Paper

Mutual Entrainment and Communication Field

Coordinative Function Distribution and Mutual Compensation in Multi Robot System

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Abstract: A mutual-entrainment-based communication field is proposed as a new paradigm to realize autonomous coordinative control in unpredictable environment. Its most interesting ability is to self-organize control information field which indicates positional relationship between each subsystem and the whole system, and it enables coordinative function distribution and mutual compensation. By using this control principle, we realized coordinative group formation in a multiple walking robot system as an example. In such case, it was shown that the control information field is encoded on the global phase relationship between walking rhythms. By interpreting this information field, each robot responded relevantly and coordinatedly to organize the group formation pattern as one whole system. Furthermore, when some robots were suddenly deleted from this system, this information field was spontaneously reorganized to compensate the group formation pattern in the whole. These results show the potentiality of this mutual-entrainment-field based control.

1. Introduction

A mutual-entrainment-based communication field is proposed as a new paradigm to realize autonomous coordinative control in unpredictable environment. Its most interesting ability is to self-organize control information field which indicates positional relationship between each subsystem and the whole system, and it enables coordinative function distribution and mutual compensation. This means that its essence is not in any definite and separated order as is seen in a conventional control system but in the ability to self-organize a flexible and integrated order as one whole system.

Recently, spontaneous function generation mechanism in multi-agent system [4] has been widely investigated, such as subsumption architecture [1], [2] and contract net protocol [17]. These control systems are, however, based on message communication between subsystems similarly to the conventional control system. In other words, since system architecture

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is definitely and independently defined and its control algorithm is previously fixed, this kind of system cannot adapt to unpredictable changes of environment. To overcome this problem, the control system should not be completely designed by external designer. Through mutual communication between subsystems, the control information field which informs each subsystem of its functional relationship in the whole system should be self-organized depending on the environmental conditions.

A biological system is a good example of such an emergent control system. Thus, we have been studying the coordinative pattern formation in taxis of *Physarum* plasmodium and investigated the intracellular communication mechanism. As shown in Fig.1, the organism migrates as a whole body toward the attractive stimulus (indicated by the arrow in the figure), and its body shape is flexibly and coordinatedly reorganized corresponding to such unpredictable change of the external environment. From our previous experiments with this organism [6]-[8], [11]-[15], we clarified the following three points. (i) The intracellular communication system is composed of coupled chemical oscillators. (ii) Local information from the environment is encoded on the period modulation in each oscillator. (iii) Control information field for pattern formation is self-organized as the phase gradient pattern by mutual entrainment between these oscillators. These experimental results strongly suggest that mutual entrainment between rhythms is essential for such emergent self-control.

Thus, we newly proposed mutual-entrainment-based communication field as a candidate to enable such emergent coordination in engineering system. Therefore, in the present paper, we focus our attention on the role of rhythmic interaction between distributed robots and attempt to realize such a communication field.

2. Communication field

We construct the emergent communication field as a kind of self-organization system [3], [16]. The dynamics of this system can be described by using two kinds of information concerning local and global states, whose circulative interaction is indispensable for organizing

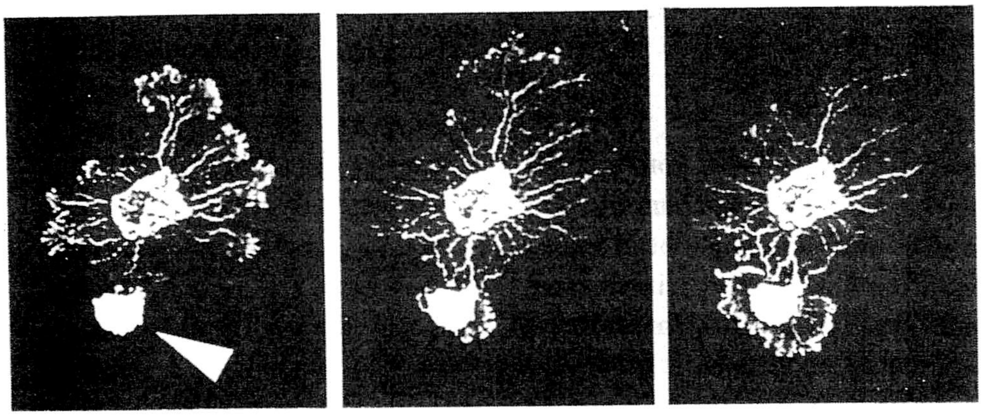

(a) (b) (c)

Fig.1. Taxis of *Physarum* plasmodium [10].

global order as one whole system. The information encoded on this global ordered state is regarded as the control information, which is a kind of field information which indicates global relationships between local states in the whole system. We called this self-organization-based communication system the "communication field".

To realize this communication field, it should be composed of subsystems having nonlinear dynamics such as rhythmic property. In particular, based on our previous biological experiments, the system is constructed using mutual entrainment between nonlinear oscillations, as shown in Fig.2. In such a case, local information is encoded on the period of each oscillator, and the control information which indicates the functional relationship between each subsystem and the whole system is self-organized as the global phase relationship between local oscillators. Thus, depending on such field information for self-control, every subsystem can autonomously and coordinatedly behave to organize the global function as one whole system. This kind of coupled oscillator model has been studied by our group [5], [10], [12] as a model of the *Physarum* plasmodium.

On the other hand, the conventional control system is designed based on the concept of message communication. Since it is achieved only by message transmission from a local sender to a local receiver and each communication subsystem is definitely and independently defined, such a system cannot include the self-organization process in itself. Thus, the message-communication-based system is not able to organize the information for self-control to achieve coordinative function, and it cannot respond to unpredictable changes of environment. Therefore, the autonomous coordinative control system should be designed from the viewpoint of the communication field. On the basis of this principle, every subsystem can cooperate to organize functional order as a whole.

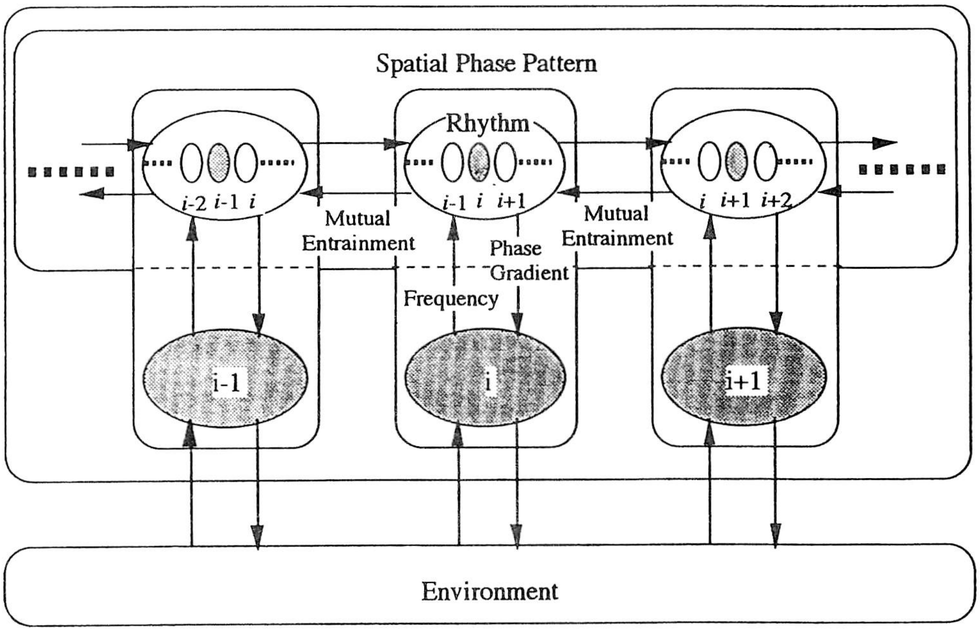


Fig.2. Communication field.

3. System configuration

3.1 Outline of the model In the present paper, coordinative group formation in a multiple walking robot system in an one-dimensional array is studied as an example of its engineering realization. The basic system structure consists of two hierarchical layers, as shown in Fig.3. One is the communication field which is composed of the rhythm generator system in each robot, and the other corresponds to non rhythmic components. Thus, regardless of their physical differences, every robotic system can communicate by using rhythmic interaction. Especially, regarding the rhythm generator of stepping cycle as a kind of nonlinear oscillation, walking locomotion in every robot can interact with each other through such communication system.

3.2 Robotic system As an elementary robot, any robot which shows nonlinear oscillation dynamics is thought to be applicable. Thus, we used a model of bipedal locomotion proposed by our group [18]-[20] as an example, and realized it by computer simulation. This model is composed of a neural rhythm generator and a physical system, as illustrated in Fig.4, and it generates locomotion as a completely autonomous oscillation through their mutual interaction.

The neural rhythm generator system is represented as

$$\begin{aligned} t_i \dot{u}_i &= -u_i + \sum_{i,j=1}^{12} w_{ij} y_j - b v_i + u_{0i} \\ &\quad + Feed_i(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{Fg}(\mathbf{x}, \dot{\mathbf{x}})) \\ t'_i \dot{v}_i &= -v_i + y_i \\ y_i &= f(u_i)\,(f(u_i) = \max(0, u_i))\ (i=1, \cdots, 12), \end{aligned} \tag{1}$$

where u_i is the inner state of the i-th neuron; y_i is the output of the i-th neuron; v_i is a variable representing the degree of adaptation or self-inhibition of the i-th neuron; u_{0i} is a signal from the higher center; w_{ij} is a connecting weight; t_i and t'_i are time constants of the inner state and the adaptation effect, respectively; and $Feed_i$ is a sensory signal.

The physical system moves according to its own dynamics and motor signals from the neural system. Its general form, derived by means of the Newton-Euler method, is written as

$$\begin{aligned} \ddot{\mathbf{x}} &= P(\mathbf{x})[C(\mathbf{x})P(\mathbf{x})]^{-1} \\ &\quad \times [\mathbf{D}(\mathbf{x}, \dot{\mathbf{x}}) - C(\mathbf{x})\mathbf{Q}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{Tr}(\mathbf{y}), \mathbf{Fg}(\mathbf{x}, \dot{\mathbf{x}}))] \\ &\quad + \mathbf{Q}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{Tr}(\mathbf{y}), \mathbf{Fg}(\mathbf{x}, \dot{\mathbf{x}})), \end{aligned} \tag{2}$$

where $\mathbf{x}$ is a vector of inertial positions and angles of links; P and C are matrixes; $\mathbf{D}$ and $\mathbf{Q}$ are vectors; $\mathbf{Tr}$ is a vector of torques; $\mathbf{Fg}$ is a vector of forces on the ankle which depend on the state of terrain; and $\mathbf{y}$ is a vector of the output of the neural rhythm generator. The sensory signals which indicate the current state of the physical system are sent to the neural system.

3.3 Communication system The communication field between these robots is composed of the neural rhythm generator in each robot and their mutual interactions. Everyone has experienced unconscious synchronization of stepping motion when walking with another person. Perhaps this phenomenon is a typical example of mutual entrainment in human locomotion through auditory interaction [9]. Thus, the interaction signal is assumed to be a periodic pulse, which can be imagined as a kind of stepping sound. Each pulse signal is generated

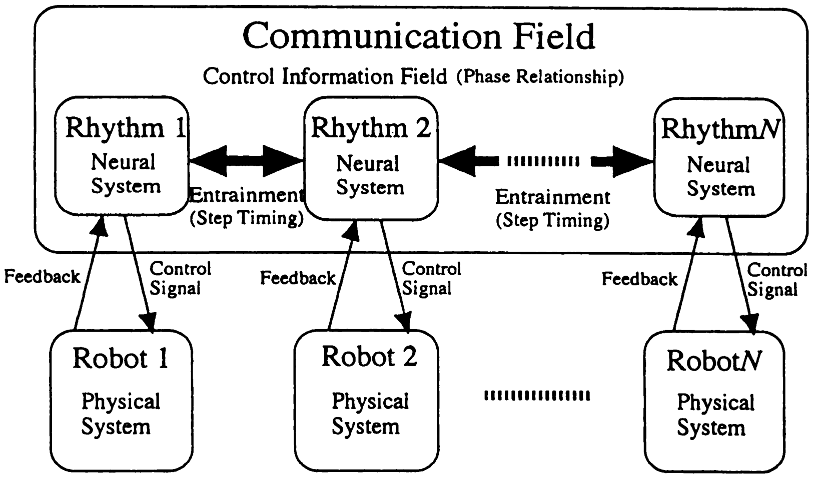


Fig.3. System configuration.

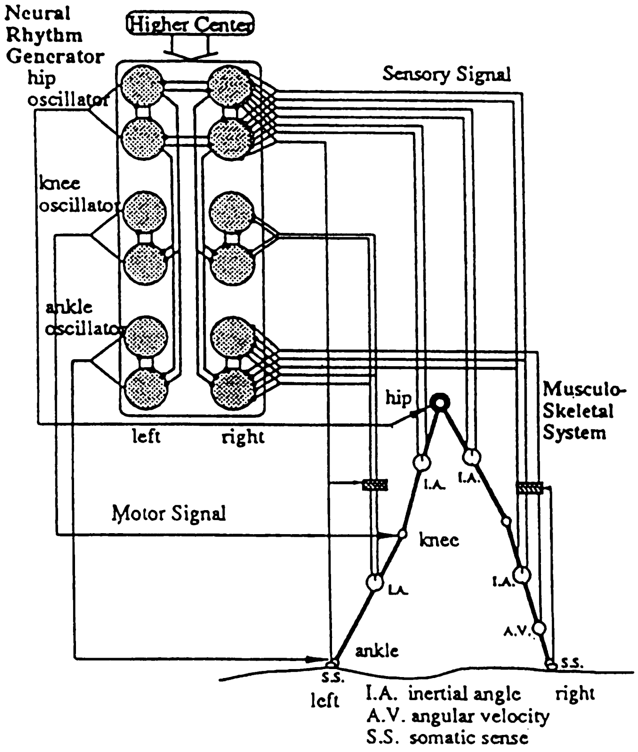


Fig.4. Robotic system [18].

at the time of contact of the ankle to the ground, and they are transmitted to the neural rhythm generator in neighboring robots [18]. The form of the interaction is represented as

$$pul_j = pu_{j-1} + pu_{j+1}$$

$$pu_j = \begin{cases} -A & for\ z_{r,j} < z_g\ and\ T_{r,j} < B \\ A & for\ z_{l,j} < z_g\ and\ T_{l,j} < B \\ 0 & otherwise \end{cases}, \tag{3}$$

where pul_j is the input signal to the neural system in the j-th robot. pu_j is the pulse signal which encodes the step timing of the j-th robot. A is pulse height and B is its duration. $z_{r,j}$, $z_{l,j}$ and z_g represent the height of the right ankle, left ankle and ground in the sagittal plane, respectively. $T_{r,j}$ and $T_{l,j}$ respectively stand for the time interval from the contact of the right ankle and left ankle in each walking cycle.

Spatiotemporal order self-organized in this communication field was analyzed as the period and phase gradient. The period was defined as the time interval between two successive steps of the same robot. The phase gradient was defined as the time difference of a corresponding two steps between the neighboring robots. These are represented as

$$pe_{j,i} = st_{j,i} - st_{j,i-1},$$

$$phg_{j,i} = st_{j+1,i} - st_{j,i}, \tag{4}$$

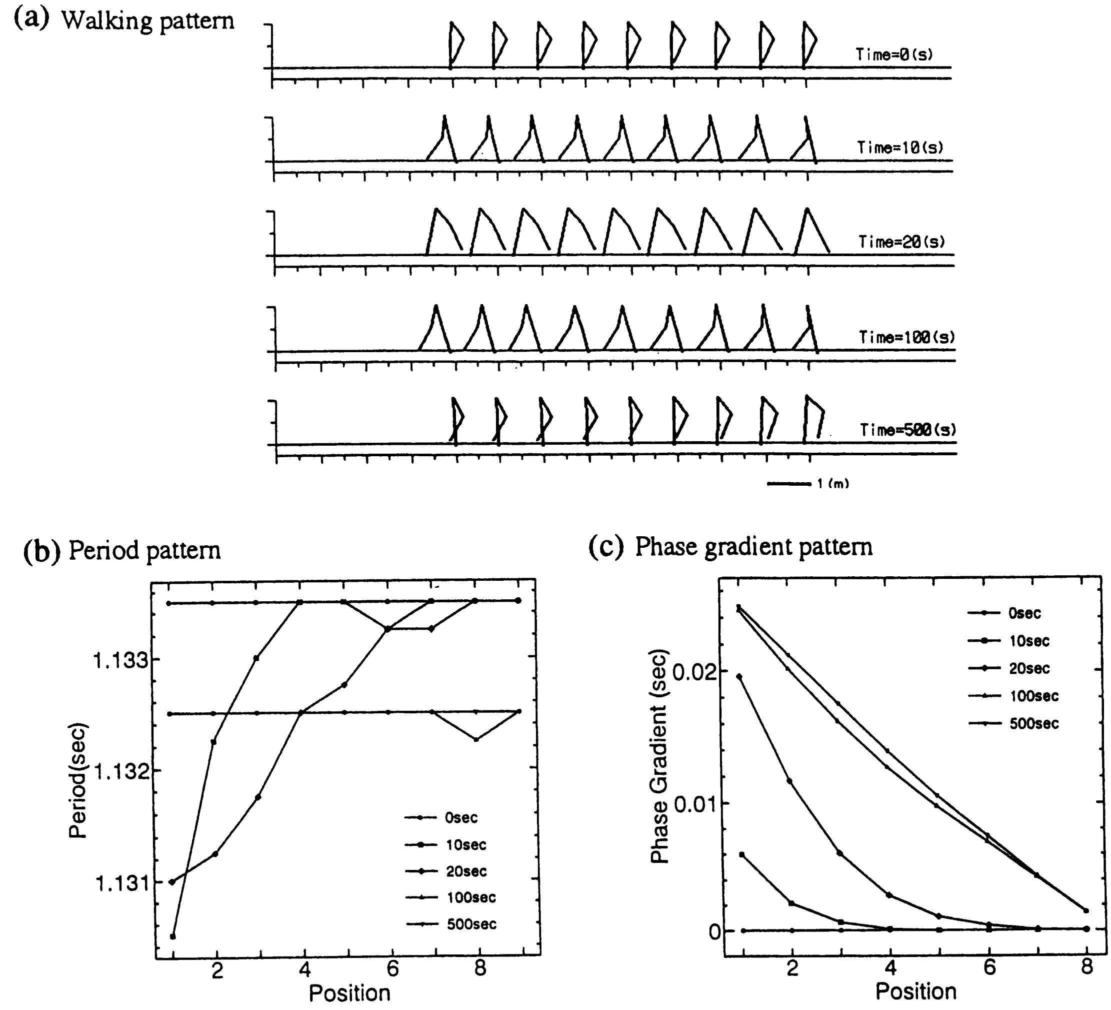
where $pe_{j,i}$ means the period, $phg_{j,i}$ stands for the phase gradient between neighboring robots, and $st_{j,i}$ is the step time of the j-th robot in the i-th walking cycle.

4. Communication-field-based control

4.1 Self-organization of control information field Time evolution of the walking pattern in the robotic system was calculated and is shown in Fig.5a. Under this condition, corresponding to our coupled oscillator model [5], [10], [12], the original period of the walking rhythm was fixed to be the same value in the whole system except for the top position ($j=1$). After the period decrease at the top position (right end in the array), their step timing gradually changes from the top to the rear of the system.

Temporal development of the period and the phase gradient in the communication field are shown in Figs.5b and 5c, respectively. After the period modulation (left end in the figure), the local response rapidly propagated to other regions, and finally the uniform distribution of the period and global phase gradient pattern were stably self-organized. Then, the phase gradient linearly decreased from the top to the rear of the system. Thus, the phase gradient pattern shows not only the global polarity but also the relative distance from the top position.

Furthermore, it was clarified that this phase gradient pattern is size invariant, independent of the total number of robots. This is because the variation range of the phase gradient does not change with system size, as shown in Fig.6. This means that the phase gradient value at each part represents not the absolute position but the relative one within the whole system. Thus, the space coordinate as a kind of control information is self-organized in this communication field. Therefore, by interpreting this control information, each robot can be informed of its relative position within the system, and group formation can be organized in a position-dependent manner.


(a) Walking pattern

(b) Period pattern

(c) Phase gradient pattern

Fig.5 . Self-organization of control information field. (a) Walking pattern. (b) Period pattern. (c) Phase gradient pattern.

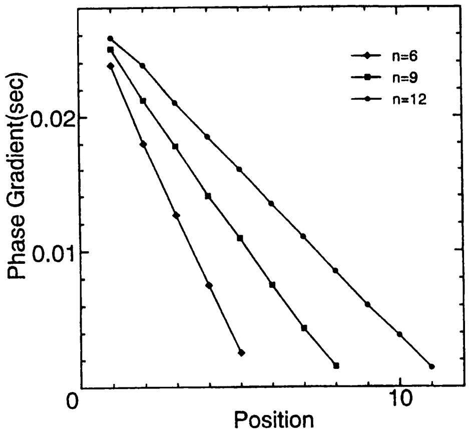


Fig.6 . Relationship between phase gradient pattern and system size.

In the present paper, since the phase gradient decreases linearly from the top to the rear, the control information field is interpreted by introducing some threshold values, as shown in Fig.7. Thus, some discrete regions of the phase gradient value can be defined according to the relative position within the system. Based on this information, the spatial distance between neighboring robots is modified and some clustered walking groups are organized. In the following cases, the number of groups was set at three.

4.2 Functional mutual compensation in unpredictable change As an example of the autonomous coordinative response under unpredictable changes of environment, mutual compensation of group formation pattern corresponding to a change in system size was studied. The system size is defined as the total number of robots, and we imagine the situation in which some robots are eliminated from the robotic system at a certain timing due to breakdown.

An example of the temporal development

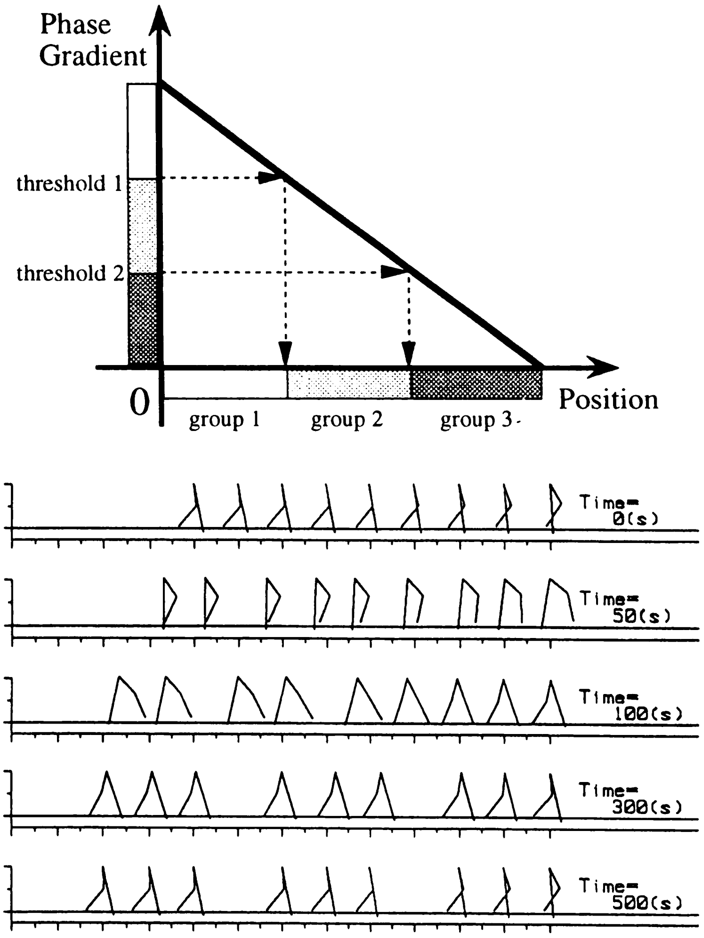
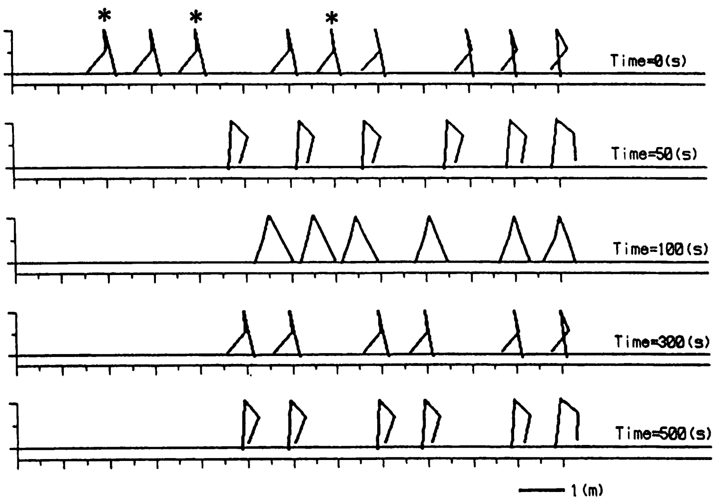


Fig.7. Interpretation of control information field.

of a group formation pattern is shown in Fig.8a. In the top figure, three stable subgroups for 9 walking robots are observed. This is based on the interpretation of control information field, as explained in the above section. After the deletion of three robots at the 5th, 7th and 9th positions indicated by * in the figure, the group formation became disordered throughout the system. However, three subgroups for 6 robots were stably reorganized, as shown in the same figure. In spite of the unpredictable change of system size, the group formation pattern was spontaneously maintained as a whole system.

Figures 8b and 8c show the temporal development of the phase gradient pattern in the communication field under the same process. After the deletion of three robots, the disordered state appeared. However, the linear phase gradient pattern was autonomously rescaled corresponding to 6 robots as the total system. In such a process, the variation range of the phase gradient between the two terminal robots did not change with change of the system

(a) Walking pattern



(b) Phase gradient pattern

(c) Phase gradient

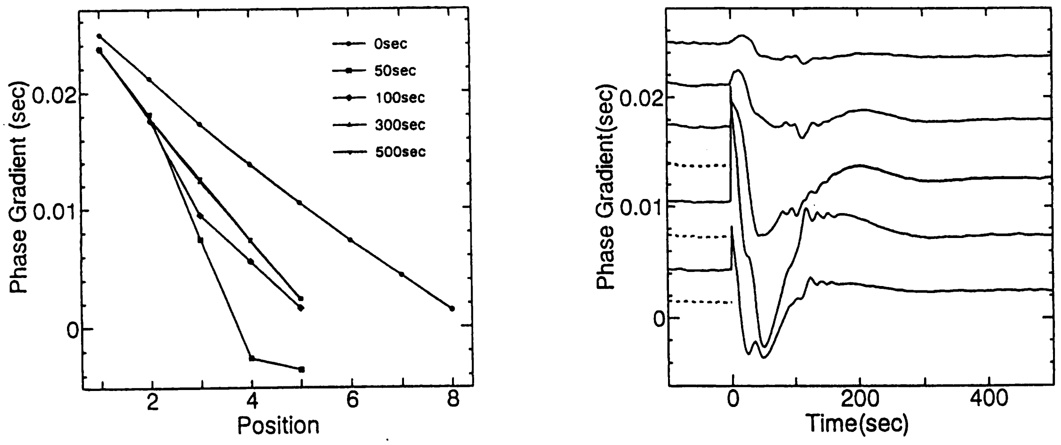


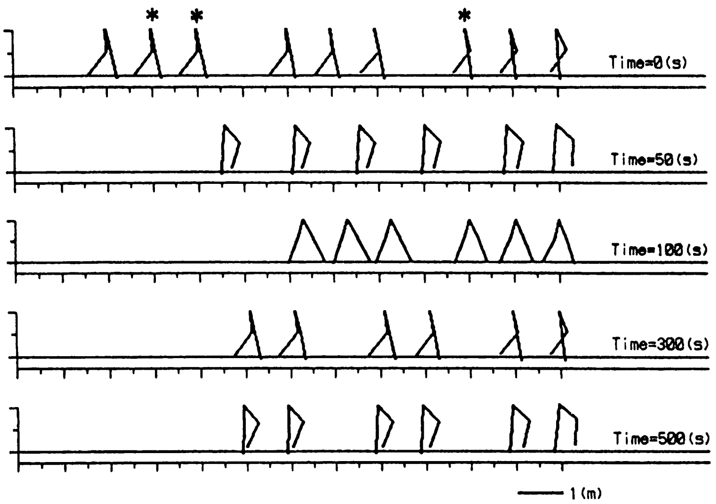
Fig.8. Mutual compensation of group formation pattern. (a) Walking pattern. (b) Phase gradient pattern. (c) Phase gradient.

size, as explained in Fig.6. This means that the control information field is spontaneously reorganized according to the change of system size.

These phenomena were observed regardless of the position and number of robots eliminated from the robotic system. Figures 9a, 9b and 9c show another example where in three robots at the 3rd, 6th and 7th positions were eliminated. After the deletion, three subgroups for 6 robots were also reorganized.

From these results, it was clarified that the control information field encoded on the phase gradient pattern is spontaneously reorganized corresponding to the change in system size. Therefore, by using this emergent property, coordinative function distribution and its mutual compensation in group formation could be autonomously achieved even under unpredictable changes of environment.

(a) Walking pattern



(b) Phase gradient pattern

(c) Phase gradient

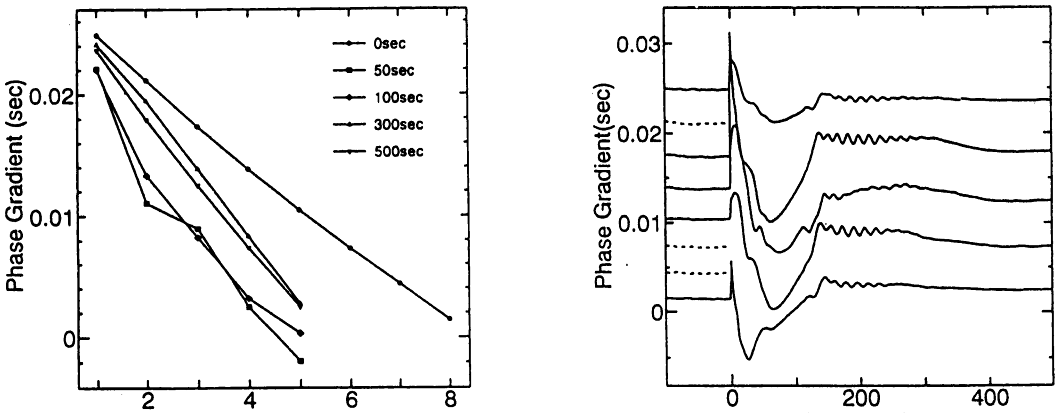


Fig.9. Mutual compensation of group formation pattern. (a) Walking pattern. (b) Phase gradient pattern. (c) Phase gradient.

5. Conclusion

In this paper, based on our previous researches of a biological communication system, a mutual-entrainment-based communication field was proposed as a new control paradigm to realize emergent control in a distributed autonomous robotic system. Its most interesting ability is self-organization of the control information field which indicates the functional relationship between each subsystem and the whole system, and realization of autonomous coordinative response to unpredictable changes of environment by using such emergent information.

Applying this approach to the present problem, we studied coordinative group formation in a multiple walking robot system. We clarified that the control information field is self-organized into the phase gradient pattern between distributed rhythms in the communication field. This phase relationship represents the relative positional relationship among individual robots in the whole system. Furthermore, this information field is spontaneously reorganized corresponding to the change of system size. Interpreting this information field, each robot is informed of its relative position within the system, and the group formation is regulated coordinatedly as one whole system. These results clarified that the mutual-entrainment-based communication field has high potentiality for realizing coordinative function distribution and its mutual compensation under unpredictable changes of environment. Since the mutual entrainment is recursive and dynamic, our distributed robotic systems are not separated into definite and individual subsystems but are spontaneously integrated into one global field. Thus, autonomous coordination in such control systems could be achieved even with unpredictable change of environment.

One could widely apply the present model to realize the coordinative function distribution and load distribution in artificial network systems. Not only the robotic system but also other distributed systems such as a computer network, electric power supply network and traffic control are good examples of where it can be applied, because such systems should work coordinatedly under changing environment and changing system size. If each subsystem has the property of nonlinear oscillation, the communication field could be easily organized by mutual entrainment among them.

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