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Mutual Entrainment Based Communication Field in Distributed Autonomous Robotic System

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***Abstract*----** Mutual entrainment based communication field is proposed as a new control paradigm to realize distributed autonomous robotic system. Most interesting ability of this field is to spontaneously generate the control information for autonomous coordination as one whole system. Applying this approach to the coordinative group formation in multi walking robot system as an example, we showed that the control information field indicating functional relationship between each subsystem and the whole system is self-organized in the communication field. It was encoded on the phase gradient pattern generated by the mutual entrainment between walking rhythms. Furthermore, the information field was reorganized in real-time depending on its system environment. Interpreting this information field, each subsystem could coordinately and relevantly behave to organize the group formation pattern as a whole. These results suggest that the essence of communication field based control is not in any definite and separated order as is seen in message communication but in the ability to self-organize flexible and integrated order in the whole system.

1. Introduction

Mutual entrainment based communication field is proposed as a new control paradigm to realize distributed autonomous robotic system. Most interesting ability of this control is to spontaneously generate the global functional order as one whole system. This means that its essence is not in any definite and separated order as is seen in conventional message communication but in the ability to self-organize flexible and integrated order in the whole system.

Recently, spontaneous order generation in multi agent system has been widely investigated [2]. These studies are, however, restricted to the system composed of definite and separated subsystems and message communication under fixed boundary conditions, such as subsumption architecture [1] and contract net protocol [12]. In other words, since system architecture is previously fixed, this kind of system can not adapt to unpredictable changes of environment. To overcome this problem, system architecture should not be completely designed by external designer. Through the communication field, the control information representing functional relationship between each subsystem and the whole system should be self-organized in real-time depending on its environmental condition.

Biological system would be a good example of such emergent control system. We have been investigated the intracellular communication process in chemotaxis of *Physarum* plasmodium, and clarified that self-organization of coherence in intracellular chemical oscillator field has close correlations with coordinative tactic migration and generation of the control information field [4]-[11]. These studies suggest that mutual entrainment between rhythms is essential for such communication field in biological system.

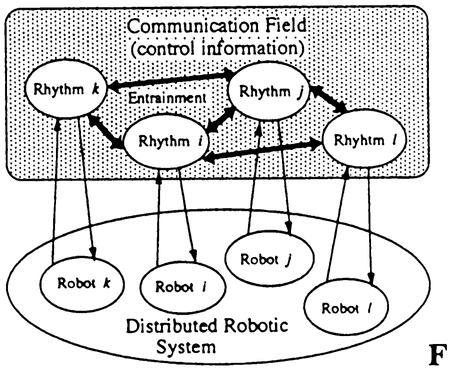

Fig.1

Thus, we newly proposed the mutual entrainment based communication field as a candidate to solve such essential problems. Therefore, in the present paper, we focus our attention on the role of rhythmic interaction between distributed robotic systems, and try to realize such integrated communication field as an essence of the autonomous coordinative control.

2. Communication Field Paradigm

The concept of communication field is illustrated in Fig.1. The field is a kind of self-organization system of control information. It includes communication subsystems and their interactions within the field. By using the mutual entrainment between subsystems having rhythmic property, the control information indicating functional relationship between each subsystem and the whole system is generated spontaneously in the field. Thus, depending on such global information for self-control, every subsystem autonomously and coordinately behaves to organize the global function as one whole system.

On the other hand, conventional artificial system uses message communication. It is achieved by the message transmission from local sender to local receiver. However, since it does not include the dynamics of communication subsystems in such process, it can not self-organize the information for self-control to achieve the global function.

We think that the essential property of biological communication is not in the message exchange but in the emergence of communication field. Based upon such field, every subsystem can cooperate to organize functional order as a whole. To realize such communication field, we use the mutual entrainment between nonlinear oscillations. This kind of model has been studied by our group [4], [6], [8], [13], [14] and the coherent phase pattern organized in such system was shown to encode the control information field. Furthermore, this approach is widely applicable to human-robot collaboration system [3].

3. System Configuration

3.1 Outline of the Model

Basic system structure consists of two hierarchical layers as shown in Fig.2a. One is communication field and the other is robotic system. The former corresponds to neural rhythm generator in robots. The latter corresponds to the other physical systems.

In the present paper, coordinative group formation in multi walking robot system in one-dimensional array is investigated as an example of its engineering realization. Everyone would have experienced unconscious entrainment of stepping motion when walking with another person. Perhaps this phenomenon would be a typical example of the mutual entrainment in walking locomotion. Thus, we try to realize the communication field by using such phenomenon. By this interaction, coherent phase relationship which encodes the control information field would be self-organized in the communication field. Interpreting this information, each robot would be able to coordinately behave as one whole system to organize the group formation pattern.

3.2 Robotic System

Any robot which shows nonlinear oscillation is thought to be applicable as an elementary robot. Thus, we used a model of bipedal locomotion robot proposed by our group [13]-[15] as an example. As illustrated in Fig.2b, it is composed of physical and neural systems, and it generates locomotion as a completely autonomous oscillation through the mutual interaction between them.

The neural rhythm generator system is represented as follows:

$$\tau_i \dot{u}_i = -u_i + \sum_{i,j=1}^{12} w_{ij} y_j - b v_i + u_{0i} + Feed_i(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{F}\,\mathbf{g}(\mathbf{x}, \dot{\mathbf{x}})) \quad ,$$

$$\tau'_i \dot{v}_i = -v_i + y_i \, ,$$

$$y_i = f(u_i) \quad (f(u_i) = \max(0, u_i)) \quad (i = 1, 12) \quad , \qquad (1)$$

where u_i is the inner state of i-th neuron; y_i is the output of i-th neuron; v_i is a variable representing the degree of adaptation or self-inhibition of i-th neuron; u_{0i} is a signal from the higher center; w_{ij} is a connecting weight; τ_i and τ'_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 oscillation dynamics and motor signals from the neural system. Its general form derived by means of the Newton-Euler method is written as,

$$\ddot{\mathbf{x}} = P(\mathbf{x})[C(\mathbf{x})P(\mathbf{x})]^{-1}[\mathbf{D}(\mathbf{x}, \dot{\mathbf{x}}) - C(\mathbf{x})\mathbf{Q}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{Tr}(\mathbf{y}), \mathbf{F}\,\mathbf{g}(\mathbf{x}, \dot{\mathbf{x}}))]$$
$$+ \mathbf{Q}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{Tr}(\mathbf{y}), \mathbf{F}\,\mathbf{g}(\mathbf{x}, \dot{\mathbf{x}})) \quad , \qquad (2)$$

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 neural rhythm generator. The sensory signals which indicate the current state of physical system are sent to the neural system.

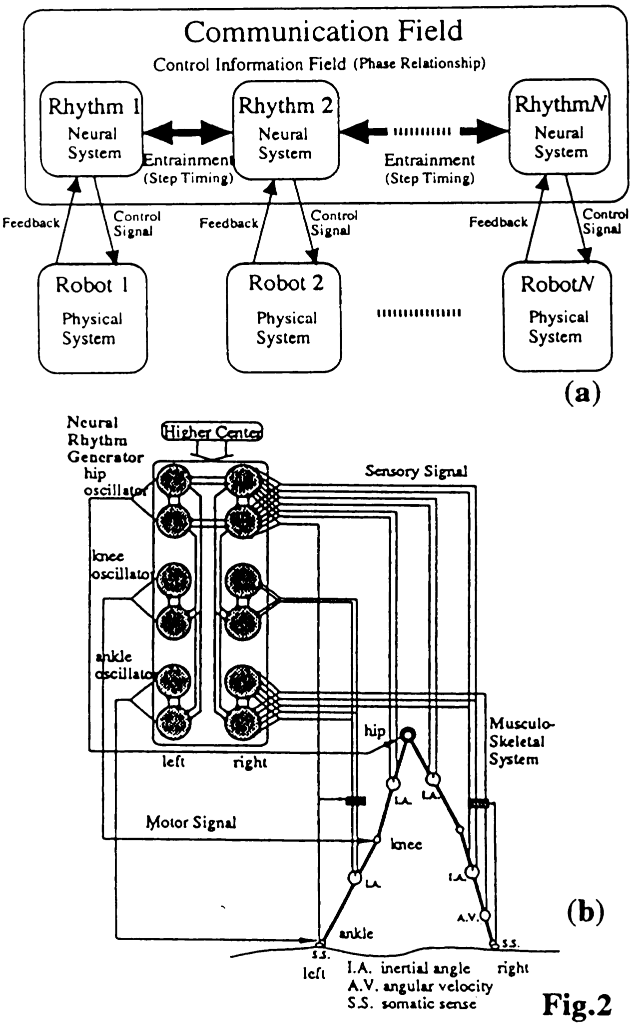

Fig.2

3.3 Communication System

Communication field is composed of neural rhythm generators and their mutual interactions. Interaction signal is assumed to be a periodic pulse, which can be imagined as a kind of stepping sound. Each pulse signal is generated at the timing of attachment of ankle to the ground, and they are transmitted to neighboring robots. The form of the interaction is represented as follows:

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

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

where pul_j is the input signal to the neural system in j-th robot. pu_j is the pulse signal which encode the step timing of j-th robot. A is pulse height and B is its duration time. $z_{r,j}$, $z_{l,j}$ and z_g represent the height of 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 attachment of right ankle and left ankle in each cycle.

Coherent order generated in this communication field is analyzed as the mutual entrainment field encoding the control information. Especially, the phase gradient between neighboring subsystems and their periods are calculated. This is based on the characteristics obtained in our coupled nonlinear oscillator model [4], [6], [8]. These are represented as follows:

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

$$phg_{j,i} = st_{j+1,i} - st_{j,i}, \qquad (4)$$

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

4. Communication Field Based Control

4.1. Self-Organization of Control Information Field

Time evolution of walking pattern in the robotic system observed after the period modulation is shown in Fig.3a. Corresponding to our coupled oscillator model [4], [6], [8], original period of walking rhythm was fixed to 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 changed from the top to the rear end of the system, and finally coherent phase relationship between them was stably self-organized as shown in the same figure.

Temporal development of the period and the phase gradient in the communication field are shown in Figs.3b and 3c, respectively. After the period modulation (left end in the figure), the local response rapidly propagated to other regions, and finally the uniform distribution of period and global phase gradient pattern were stably self-organized. Then, the magnitude of the phase gradient linearly decreased from the top to the rear end of the system. Thus, the phase gradient pattern shows not only the global polarity but also the relative distance from the top position.

Furthermore, the relationship between this phase gradient pattern and the system size was investigated. As a result, variation range of the phase gradient does not change depending on the system size as shown in Fig.4. Thus, the pattern of phase gradient was shown to be size invariant independent of the number of robots. This means that the phase gradient pattern represents the relative positional relationship between each subsystem and the whole system.

Therefore, space coordinate as a kind of control information field is clarified to be self-organized in this communication field.

4.2 Autonomous Coordinative Control in Distributed Robotic System

Group formation in such robotic system is realized by interpreting the control information field. Since the phase gradient decreases linearly from the top position, the control information field is interpreted by introducing some threshold values. Thus, some discrete regions of the phase gradient value are defined according to the position within the system. Based on this information, spatial distance between neighboring robots is modified and some walking groups are organized. In the following cases, the number of group was fixed to three.

As an example of the autonomous coordinative control, reorganization of group formation corresponding to the system size change was studied. The system size is defined as the number of robots, and we imagine the situation that some robots are deleted from the robotic system at a certain timing due to their breakdown.

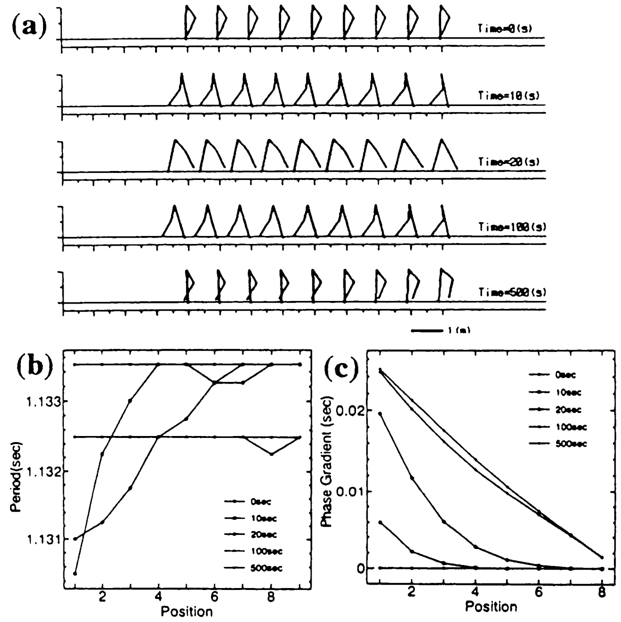

Fig.3

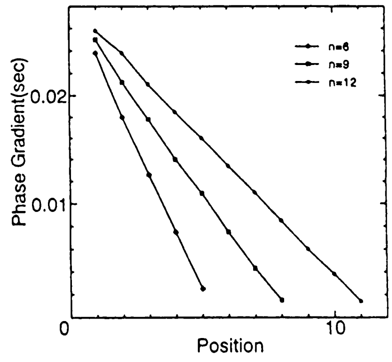

Fig.4

An example of the temporal development of group formation pattern was shown in Fig.5a. In top figure, three stable subgroups in 9 walking robots are observed. After the deletion of three robots at 5-th, 7-th and 9-th position indicated by * in the figure, the group formation became disordered state throughout the system. However, by the mutual entrainment, three subgroups in 6 robots were stably reorganized as shown in the same figure. In spite of the system size change, the group formation pattern was shown to be maintained as a whole.

Figures 5b and 5c show the temporal development of phase gradient pattern in the communication field under the same process. After the deletion of three robots, disordered state appeared. However finally linear phase gradient which corresponds to 6 robots was stably organized as a whole system. In such process, variation range of the phase gradient between both terminal robots did not change depending on the system size change as explained in Fig.4.

These phenomena were observed regardless of the position and number of robots deleted from the robotic system. Figs.6a, 6b and 6c show another example that three robots at 3-th, 6-th and 7-th position were deleted.

From these results, it was clarified that the control information field encoded on the phase gradient pattern is spontaneously reorganized in real-time corresponding to the system size change. By using such emergent property in the communication field, group formation is autonomously and coordinately achieved even under unpredictable changes of system environment.

5. Conclusion

In this paper, based on our previous studies in biological communication system, mutual entrainment based communication field was proposed as a new control paradigm in distributed autonomous robotic system.

Applying this approach to the present problem, we showed that the control information field is self-organized as the phase gradient pattern between distributed rhythms in the communication field. This phase relationship represents the positional and functional relationship between subsystems and the whole system. Furthermore, the information field is reorganized in real-time according to its environmental conditions. Interpreting this information field, each robot is informed of its relative position in the system, and the group formation is regulated as one whole system.

These results clarified that the mutual entrainment based communication field has large potentiality for realizing autonomous coordinative control. Since the mutual entrainment is recursive and dynamical, distributed robotic system are not separated into definite subsystems but spontaneously integrated into one unity field. Thus, autonomous coordination in such control system could be achieved even under 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 the large scale systems such as computer network, electric power supply network and traffic control would be good examples of its application, because such systems should work coordinately under changing environment and changing system size. If each subsystem has the property of nonlinear oscillation, the communication field could be easily organized by the mutual entrainment between them.

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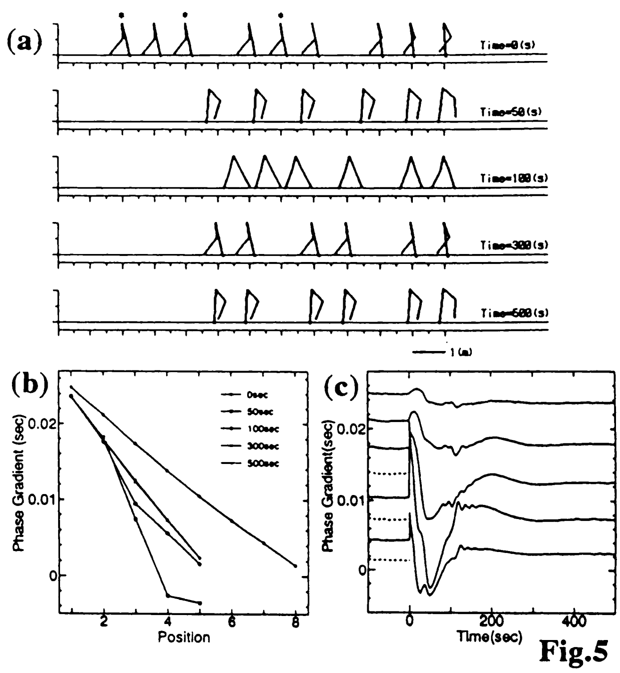

Fig.5

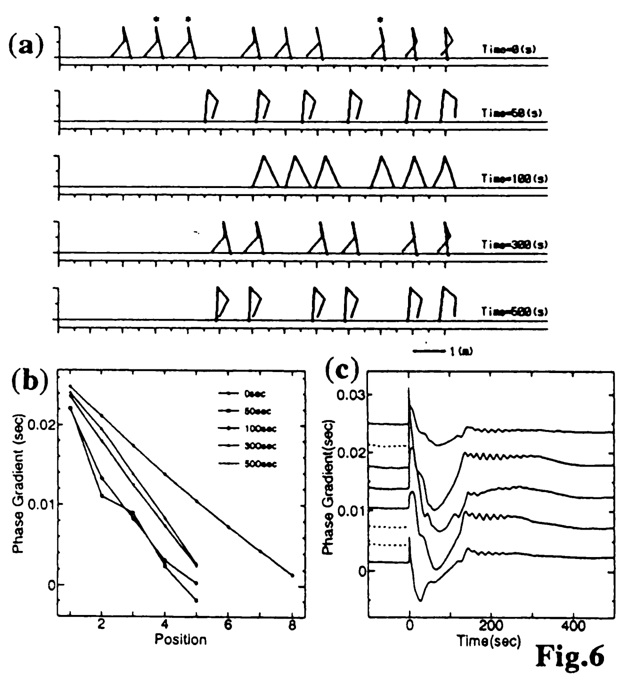

Fig.6

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