Mutual-entrainment-based internal control in adaptive process of human-robot cooperative walk

Yoshihiro MIYAKE and Junichi TANAKA

Dept. of Computational Intelligence and Systems Science
Interdisciplinary Graduate School of Science and Engineering
Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama, 226 Japan
(miyake@dis.titech.ac.jp, http://www.myk.dis.titech.ac.jp)

Abstract

Mutual-entrainment-based internal control is proposed to overcome the limitation of the control theory which is based on the separation between the system and its environment. In this new approach, since the system's dynamics is inseparable to that of environment, it should be composed of two different activities. One self-organizes the relationship between the system and the environment by using "mutual entrainment" as a non-linear interaction, and the other controls the organized relationship based on that relationship. This relationship-based internal control is realized as a mutual adaptation process in autonomous robot which walks cooperatively with humans.

1. Introduction

Can artificial systems adapt to dynamical and complex environments? Especially, it seems rather difficult to realize such an adaptation when the system's dynamics cannot be separated from that of environment. Thus, in this study, we attempt to solve this problem by constructing an autonomous robot which works cooperatively with humans, since an environment which includes human behavior becomes inseparable to the system's dynamics.

The reason why this kind of cooperation is difficult for artificial system is strongly related to the limitation of the framework in the control theory. Conventionally, control is based on the separation between a controller and a controlled object. In other words, inseparable nonlinear interaction between the system and the environment is approximately divided into two linear independent processes, observation and action, as shown in Fig. 1. Within this conventional

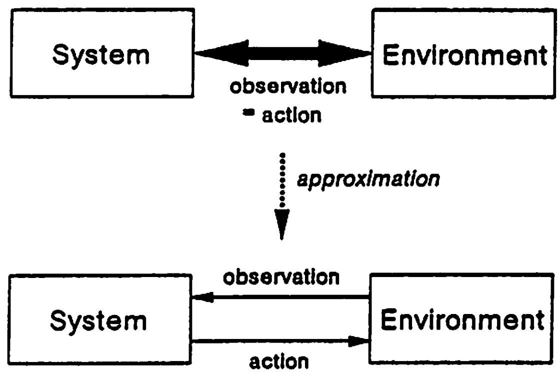

Fig. 1 Framework of control theory.

framework, a dynamical and complex environment was modeled as a stochastic process, and its extension to a non-Markov process has been necessitated in many fields. Thus, the most important problem is how to overcome the separation between the system and its environment as a limitation of the control theory. A new framework of control based on the inseparable relationship is required.

In this study, we propose a relationship-based internal control using mutual entrainment between nonlinear oscillations as a mechanism for generating and representing the inseparable relationship. This framework is realized as a mutual adaptation process in human-support walking robot for aged or handicapped persons.

2. Mutual-entrainment-based internal control

To establish an extended framework, we have been studying *Physarum* as a model of relationship-based internal control. This organism is a large amoeboid

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cell (up to 10 cm in diameter) which has no centralized control system. However, as shown in Fig. 2, it can cooperatively differentiate as a whole system in pattern reorganizing process. We have already clarified the mechanism for achieving such coordination without previously fixed differentiations such as between a controller and controlled objects [1, 2].

Physarum can be regarded as a distributed autonomous system. Each local system self-organize a dynamical relationship with other local systems through mutual entrainment between intracellular oscillations. Based on this temporal relationship, differentiation as a pattern formation in each local system is modified, and this differentiated spatial pattern recursively modifies the temporal relationship. We focus on this mutual modification process between the two activities as a model of the internal control. Here, "internal" means that the system controls the inseparable relationship which includes the system as a part. In other words, this is the relationship-based control, and a trick play in sports would be a good example.

To realize this internal control, the system should be composed of two different activities, as shown in Fig. 3 [3]. One self-organizes the inseparable relationship between the system and its environment in real time, and the other controls the relationship based on the internal model of the relationship. In the first activity, the system self-organizes an inseparable relationship by mutual entrainment, and complexity of the environment is compressed into a dynamically stable relationship. In the second activity, the relationship obtained in the first activity is observed by the internal model, and it is controlled as an action of the internal model. Relevancy of the model is estimated in the reciprocal interaction between the first and second activities.

3. Human-support walking robot

Everyone has experienced unconscious synchronization when walking with another person. By making use of this mutual entrainment phenomenon for organizing an inseparable relationship, we construct a human-support walking robot as an example of the application of mutual-entrainment-based internal control. Since the purpose of the present robot is to support walking of aged and handicapped persons, cooperative walking between the robot and humans is realized. In the following, the robot is composed of two different

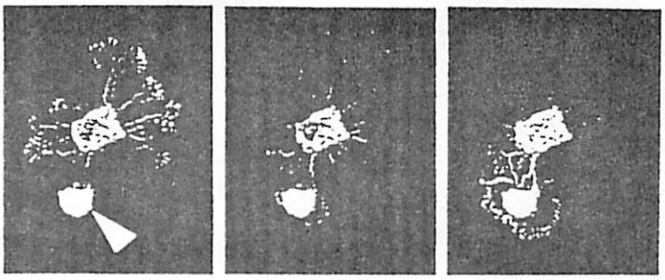

Fig. 2 Pattern reorganization in *Physarum*.

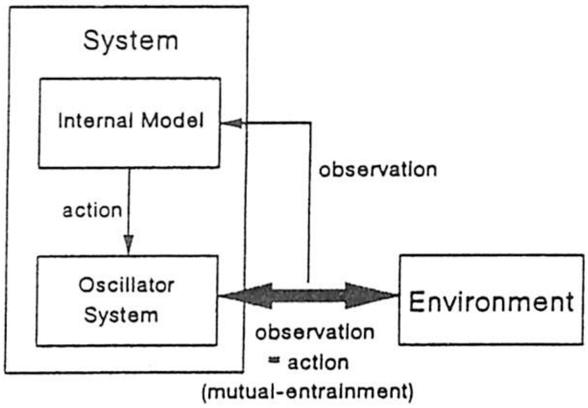

Fig. 3 Mutual-entrainment-based internal control.

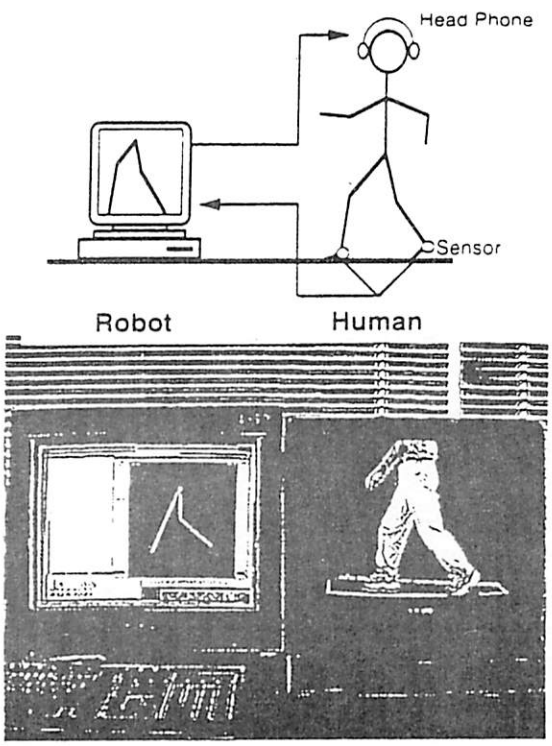

Fig. 4 Human-support walking robot.

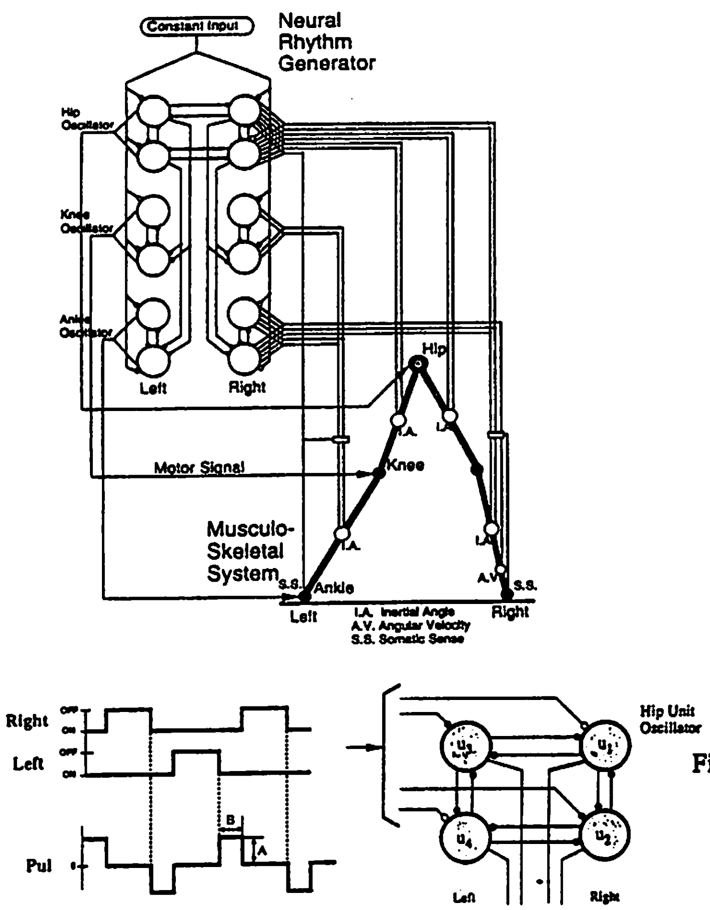

Fig. 5 Bipedal locomotion model and its interaction with human walking.

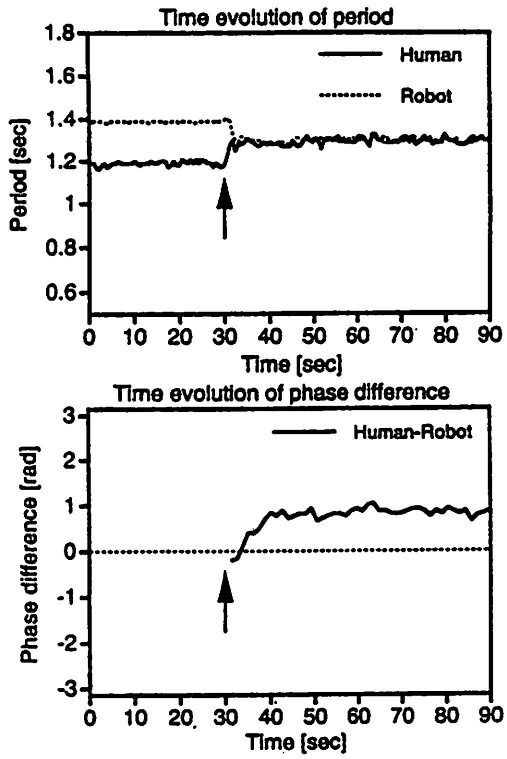

Fig. 6 Mutual entrainment between robot and human.

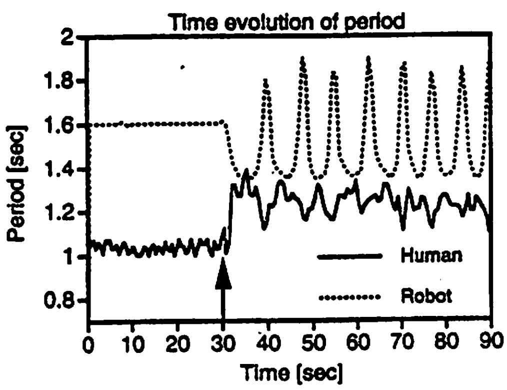

Fig. 7 Failure of mutual entrainment.

activities, one is the organization of relationship and the other is to control the relationship.

3.1 Organization of relationship

We use a kind of virtual-reality environment instead of constructing a real robot, as shown in Fig. 4. Mutual interaction between the robot and a human is realized through the sound of steps [4]. The timing of steps of a walking person is detected by sensors attached to the shoes, and the signals are transmitted to the simulated robot. On the other hand, the timing of steps of the robot is detected in the simulator, and it is transmitted to the human as sound through headphones. In this setup, bipedal locomotion model proposed by Taga et al. [5] is used as an example of the robot model, however, any model which has rhythmic activity is applicable. The interaction mechanism between the robot and the timing of steps of a walking person is summarized in Fig. 5.

Under this conditions, mutual entrainment between a robot and walking person was observed. As shown in Fig. 6, the period of walking rhythms coincided with each other after the start of mutual interaction via the sound of steps (black arrow in the figure). The entrained period was an intermediate value between the original period of the walking person and that of the robot. The phase difference between them was defined as the time difference of corresponding two steps, and it became stable as shown in the figure. However, when the difference between the two original periods is larger than about ±30%, mutual entrainment was not observed, as shown in Fig. 7. In these mutual interaction processes, the person walks unconsciously. At least, the person cannot consciously neglect the stepping sound of the robot.

These results show that a relationship between a robot and a walking person is spontaneously organized by mutual entrainment, as an inseparable nonlinear interactions. In addition, under entrained states, the phase relationship changed depending on the change of the original period. When the person changes his original walking period by gradually changing his arm's shape such as bending or straightening, the walking periods and the phase difference between them change correspondingly as shown in Fig. 8. Similar results were obtained with stepwise changes in the pattern, as shown in Fig. 9.

3.2 Control of relationship

Control of the phase relationship between the robot and the walking person is realized. Since the purpose of this robot system is to achieve cooperative walking, the phase difference is regulated to decrease to zero. As shown in Fig. 10, the phase difference changes depending on the difference between the original walking period of the robot and the human, and there is a one-to-one correlation between them. Thus, the phase relationship can be controlled by modulating the original period based on this phase difference. When the phase difference is positive, the original walking period of the robot should be increased, and vice versa. Then, time constant in the robot model is modified proportional to the phase difference. These rules correspond to a kind of internal model concerning to the phase relationship. However, the general method of organizing the internal model still remains obscure in the present framework.

To check the relevancy of the control dynamics, mutual interaction between the robot and the walking person was suppressed under the entrained state and the response was measured. As shown in Fig. 11, original walking periods were different before the start of interaction, however, they became identical at the entrained period after suppressing the mutual interaction (white arrow). This means that the original periods for both the robot and the human were modified during entrainment through the control mechanism described above. Thus, the phase difference decreased to zero under the entrained state. Furthermore, it is suggested that the human walking is similarly controlled to that of the present robot.

When the human changes his original walking

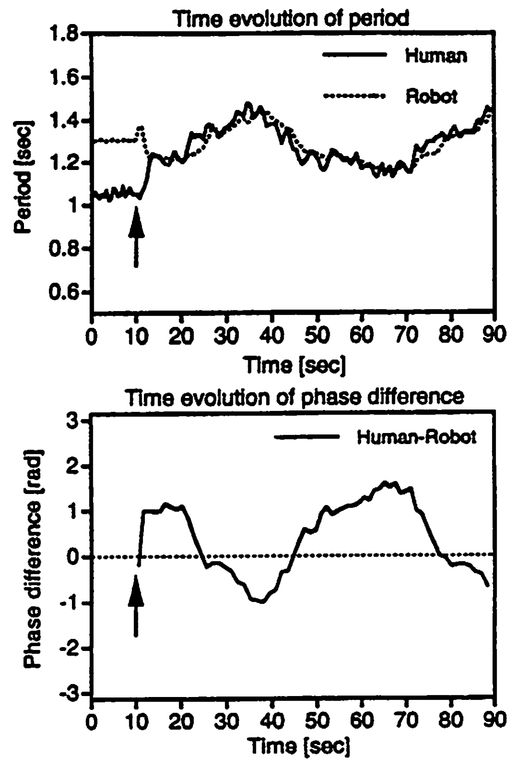

Fig. 8 Time evolution of period and phase difference under entrainment between robot and human.

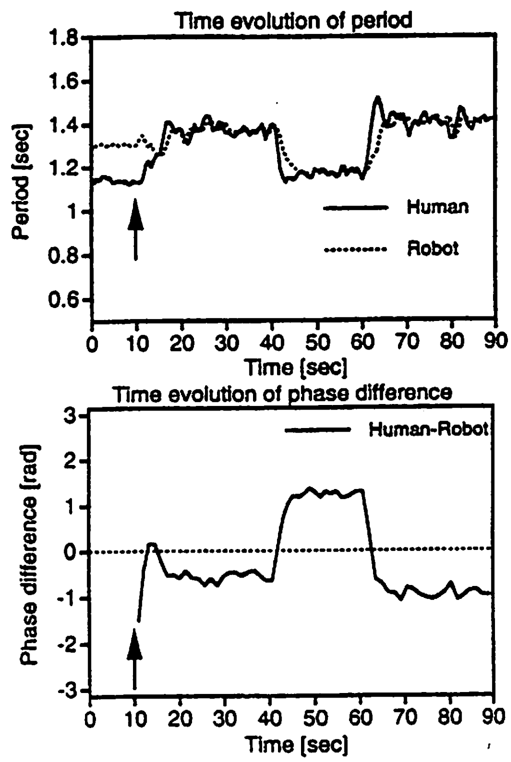

Fig. 9 Time evolution of period and phase difference under entrainment between robot and human.

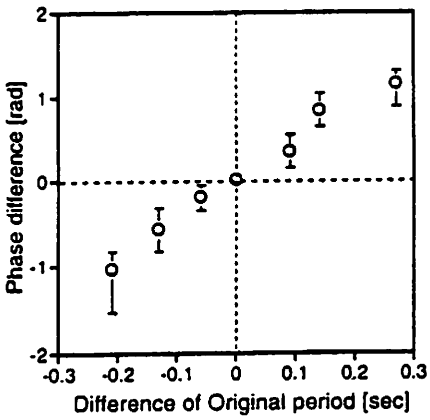

Fig. 10 Relationship between original period difference and phase difference

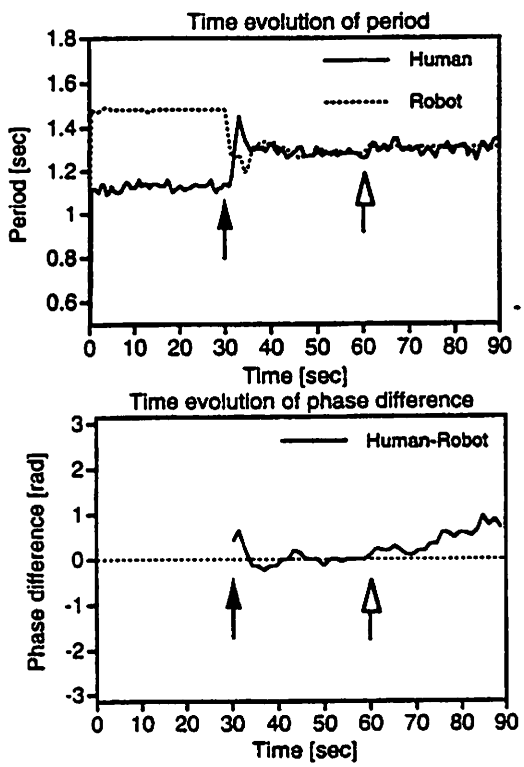

Fig. 11 Time evolution of period and phase difference before and after suppressing mutual interaction.

period by changing his arm's shape, the walking period of the robot changes synchronously and the phase difference decreases to zero, as shown in Figs. 12 and 13. This means that cooperative walking was realized through the present mechanism. Thus, it was shown that the present framework is suitable for controlling the inseparable relationship between a system and its environment.

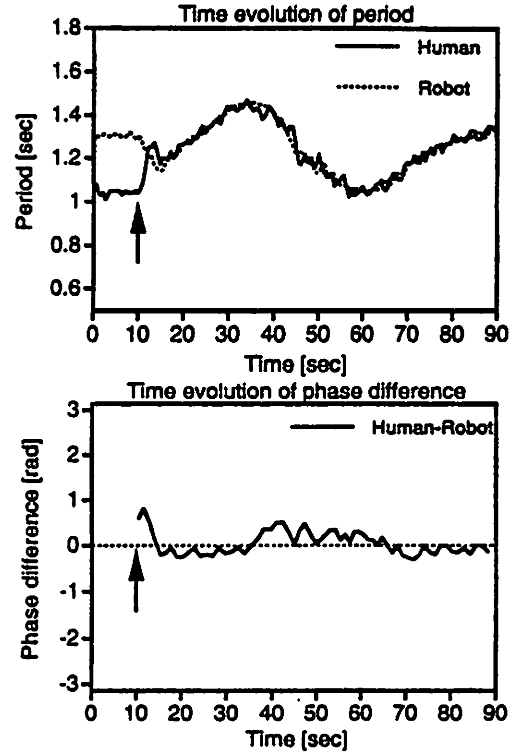

Fig. 12 Time evolution of period and phase difference under internal control between robot and human.

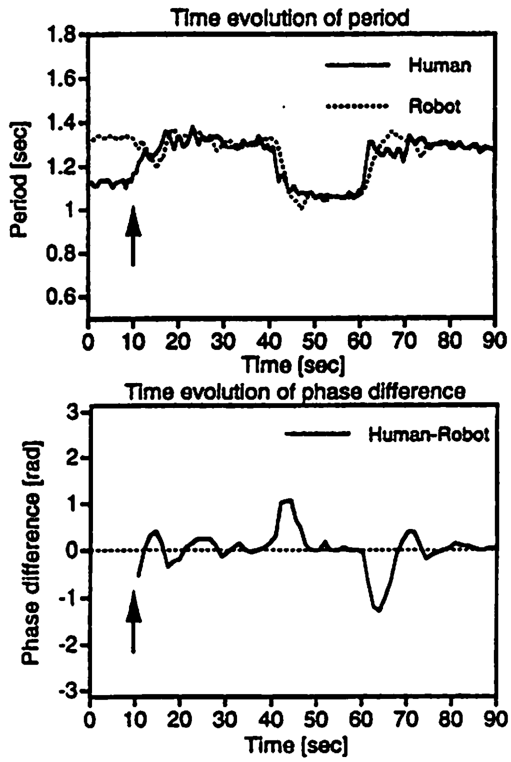

Fig. 13 Time evolution of period and phase difference under internal control between robot and human.

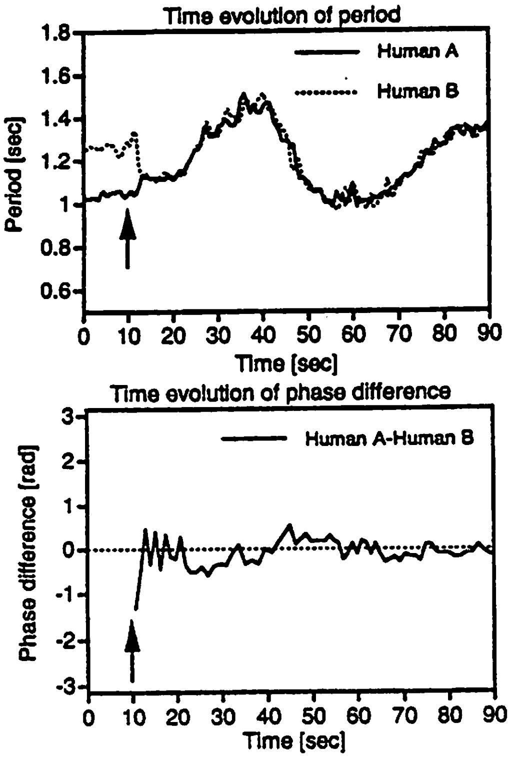

Fig. 14 Time evolution of period and phase difference under interaction between humans.

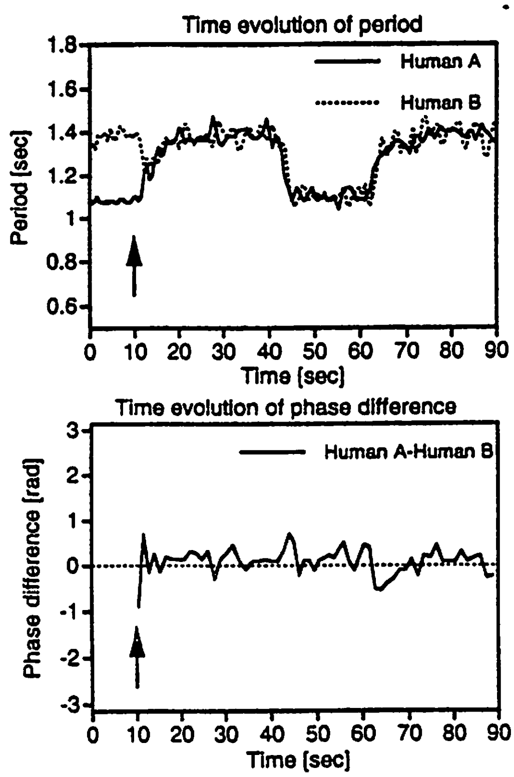

Fig. 15 Time evolution of period and phase difference under interaction between humans.

3.3 Comparison to human walking

Using the same experimental setup, mutual interaction between two walking persons was realized. When one person changes his original walking period, similar results as described above were obtained, as shown in Figs. 14 and 15. These results indicate that mutual-entrainment-based internal control is similar to the control mechanism of cooperative walking between humans.

4. Conclusions

In this report, we proposed mutual-entrainment-based internal control as an extended framework of control theory under a dynamical and complex environment. By self-organizing the relationship between a system and its environment, the relationship can be regulated based on the internal model of the relationship. Using this method, we demonstrated that a human-support robot which walks cooperatively with a human can be realized. In addition, we have already found that this method increases human comfort in such inseparable relationship. Thus, it is suggested that this framework would be applicable for human support in such fields as welfare, amusement and communications.

5. References

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