Addr-L	S: address of slave cell
16		●	$0	Ctrl-H	Confirmation by
17		●	$S	Ctrl-L	slave cell S

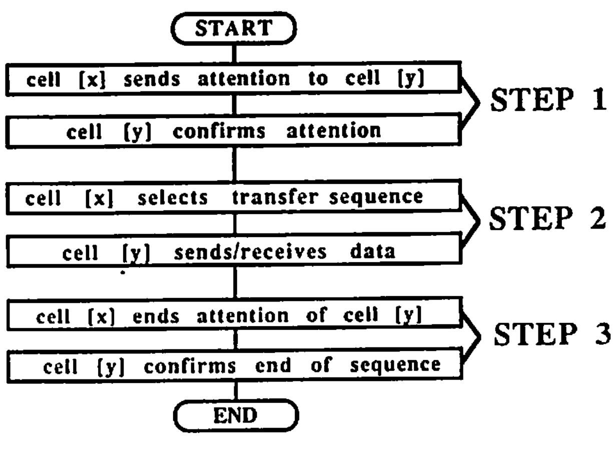


Fig. 9 Three-step handshake communication sequence

pulse. The output of the photodiode is taken in A/D and whether the output value of pulse is larger than the threshold or not is recognized. The relative distance between the sender cell and the receiver cell is measured according to the output value of the photodiode. The output value of LED and photodiode which is the experimental result of communication under the undocked state is shown in Fig. 12. Figure 13 shows the relation between the relative distance (x) and the output value of the photodiode. The communication speed is about 1 Kbps, as shown in Fig. 12. The direction of the rotating sensor is measured by a potentiometer in the sensor module.

5.2 Communication method under docked state

In the docked state, the communication is carried out through COMBUS connected by 14-pin connector (see Fig. 14). Transmitting and receiving are performed by DI/DO.

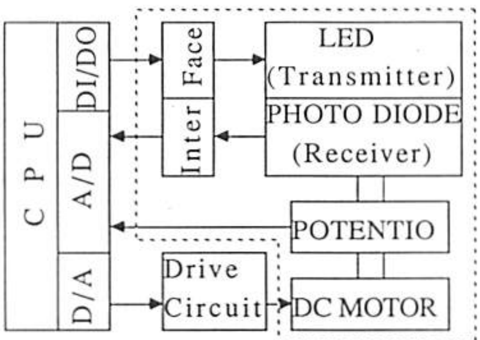


Fig. 10 Control system of rotating sensor

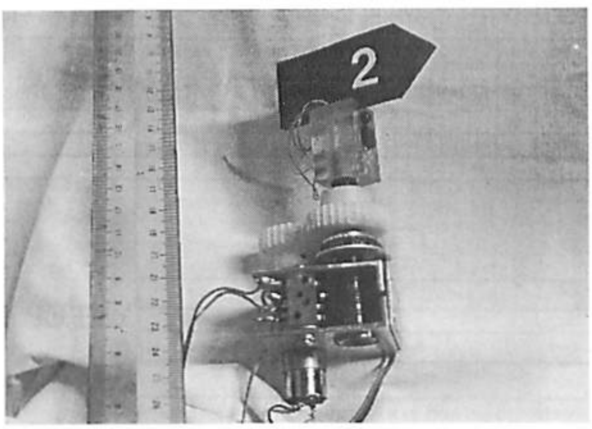


Fig. 11 Photo of rotating sensor

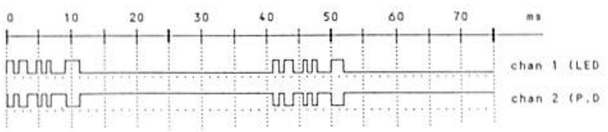


Fig. 12 Signal timing diagram

6. Experimental Results

The communicatin experiments are performed on the basis of the communication protocol.

6.1 Experimental results of communication in the undocked state

Two of the purposes of communication are cell identificatin and automatic measurement of the relative distance and angle. Three cells are arranged as shown in Fig. 15, and communication between the master cell (cell-0) and the slave cell (cell-1) is achieved. Figure 16 shows the communication sequence as shown on a computer monitor. In Fig. 16,

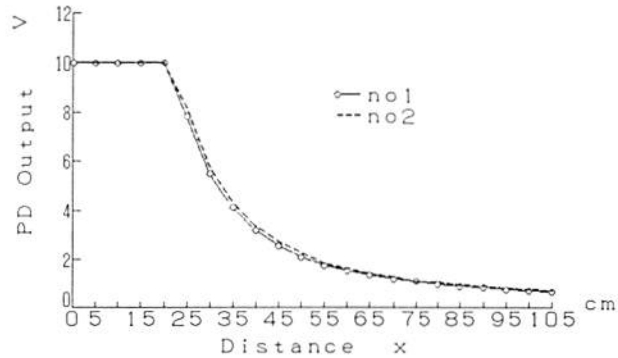


Fig. 13 Output of photodiode dependent on LED distance

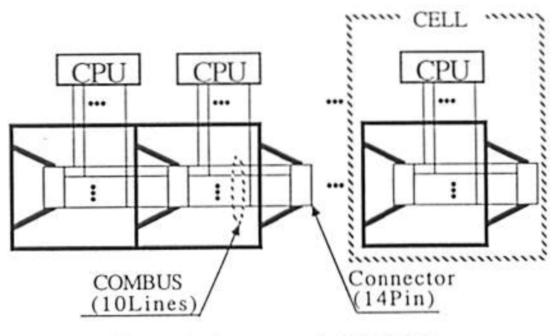


Fig. 14 Concept of COMBUS

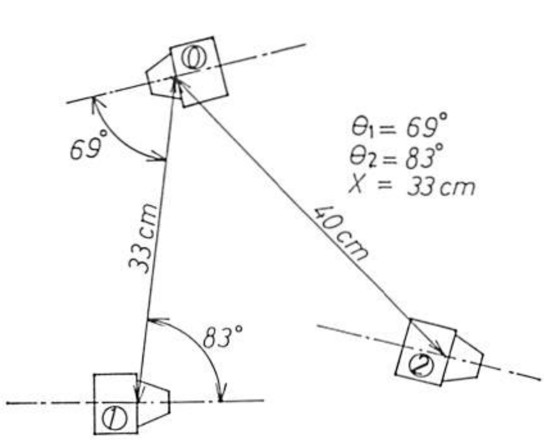


Fig. 15 Setting of mobile and object cells

the communication statements are shown as comments, and the numbers to the left of the comments indicate the communication step as follows.

①-②: Decision of master cell's address and desired cell function.

③-④: All cells except the communication master cell adjust their sensors to the sender cell.

⑤-⑪: The communication sequence is followed in order.

⑫: The communication master cell calculates the relative distance and angle.

The experimental results show that after the master cell address and desired function are decided by the operator, automatic communication is executed and the master cell recognizes the relative angle, which is θ_1, θ_2 and the distance, which is x as 51.4°, 67.7°, and 29 cm. The angle error is about 15° and the distance error is about 2 cm (6.1 %). The angle error is caused by the directivity of a photosensor, so the angle error can be reduced by using a more strongly focused sensor. The most important aim of the communication in the undocked state is cell identification; therefore, it is not necessary to use a strongly focused sensor. After identifying the cell, automatic approach and docking are realized by the existing sensor arrangement (see Fig. 4), so it is sufficient for a master cell to measure the relative distance as shown in Figs. 17, and 18. Figure 17 shows the output of the potentiometer in the case of communication between cell-0 and cell-1 while Fig. 18 does that between cell-0 and cell-2. All numbers in Figs. 17, and 18 correspond to step numbers in Fig. 16. Both Fig. 17 and Fig. 18 show that the object cell has two sensor adjustments, one of which is a rough adjustment and the other, a fine adjustment. The other cells start to rotate the sensor for preparation of the next communication after rough adjustment.

```
1   sender ?0

    MOVING_CELL=1
    TARGET_CELL=2
2   BENDING_JOINT_CELL=3
    ROTATING_JOINT_CELL=4
    SLIDING_JOINT_CELL=5
    function ? 1

3   cell #1 rough adjustment ended.
4   cell #2 rough adjustment ended.
    data error.   808
    data error.   800
5   data error.   0
    cell #2 has received data 101 .
    ***cell #0 calls cell with function 1.
6   cell #1 has received data 101 .
    ***cell #0 calls cell with function 1.
7   cell #2 has not the desired function!
    cell #0 has sent data 101
8   cell #0 has received data 210 .
    ***cell #1 with function 0 answers.
    cell #1 has sent data 210
    cell #1 has received data 301 .
9   ***cell #0 acknowledges receiver 1.
    cell #0 has sent data 301
    cell #0 has received data 410 .
10  ***cell #1 sends adjustment request to cell 0.

    cell #0 fine adjustment ended.
    cell #1 has sent data 410
    cell #1 has received data 501 .
    ***cell #0 finishes fine adjustment and
11                 sends fine adjustment request to cell 1.

    cell #1 fine adjustment ended.
    cell #0 has sent data 501
    cell #0 has received data 62f .
    ***cell #1 finishes fine adjustment and  transfers data.
    Transfer sequence ended successfully!
12  cell #0 has received theta2 = 67.7
    cell #0 theta 1 = 51.4
    distance x =   29 cm
```

Fig. 16 Communication experimental result

6.2 Experimental result of communication in the docked state

The experiment on communication with COMBUS is performed under the cell location, as shown in Fig. 19. The communication sequene is shown in Table 6, the description of communication words is shown in Tables 3 and 4, and the output of COMBUS is shown in Fig. 20. In each step number in Fig. 20, the communication is executed as follows:

①; Cell-0 calls cell-3.

②; Cell-3 answers it.

③; Cell-0 requests the data value of PD1 from cell-3.

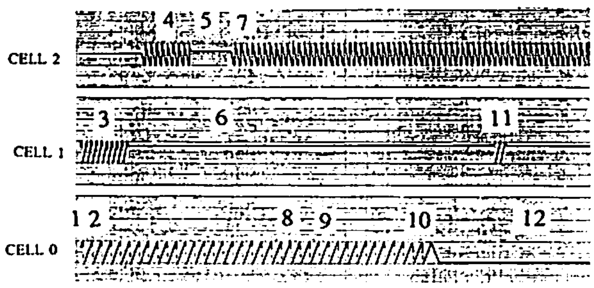


Fig. 17 Sensor behavior (sender cell-0, receiver cell-1)

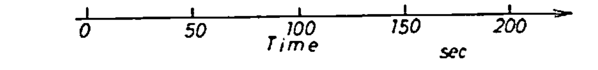


Fig. 18 Sensor behavior (sender cell-0, receiver cell-2)

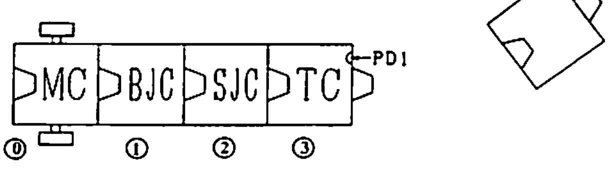


Fig. 19 Communication example for a docked CEBOT structure

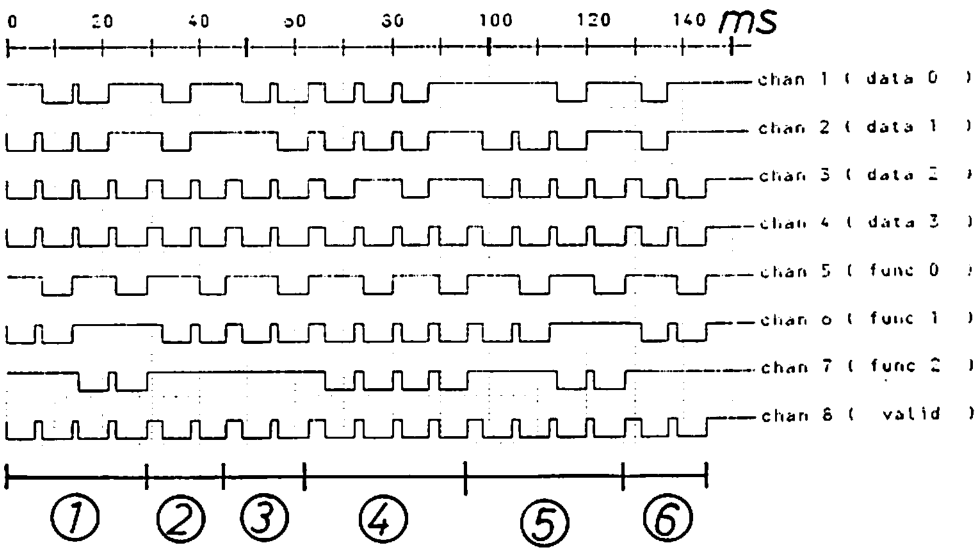


Fig. 20 COMBUS timing diagram

④; Cell-3 transmits the data value of PD1.

⑤; Cell-0 announces the end of communication with cell-3.

⑥; Cel-3 responds to it.

In this experiment, the output value of PD1 of cell-3 is recognized as 407 in the hexa-decimal sysetem number by cell-0. Thus the aim of the communication is achieved. It takes about 140 ms to complete this communication, as shown in Fig. 20.

7. Conclusions

(1) We have explained the necessity of the communication in both the docked and undocked states for CEBOT as an autnomous decentralized coordinated system and we have proposed a method for achieving this.

(2) We defined the communication protocol in the undocked state and realized it by optical sensor (LED, PD).

(3) We determined the communication protocol in the docked state and realized it by sending the PD value by COMBUS in the cell structure.

In this paper, we have reported the recognition and communication system of CEBOT. This communication makes CEBOT flexible for tasks and realizes the control of the cell structure. This system necessitates future research in the field of advanced robotics. By solving these probems, the dynaically reconfiguble robotic system which can execute many tasks under various environments will be realizd.

References

(1) Fukuda, T. and Nakagawa, S., "A Self Recognized Robotic System with Cell Structure" Trans. IEE Japan,(in Japanese),Vol. 107-C, No. 11(1987), p. 1019.

(2) Fukuda, T. and Nakagawa, S., "A Dynamically Reconfiguable Robotic System (Concept of a System and Optimal Configuration)", Proc. IECON'87, (1987), p. 588.

(3) Fukuda, T. and Nakagawa, S.: "Approach to the Dynamically Reconfigurable Robotic System", Journal of Intelligent and Robotic Systems, Vol. 1, No. 1 (1988), p. 55.

(4) Fukuda, T., Nakagawa, S. Kawauchi, Y and Buss, M., "Self Organizing Robots Based on Cell Structures-CEBOT", Proc. 1988 IEEE International Workshop on Intelligent Robots and Systems (IROS'88), p. 145.