Networking and Information Distribution in Robots Composed of Identical Units*

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Robotic systems composed of identical units can be made flexible in size, degrees of freedom, and output motions in response to desired tasks. There are three basic characteristics which are desirable in such systems: (1) expandability, (2) perceptibility of unit's location, and (3) fault tolerance. These characteristics can be varied depending on the networking and information distribution scheme adopted. The present paper proposes a method of classifying and comparing networking schemes for such robotic systems based on the above-mentioned basic characteristics, and the optimal networking scheme is then clarified for a particular application. An experimental transfer robot composed of identical units, each of which has nineteen arms, was constructed, and the experimental results are shown to support the proposed method.

Key Words: Robotics, Networking, Information Distribution, Cellular Robot, Control System

1. Introduction

With the composition of robots with identical units, robotic systems can be made flexible in size, degrees of freedom and output motions for a desired task, and some such robots have already been proposed^{(1),(2)}. In such robotic systems, three basic characteristics are required: (1) expandability, with which any number of units can be added to or removed from the robotic system, (2) perceptibility of unit's location in the robotic system, and (3) fault tolerance to errors in the system. These characteristics are greatly dependent on networking configurations for information exchange among units and information distribution schemes in the system.

In the present paper, the hardware and software of the control systems of robotic systems composed of identical units are examined. First, networking configurations and information distribution schemes

are classified and compared with respect to the three characteristics mentioned above. Then, based on the results, an experimental transfer robot composed of identical units is constructed and tested.

2. Networking Configurations

2.1 Classification of networking configurations

Several networking configurations have been proposed for application to multiprocessor and distributed control systems⁽³⁾. These configurations can be classified into eight patterns as shown in Fig. 1. These eight configurations are examined and their suitability to the networking configurations for information exchange among units is evaluated. In Fig. 1, marks ○ denote units, and the units connected mutually by solid lines can exchange information with each other.

2.2 Criteria for evaluation

To make it possible to expand the size of the system easily, it is desirable to use a networking configuration in which it is unnecessary to cut the existing connections in order to add a unit to the system, and in which the number of connections in the entire system and the number of units connected to

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each unit are small. Then, considering expandability, it is proposed that networking configurations should be evaluated by the ease of addition A_d , the average number of connections N_c , and the maximum number of units connected to one unit in the system F_0 . Here, networks are judged to have the ease of addition A_d if the existing connections are unnecessary to be changed when a unit is added to the system. The average number of connections N_c is the total number of connections in the system divided by the total number of units.

Although it is possible to give each unit the ability to perceive its location independently regardless of the networking configuration, it is desirable that each unit perceives its location by exchanging information with units which have already perceived their locations. In this case, when the connection line is commonly used by more than two units, each unit must specify the unit to exchange information with in order to perceive its location. However, when the connection line is used between only two units, such a specification is not needed. When the rule of connection is the same with every unit, the relative positions of the units with which information is exchanged are the same, and so each unit can perceive its location easily and with certainty. Then, from the point of

view of perceptibility of a unit's location, networking configurations can be evaluated by the type of connection C_t and the regularity of rules of connection R_e . The type of connection C_t is denoted as binary or multiple, where a binary-type connection is a connection between only two units, and a multiple-type connection means that there is a common connection line among three or more units. The regularity of rules of connection R_e is denoted by whether the rules are the same with all units or whether some units have unique connection rules.

When there are faults in units or connections, if dataflows to all the working units are possible, all the units can receive all the available information and fault tolerance of the system can be achieved. Then, from the point of view of fault tolerance, networking configurations can be evaluated based on robustness to faults in units T_u and in connections T_c . Robustness T_u and T_c are determined by whether dataflow to other units is possible or not when there is a breakdown in the port for information exchange in any unit, and in any connection in the system, respectively.

2.3 Evaluations

The results of evaluations of networking configurations are listed in Table 1. When A_d is $\bigcirc$, it is unnecessary to change existing connections when units are added to the system. When A_d is $\times$, it is necessary to change the existing connections. In the N_c and F_0 columns, N denotes the total number of units. In the C_t column, *Bt.* and *Mt.* denote binary-type connection and multiple-type connection, respectively. In the R_e column, *R.* and *Ir.* denote regular connection and irregular connection, respectively. When T_u or T_c is $\bigcirc$, fault tolerance to respective faults can be achieved. The symbol $\times$ indicates that fault tolerance cannot be achieved. In the case where fault tolerance can be achieved when only one unit or connection breaks down, T_u or T_c becomes Δ . For mesh-type configuration, evaluations are made for not only the quadrangular type shown in Fig. 1, but also for triangular and hexagonal types.

From the results of evaluations as shown in Table 1, the mesh-type configuration is known to have the best characteristics for the networking configuration. In addition, when radio communications are permitted, fault tolerance in connections is no longer necessary, so a parallel connected networking configuration has good characteristics as well, in that each unit is equipped with a tag and a sensor to measure relative positions of other units in order to perceive its own location.

Fig. 1 Types of networking configurations

Table 1 Evaluation of networks

Type	A_d	N_c	F_0	C_t	R_e	T_u	T_c
Linear Array	$\bigcirc$	$(N-1)/N$	2	Bt.	R.	$\times$	$\times$
Ring	$\times$	1	2	Bt.	R.	Δ	Δ
Star	$\bigcirc$	$(N-1)/N$	$N-1$	Bt.	R.	$\times$	$\times$
Tree	$\bigcirc$	$(N-1)/N$	3	Bt.	R.	$\times$	$\times$
Mesh	$\bigcirc$	1.5~3	3~6	Bt.	R.	$\bigcirc$	$\bigcirc$
Chodal Ring	$\times$	1.5~2	3~4	Bt.	Ir.	$\bigcirc$	$\bigcirc$
Completely Connected	$\bigcirc$	$(N-1)/2$	$N-1$	Bt.	R.	$\bigcirc$	$\bigcirc$
Parallel Connected	$\bigcirc$	1/N	$N-1$	Mt.	R.	$\bigcirc$	$\times$

3. Information Distribution Schemes

3.1 Classes of information

In systems composed of identical units, two classes of information are required; one is information necessary for each unit to perceive its location, the other is information to control motion of the system and the units. The latter can be classified into three levels: the goal of the task, the desired motion of the system and the units at every instant to achieve the goal, and the desired values of all of the actuators at every instant to achieve the desired motion.

3.2 Classification of information distribution schemes

Information distribution schemes can be roughly classified into two classes depending on whether or not there exists a so-called host unit which manages all the information of all units in the system. In the case where a host unit exists in the system, we call the system a centralized system, and in the case where a host unit does not exist, a decentralized system.

In the systems whose networking configurations are chodal ring or parallel connected, not all units can perceive their location by the method proposed in chapter 2. Thus in addition to the method proposed in chapter 2, we will take into account the case where each unit has the function to perceive its own location without exchanging information with other units ($f-1$), and the function to control dataflow patterns ($f-2$). Therefore, information distribution schemes to perceive each unit's location are classified into four types: P-I, P-II, P-III and P-IV. Namely, in P-I, the system is centralized and the host unit has the function ($f-1$). In P-II, the system is centralized and the host unit has the functions ($f-1$) and ($f-2$). In P-III, the system is decentralized and the units do not have any functions by which to independently perceive their location. In P-IV, the system is decentralized and each unit has the function ($f-1$). P-I is applicable to star networking configuration, P-III is applicable to linear, ring, star, tree, mesh, and completely connected networking configurations, and P-II and P-IV are applicable to all networking configurations shown in Fig. 1.

The goal of the task is not to be different information among units including the host unit, and not to be varied by types and motion of the system, but that the desired motion of the system and the units and the desired values of the actuators are different among units managing such information. The desired motion can be classified into that relating to the whole system and that relating only to each unit. Then, distribution schemes for motion control can be classified into nine types, as shown in Fig. 2, when distributing informa-

tion to the user, the host unit, and among the units. In Fig. 2, C-I ~ C-VII are centralized, C-VIII and C-IX are decentralized, and ①, ②, ②' and ③ denote the goal of the task, the desired motion of the system, the desired motion of each unit, and the desired values of the actuators, respectively. The information enclosed by the solid line is given by the user, while the information enclosed by the broken line is processed by the units.

3.3 Criteria for Evaluation

It becomes difficult to construct large-scale robotic systems employing information distribution schemes in which increasing the number of units increases the amount of information to be given by the user and to be managed in each unit. Then, expandability of information distribution schemes can be evaluated by the invariance of the amount of information to be inputted by the user I_i and to be managed in each unit I_m . I_i and I_m are determined by whether or not the amount of information to be inputted by the user and be managed in each unit is invariant for different numbers of units in the system.

Each unit must perceive its location without being told directly by the user. Then, the perceptibility of unit's location of information distribution schemes can be evaluated by the availability of information used for perception of unit's location A_i . This criterion is determined by whether or not all the units can acquire information to perceive their own location without being given such information directly by the user.

In systems employing information distribution schemes in which some units manage information concerning other units or some units deliver information processed by them to other units, when such units break down, other units cannot operate normally even if they still function correctly. Therefore, fault tolerance of information distribution schemes can be

Type	User	Host Unit	Unit
C-I	①	① ② ③	③
C-II	①	① ② ②'	② ③
C-III	①	① ②	② ②' ③
C-IV	①	①	① ② ③
C-V	① ②	② ③	③
C-VI	① ②	② ②'	② ③
C-VII	① ②	②	② ②' ③
C-VIII	①	—	① ② ③
C-IX	① ② ②'	—	② ③

Fig. 2 Types of information distribution schemes for motion control

evaluated by the nonvolatility of information V_i . This is determined by whether or not the working units can operate when any other unit in the system breaks down.

3.4 Evaluations

The results of the evaluations are shown in Table 2. In the table, $\bigcirc$ indicates that the information distribution scheme satisfies the criterion for evaluation, $\times$ indicates that it does not satisfy the criterion, and $-$ indicates that the criterion for evaluation is not concerned. As can be seen in the table, P-III and P-IV are known to be the optimal distribution schemes of information for perception of unit's location. As for the distribution of information for motion control, there are no schemes suitable for all criteria. In the case where the expandability is considered to be more important, C-III, C-IV and C-VII are optimal, whereas C-VIII and C-IX are optimal when fault tolerance is considered to be more important.

4. Discussions on an Experimental Transfer Robot

An experimental transfer robot composed of identical units, each of which has many arms, has been constructed based on the results presented above, and was examined experimentally.

Table 2 Evaluation of information distribution schemes

Type	I_i	I_m	A_i	V_i
P-I	-	$\times$	$\bigcirc$	$\times$
P-II	-	$\times$	$\bigcirc$	$\times$
P-III	-	$\bigcirc$	$\bigcirc$	$\bigcirc$
P-IV	-	$\bigcirc$	$\bigcirc$	$\bigcirc$
C-I	$\bigcirc$	$\times$	-	$\times$
C-II	$\bigcirc$	$\times$	-	$\times$
C-III	$\bigcirc$	$\bigcirc$	-	$\times$
C-IV	$\bigcirc$	$\bigcirc$	-	$\times$
C-V	$\bigcirc$	$\times$	-	$\times$
C-VI	$\bigcirc$	$\times$	-	$\times$
C-VII	$\bigcirc$	$\bigcirc$	-	$\times$
C-VIII	$\times$	$\bigcirc$	-	$\bigcirc$
C-IX	$\times$	$\bigcirc$	-	$\bigcirc$

Fig. 3 A single unit

4.1 Schematic apparatus

An experimental unit is shown in Fig. 3. Each unit has nineteen arms, and the outline of each unit is a regular hexagonal prism (each side of the regular hexagon is 75 mm, the height is 320 mm). A transfer robot suitable in size for the desired work can be built by combining units, as in a honeycomb. Each arm is composed of three shape-memory-alloy (SMA) wires, a coil spring and an end-effector made of rubber, as shown in Fig. 4. Each SMA wire contracts about three percent in length by applying an electrical current. By selectively contracting one of the three wires the motion of the tip of each arm can be moved in three directions. The base of an object to be transferred contacts with lots of the arms, and the object is moved due to friction.

4.2 Networking configuration

The experimental robotic system employs the mesh-type networking configuration, in which the average number of connecting lines is three and the number of units connected to one unit is six. The overall control system is shown in Fig. 5. The hardware and software of all units, including the host unit, are the same. The host unit is connected to a personal computer which acts as the interface between the user and the robot. In a unit i , a coordinate system $o_i-p_iq_i$ is fixed on it, and each unit is connected with each other such that all coordinate systems may become

Fig. 4 One view of an arm

Fig. 5 Networking scheme used in experiments

parallel.

4.3 Information distribution scheme

The information distribution scheme P-III for perception of each unit's location is adopted. Therefore, each unit perceives its location through the exchange of information with the neighboring units which have already perceived their location.

The information distribution scheme C-VII for motion control is adopted, taking advantage of high expandability. The information for motion control given to the host unit through the interface by the user is the desired motion of the system, and this information is distributed to each unit through the host unit. Although this type of information distribution scheme does not facilitate fault tolerance, it can achieve fault tolerance to errors in connections and in units other than the host unit because the mesh-type connection is adopted as the networking configuration in which dataflow patterns can be changed to a great extent.

If information is exchanged among units in a disorderly manner, a same information passes through the units repeatedly until the information is transmitted to all units. In such a case, each unit must judge whether the information is new or not, and the management of information becomes complicated. To avoid this, the hardware and software are adopted in each unit to determine the dataflow pattern automatically so that the information from the host unit may pass each unit only once. The dataflow pattern is determined as follows.

First, a unit u_i which has received an information requires all the neighboring units to prepare to receive information. When a unit u_j receives the message, it connects its input terminal to the connecting terminal. If u_j receives the message not only from the unit u_i but from other connected units, the connecting terminal is selected according to the order of priority determined already at manufacturing. Thus the unit u_j does not receive the same information from other units. According to this procedure, the pattern where data flow only once through each unit is determined. This operation is carried out only for perceiving each unit's location, and afterwards, all information is sent according to this dataflow pattern. For example, a dataflow pattern is determined as shown in Fig. 6, where information is transmitted to all units according to the arrows. Here, the dataflow pattern can be changed using the software installed in each unit, without changing the hardware.

4.4 Procedure of motion control

Each unit perceives its location and the position of the object before starting motion control. In addition, the size of the object, for example the diameter of a circumscribed circle of the object, is given to each

unit by the user through the host unit. Then, the type of transfer motion (translation or rotation), transfer direction, and transfer distance are informed to all units from the host unit as the desired motion of the system. From this information, each unit determines its own desired motion and desired value of actuators, and controls the motion of its arms.

When the type of transfer motion is a translation, each unit calculates the position of the end point P_E of translation from the start position P_S , the transfer direction and the transfer distance d . Then from these two positions and the size of the object (the circumscribed circle of object), each unit calculates the dotted transfer region shown in Fig. 7, and moreover each unit selects its own arms located in the transfer region which is shown by the fine-dotted region of Fig. 7. Next, based on the direction of translation, each unit divides the arms into two groups, as shown in Fig. 8 (a). It then controls the motion of the arms according to the four motion patterns shown in Fig. 8 (b).

When the type of transfer motion is a rotation, each unit calculates the transfer region, divides the arms into two groups, and controls the motion of each arm. In the case where the object is required a clockwise rotation at about a point as shown in Fig. 9, the

Fig. 6 A data-flow pattern

Fig. 7 Determination of region in translational transfer motions

Fig. 8 Grouping and motion patterns for translational transfer motions

Fig. 9 Grouping for rotational transfer motions

Fig. 10 A view of an experimental transfer robot

dotted region is the transfer region, and the fine-dotted part is the region where the unit u_i must control its arms. The directions of motion of the arms in each part (I ~ VI) of the circumscribed circle of the object is indicated by the white arrows in Fig. 9. The arms in the parts I, III, V and the parts II, IV, VI are regarded as the groups A and B, and they are controlled according to the steps shown in Fig. 8(b).

4.5 Experiments

Three experimental transfer-robot units have been built, and experiments have been carried out for the case where the number of units composing the robot and the relative positions of units were changed variously. One of the experimental transfer robotic systems composed of three units is shown in Fig. 10. In all situations, each unit perceived its location, the motion of each arm was properly controlled, and transfer motions were successfully achieved.

5. Conclusions

In order to render robotic systems flexible in size, degrees of freedom and output motions, networking configurations and information distribution schemes in systems composed of identical units have been examined. The results are summarized as follows.

(1) Networking configurations have been classified into eight types, compared from the point of view of the three basic characteristics of expandability, perceptibility of unit's location, and fault tolerance. As a result, the mesh-type configuration is identified as optimal.

(2) As information to be managed in systems has been classified into information used to perceive each unit's location and information for motion control, distribution schemes for each type of information have been examined separately. For the distribution schemes in the perception of each unit's location, the decentralized scheme in which each unit perceives its location using information of the positions of neighboring units is identified as optimal. As for the distribution schemes for motion control, in the case where expandability of the system is considered more important, the centralized schemes in which only the goal of the task and the desired motion of the system are determined by the user and the host unit is identified as optimal, and in the case where fault tolerance is considered more important, the decentralized schemes in which each unit determines the desired values of actuators based on the desired motion of the system are identified as optimal.

(3) An experimental transfer robot composed of identical units, each of which has nineteen arms, has been constructed. For networking configuration, the mesh-type configuration, in which the average number

of connections is three and the number of units connected to each unit is six, and a centralized information distribution scheme are adopted. Experiments have been carried out, and experimental results have been shown to support the proposed method.

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