Mutual Entrainment Based Human-Robot Communication Field
----Paradigm shift from "Human Interface" to "Communication Field"----

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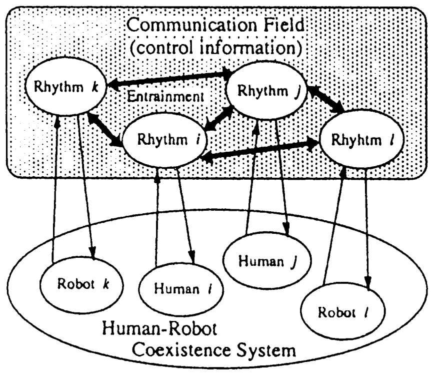
***Abstract*-----** Mutual entrainment based communication field is proposed as a new communication paradigm to realize human-robot collaboration system. Most interesting ability of this field is to spontaneously generate control information field for autonomous coordination including both human and robotic dynamics. Applying it to the coordinative walking process between human and robotic system as an example, we showed that the control information field indicating functional relationship between human and robot is self-organized in the communication field. It was encoded on the spatial phase pattern generated by the mutual entrainment between walking rhythms. Interpreting this information, each subsystem would be able to coordinately behave as one whole system. This result suggests that the essence of communication is not in any definite and separated order as is seen in conventional human interface but in the ability to self-organize flexible and integrated order in the communication field.

1. Introduction

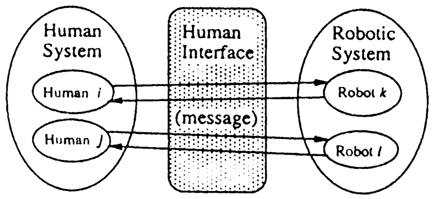
Mutual entrainment based communication field is proposed as a new communication paradigm to realize human-robot collaboration system. Most interesting ability of this approach is to spontaneously generate the control information field for autonomous coordination including both human and robotic dynamics. This means that its essence is not in any definite and separated order as is seen in conventional human interface but in the ability to self-organize flexible and integrated order in the communication field.

Recently, intelligent human interface which can supplement insufficiency in the communication between human and artificial system has been studied [3]-[5]. Furthermore, communication for spontaneous order generation has been investigated in multi agent system [1], [2], [6], [18]. These studies are, however, restricted to the system composed of definite and separated subsystems and fixed boundary conditions. In other words, communication is achieved by the message exchange between completely defined subsystems, and their architecture is previously fixed. Thus, this kind of system could not emergently respond to unpredictable changes such as human behavior.

Since human behavior changes from time to time, to overcome this problem, system architecture should not be completely designed by external designer. Through the communication process, control information representing functional relationship between each subsystem and the whole system should be self-organized depending on its environmental condition in real-time.



(a) Communication Field



(b) Human Interface

Fig.1 Concept of communication field and human interface.

Biological system would be a good example of such emergent communication. 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 [8]-[17]. These studies suggest that mutual entrainment between rhythms is essential for autonomous coordination in biological communication system.

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 in the communication between human and robotic system, and try to realize such integrated communication field as an essence of biological communication process.

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2. Communication Field Paradigm

The concept of communication field is illustrated in Fig.1a. The field is a kind of self-organization system of control information. It includes communication subsystem and their mutual interaction 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, the concept of human interface is illustrated in Fig.1b. 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. Especially, we recently applied this model to the coordinative group formation control in distributed robotic system [7]. Thus, based on this mechanism, human and robot would be able to communicate by using rhythm language and could generate the control information field as one whole system.

3. System Configuration

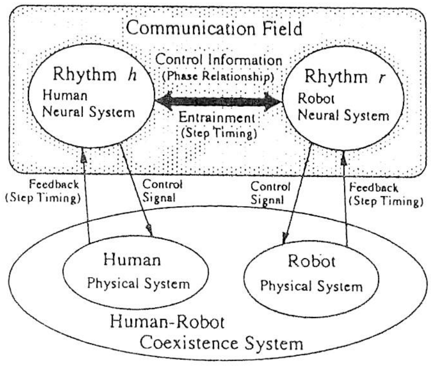
3.1 Basic System Structure

Everyone would have experienced unconscious synchronization of stepping motion when walking with another person. Perhaps this phenomenon would be a typical example of mutual entrainment in human auditory communication. Thus, in the present paper, we try to realize the communication field by using such entrainment between human and robotic walking as an example.

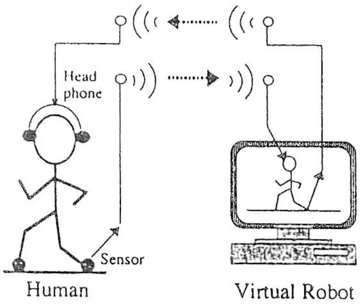
Basic system structure consists of two hierarchical layers as shown in Fig.2a. One is communication field and the other is human-robot coexistence system. The former corresponds to the neural rhythm generator in human and robotic system. The latter corresponds to the other physical systems. Thus, regardless of their physical difference, both human and robot can communicate by using same rhythm language and its mutual entrainment. Especially, regarding the stepping cycle as a kind of rhythm, walking movement in both human and robot can mutually interact with each other in such system. Through this mutual entrainment in communication field, coherent phase relationship encoding the control information field would be self-organized.

Experimental system was composed of human and virtual robot system as shown in Fig.2b. The step timing of human walking is detected as an attachment of ankle by using optical sensor and transformed into pulse signal. It is transmitted to personal computer in which robotic system is virtually constructed and is input into its neural system. The response of neural oscillation is transformed into stepping movement in the robot walking. This step timing is further transformed into pulse signal and transmitted to the human system. It is received as a sound signal in the headphone and human walks unconsciously to the stepping sound. These experimental apparatus are shown in Fig.2c.

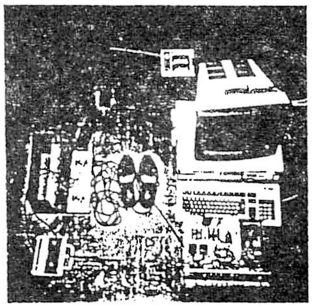
Every experiment was achieved in a large room having flat floor and homogeneously illuminated from the above. Human walks according to circle pathway and its radius is about 20 m. Three naive students were used as the human system. One scene in this experiment is shown in Fig.2d.



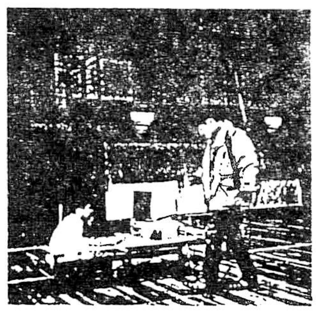
(a) Basic System Structure



(b) Experimental System



(c) Experimental Apparatus



(d) Appearance of Experiment

Fig.2 System configuration.

3.2 Robotic System

An example of walking robot system is virtually constructed by using neural oscillator model as shown in Fig.3a. It is composed of both neural system and physical system.

The neural system is composed of two unit neural oscillators which controls right and left legs respectively. Each oscillator which generates stable oscillatory activity consists of two neurons linked reciprocally [21]. Using this model, neural rhythm generator system is constructed as follows:

$$\frac{du_1}{dt} = -u_1 + w_{12}x(u_2) + w_{11}x(u_1) + u_{01} + pul_{rh} \quad (1.1)$$

$$\frac{du_2}{dt} = -u_2 + w_{21}x(u_1) + w_{24}x(u_4) + u_{02} \quad (1.2)$$

$$\frac{du_3}{dt} = -u_3 + w_{34}x(u_4) + w_{33}x(u_3) + u_{01} - pul_{rh} \quad (1.3)$$

$$\frac{du_4}{dt} = -u_4 + w_{43}x(u_3) + w_{42}x(u_2) + u_{02} \quad (1.4)$$

$$x(u) = \begin{cases} 1 & for \quad u \geq 0 \\ 0 & for \quad u < 0 \end{cases} \quad (1.5)$$

where u_i is the inner state of i-th neuron; u_{0i} is the offset signal; w_{ij} is the connecting weight; and pul_{rh} is the pulse signal from human system. t stands for time.

Under this condition, physical system is assumed as follows. Since the sign of u_1 and u_3 change cyclically, it can be regarded as attach / detach of ankle to the ground. Thus, walking trajectory of this robot is represented by two desecrate states in each leg. They are represented as follows:

$$y_{ro,r} = x(u_1) \quad (2.1)$$

$$y_{ro,l} = x(u_3) \quad (2.2)$$

where $y_{ro,r}$ and $y_{ro,l}$ stand for the state of right and left legs in robotic system. In this case, detach and attach state correspond to value 1 and 0, respectively. Change of the value from 1 to 0 is regarded as the step motion. An example of the relationship between neural oscillation and stepping movement is illustrated as shown in Fig.3b.

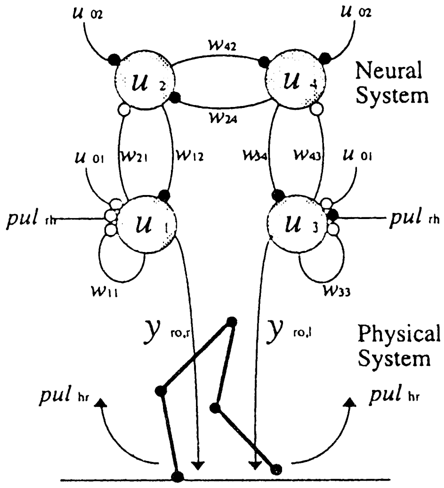
In the present paper, we used the above model as the most simple example, however any model is thought to be applicable when it shows oscillation dynamics.

3.3 Communication System

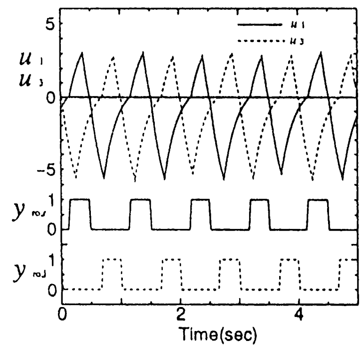
As explained in the above, communication field is composed of human neural system, robot neural rhythm generator and their mutual interaction.

Communication signal from human to robotic system is periodic pulse signal, which can be imagined as a kind of stepping sound. The pulse is generated at every timing of attachment to the ground in human ankle. This is represented as follows:

$$pul_{rh} = \begin{cases} -A & for \quad y_{hu,r} = 0 \; and \; T_{hu,r} < B \\ +A & for \quad y_{hu,l} = 0 \; and \; T_{hu,l} < B \\ 0 & otherwise \end{cases} \quad (3)$$



(a) Robot Model



(b) Oscillation Pattern

Fig.3 Robotic system. This model was simulated by using the fourth-order Runge-Kutta-Gill method. We used w_{12}=-10, w_{21}=4, w_{34}=-10, w_{43}=4, w_{24}=-3, w_{42}=-3, u_{01}=1, u_{02}=-1, A=4.0, B=0.25 sec.

where A is pulse height and B is its duration time. $y_{hu,r}$ and $y_{hu,l}$ stand for the state variable of right and left legs in human, respectively. Their expressions are similar to that of Eq.(2). $T_{hu,r}$ and $T_{hu,l}$ respectively stand for the time interval from the attachment of right and left ankle in each cycle. Thus, each pulse is generated when human ankle attaches to the ground, and it continues for time B.

In the similar way, signal from robotic system to human system is assumed as follows.

$$pul_{hr} = \begin{cases} Tone\,1 & for \quad y_{ro,r} = 0 \; and \; T_{ro,r} < B \\ Tone\,2 & for \quad y_{ro,l} = 0 \; and \; T_{ro,l} < B \\ 0 & otherwise \end{cases} \quad (4)$$

where $Tone1$ and $Tone2$ stand for the different sound. $T_{ro,r}$ and $T_{ro,l}$ respectively are the time interval from the attachment of right ankle and left ankle in each cycle. Thus, each sound signal is generated when robot ankle attaches to the ground, and it continues for time B.

Coherent order generated in this communication system is analyzed as mutual entrainment field encoding the control information. Especially, the phase relationship between human and robotic system and their periods are calculated. This is based on the characteristics obtained in our coupled nonlinear oscillator model [10], [12], [14]. These are represented as follows:

$$pe_{r,i} = st_{r,i} - st_{r,i-1}, \quad (5.1)$$

$$pe_{h,i} = st_{h,i} - st_{h,i-1}, \quad (5.2)$$

$$phd_i = \frac{st_{h,i} - st_{r,i}}{(pe_{h,i} + pe_{r,i})/2} \cdot 360, \quad (5.3)$$

where $pe_{r,i}$ and $pe_{h,i}$ mean period of robot and human in i-th walking cycle, respectively. phd_i stands for the phase difference between the two. $st_{r,i}$ and $st_{h,i}$ are stepping time of robot and human in i-th walking cycle, respectively.

4. Mutual Entrainment Based Communication Field

4.1 Self-Organization of Mutual Entrainment Field

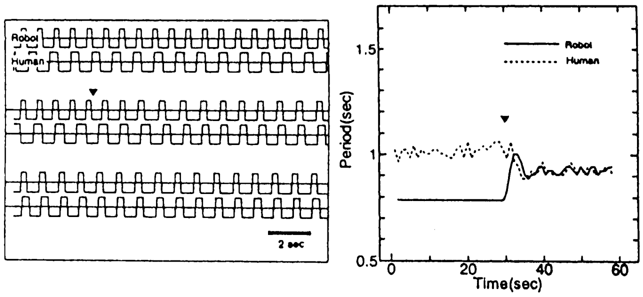
Communication process between human and robot system was observed. Temporal development of stepping rhythm is shown in Fig.4a. Arrow indicates the onset of mutual interaction. High and low levels correspond to detach and attach state of ankle, respectively. At first, each stepping rhythm oscillated independently. However, once communication starts, they gradually synchronized and finally stable phase relationship between them was self-organized. Thus, mutual entrainment field between human and robotic system was established in the communication system.

The time evolution of period in the same process is shown in Fig.4b. Before communication, original period of robotic system was 0.8 sec and that of human was about 1.0 sec. After the onset of communication, their difference gradually decreased and the periods coincided with each other at the period between the two original ones. In such state, they stably synchronized in spite of the period fluctuation in human system.

An example which shows no mutual entrainment was also observed. In such case, as shown in Figs.5a and 5b, temporal development of each stepping rhythm and its period largely fluctuated after the start of communication, and they could not entrain with each other owing to their large difference of the two original periods. The region of period difference which enable mutual entrainment between human and robotic system was about $\pm$30 %.

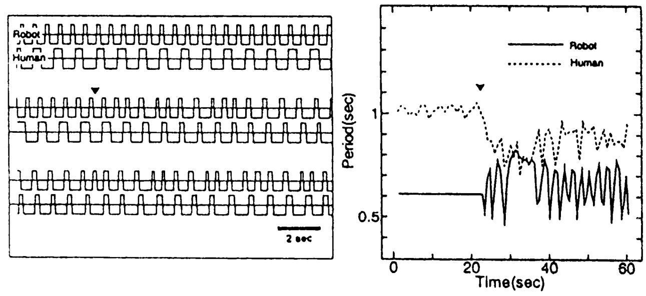
To clarify the property of this mutual entrainment field, we further analyzed the entrained period and the phase relationship between human and robotic system. Changing the original period of robot under the same original period of human, they were measured.

The relationship between original period and the entrained one is shown in Fig.6a. In the figure, every period was normalized by the original period of human system. Thus, abscissa means the relationship between original period of robot and that of human. Ordinate stands for the normalized entrained period. It clearly shows that



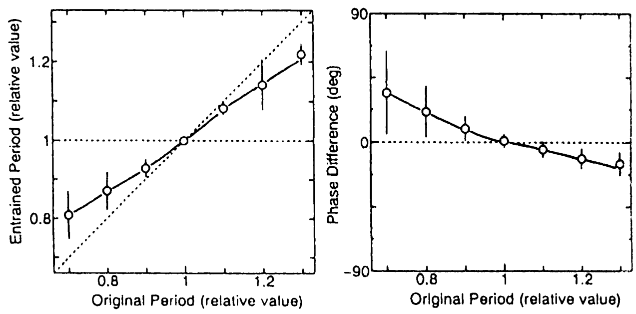
(a) Stepping Rhythm (b) Period

Fig.4 Mutual entrainment between human and robotic system.



(a) Stepping Rhythm (b) Period

Fig.5 Unentrainment between human and robotic system.



(a) Entrained Period (b) Phase Difference

Fig.6 Analysis of entrained states (n=8).

the entrained period locates between the two original periods in human and robotic system, which mean that human and robot do not interact one-sidedly but mutually interact.

The relationship between original period and the phase relationship is shown in Fig.6b. In the figure, ordinate stands for the phase difference between human and robotic system observed under the entrained state. It clearly shows that the phase relationship is determined by the relationship between the two original periods in human and robotic system. When period of robot is smaller than that of human, the phase of the robotic system advances to the human system, and *vice versa*.

This result clarified that the relative relationship in the original period between human and robotic system is encoded on the phase relationship between them. Thus, if local condition in each subsystem is encoded on its original period, this phase pattern represents the global relationship between each subsystem. By using this information, they could behave coordinately as one whole system. This means that the control information field which enables coordination between human and robotic system is self-organized in this communication field.

4.2 Real-Time Response of Mutual Entrainment Field

At first, stability of this mutual entrainment field was studied. Especially, real-time response to unpredictable change of human behavior is analyzed. As an example, perturbation was applied from the human system by setting an obstacle (30 cm width and 40 cm height) in the pathway of human walking.

In this condition, the temporal development of stepping rhythm is illustrated in Fig.7a. After applying the external perturbation at the time indicated by arrow in the figure, stepping cycle in both human and robot fluctuated largely, however they gradually synchronized with each other and the fluctuation converged.

The time evolution of period and phase difference in the same process are shown in Figs.7b and 7c. Before the perturbation, stepping rhythm of human and robot were mutually entrained. In such condition, since the original period of robotic system is faster than the other, the phase of robot advanced to the human system. After applying the external perturbation, these relationship largely fluctuated, however such transition state soon converged as shown in the same figure.

This means that the control information field organized by the mutual entrainment in the communication field between human and robotic system is robust to unpredictable change of environmental condition.

In the next, flexibility of this mutual entrainment field was studied. Especially, real-time response to the change of original period in human system is analyzed. As an example, the original period was varied by changing the walking form of human such as shape of shaking arm.

An example of temporal development of stepping rhythm is illustrated in Fig.8a. After changing the original period in human system, stepping cycle in both systems fluctuated, and their relationship was reorganized according to the new condition.

The time evolution of period and phase difference between them in the same process are shown in Figs.8b and 8c. Before changing the period, entrained period was about 0.95 sec, and the phase of robotic system advances to the human system. This is because the original period of human and robot are 1.0 and 0.8 sec respectively. After decreasing original period from 1.0 sec to about 0.60 sec in human system, entrained period decreased to about 0.70 sec and the polarity of phase relationship reversed as shown in the same figure.

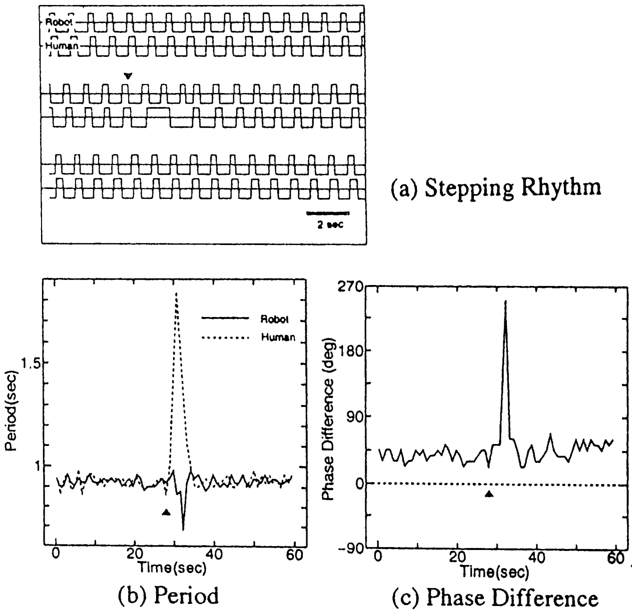


Fig.7 Response to external perturbation.

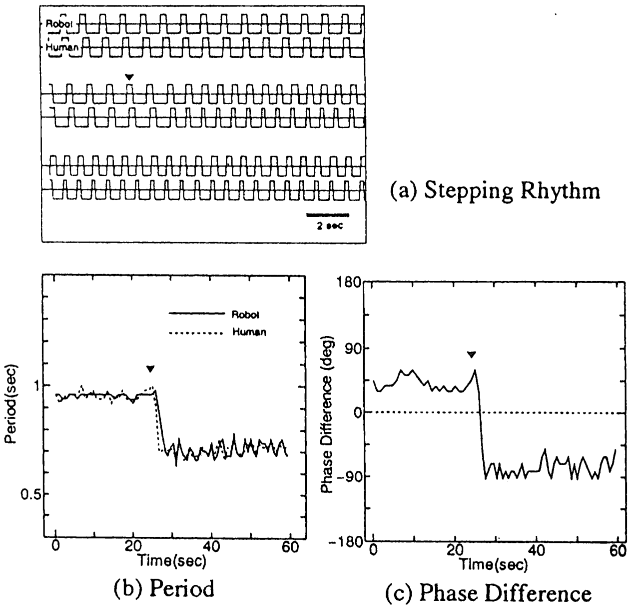


Fig.8 Response to period modulation.

This means that mutual entrainment field which encode the control information field is flexibly reorganized corresponding to the relationship between original periods in the communication field. Thus, when local condition is encoded on the period, relevant control information field could be autonomously and flexibly reorganized according to their environmental condition in real-time. Interpreting this control information field, each subsystem would be able to coordinately and relevantly behave as one whole system.

5. Conclusion

In this paper, based on our previous studies in biological communication system, a mutual entrainment field based approach was proposed as a new communication paradigm in human-robot collaboration system.

Applying this approach to the present problem, we showed that control information field is self-organized as the phase relationship between rhythms in human and robotic system. When local condition in each subsystem is encoded on its original period in this communication field, this phase pattern represents the relationship between each subsystem and the whole system. Furthermore, the control information is autonomously reorganized according to its environmental condition. Thus, by interpreting this information field, each subsystem could coordinately and relevantly behave as one whole system.

These results clarified that the property of mutual entrainment in nonlinear oscillation dynamics has large potentiality for realizing emergent communication field. Since the mutual entrainment is recursive and dynamical interaction, human and robotic system are not separated into two definite subsystems but autonomously integrated into one unity field. Thus, real-time control of such system could be achieved even under unpredictable environment including human factors.

Owing to its simple and plausible assumptions in this proposed principle, one could widely apply the present model to many human-robot collaboration systems. If each subsystem has the characteristics of nonlinear oscillation dynamics, the communication field is thought to be easily organized by the mutual entrainment between them. This new approach will lead the new technologies which realize human support robotic system, such as rehabilitation robot, amusement robot and so on. They should be further investigated experimentally and theoretically.

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