Trans. of the Society of Instrument and Control Engineers
Vol.E-2, No.1, 195/206 (2002)

Man-Machine Interaction as Co-emergence Communication

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Human-human system can self-organize relational functions by their communication. In this study, we aimed at establishing the design principle of man-machine system to realize such co-emergence process observed in the interaction between humans. This developmental dynamics is modeled based on "duality" of human communication which is composed of embodied process in open system and causal process in closed system. The former is represented by body model and is to organize coherent relationship between human and machine, and the latter is internal model to separate the coherence into two one-sided relations. Through the mutual constraint between these two sub-dynamics, relational functions as a whole system are generated in the man-machine interaction. Using this duality model, "co-emergence" process was realized as the mutual-adaptation process between human and machine, and its effectiveness was shown in a walk support robot.

Key Words: man-machine interaction, co-emergence, duality, duality model, mutual-adaptation

1. Introduction

Human-human system can self-organize relational functions as a community in real time through their communication. This study aims to establish a design principle for the relationship between human and artifacts to realize such co-emergence process observed in the interaction between humans.

In this background, we can widely find the large difficulty in modern man-machine system. As Norman had pointed out, a set of functions to be prepared in artifacts is rapidly expanding, especially in intelligent artifacts. And such system finally becomes a large black box with low usability [1) 2)]. They are constructed based on the design principle that designers prepare a set of functions previously and users choose the function corresponding to their situation. And, as long as the design principle is on the basis of this "search" paradigm, it is inevitable that the complexity of the user's situation promotes the complexity of artifacts unlimitedly.

From the limitation of this search paradigm realized in closed functional space, we propose new design principle so that human and artifacts self-organize the functions in real time through their open interaction. We aim at the man-machine system with "co-emergence" that human and artifacts self-organize functions together as if human and human interaction organizes [3)]. This means the design principle which doesn't distinguish design and use.

In this study, we focus on "duality" which enables co-emergence in human communication and formalize it as "duality model." And, we embed it into the interface of man-machine system and represent it as our co-emergence communication. We describe co-emergence and duality in chapter 2, and propose duality model in chapter 3. We simulate the model and construct co-emergence process using walking support robot as an example in chapter 4.

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2. Co-emergence communication

2.1 Duality and co-emergence

As long as the functions of artifacts are limited to the search process in closed space, it is clear that the emergence process could not be obtained. This means that the emergence of the functions requires not only closed space but also open space involving closed one as a part. It is also considered that human communication is based on duality which consists of these two kinds of space.

For example, it is clear by Polany's comparison of implicit intelligence and formal intelligence [4)] that not only exchanging messages but also sharing contexts are essential in human co-emergence communication. And, the one-sided actions such as exchanging message in closed space (causality) are involved by the mutual relationship as context sharing in open space (simultaneity). It can be regarded as the connotation relation between the limitation process of consciousness and the open process of body. This duality is regarded as the fundamental structure of emergence in the concept of "Ba" proposed by Shimizu [5) 6) 7)].

Heidegger thought that human being is the expression of "Dasein" in the space of possibility and Dasein has duality. He studied the relationship between "Geworfen-

heit" and introspection. In his framework, the practice was regarded as the action with "Besorgen," and the introspection by breakdown was regarded as the knowledge with Uberlegung [8]. Merleau=Ponty also thought the duality of Dasein as that of body, that is touching body and touched one, and further considered the importance of pre-linguistic embodied "communication" in the process to prepare linguistic communication [9].

In addition, some experimental results to support duality are reported. For example, Condon found that neonate moves their hands and legs in synchronized with their mother's voice, and called it entrainment [10) 11]. This means that the open interaction of body exists outside the space which human is conscious of. Poppel reported that the state of being conscious emerges cyclically as discrete state which continues about 3 seconds, by analyzing the process of figure-ground separation in visual perception [12) 13]. And, he also found that the distinction of events is different from the distinction of its sequence, and clarified the relationship between the identification of sequence as one-sided causality and the state of being conscious.

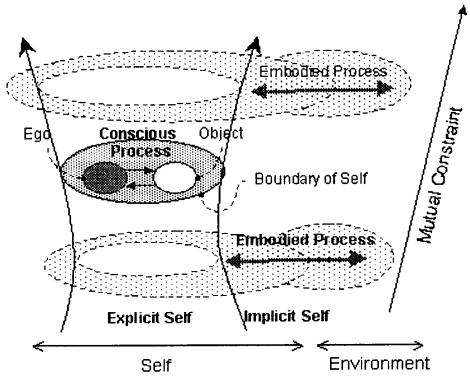


Fig.1 Duality of self

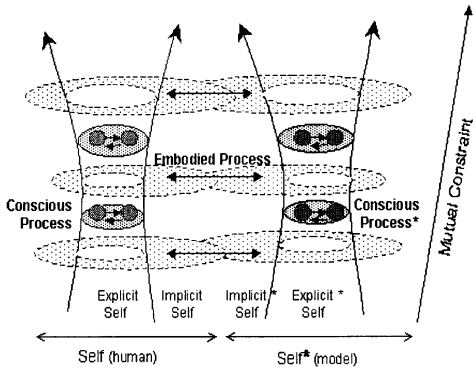


Fig.2 Co-emergence process

We regard the fundamental structure of emergence as "duality of self," as shown in **Fig.1**, on the basis of this information. This is the emergence cycle of self consciousness through the mutual constraint between the conscious process to close in explicit self and the embodied process to open in implicit self. In this duality, it is possible that implicit self is shared by the open interaction of embodied process and different emergence cycle of self become coherent. We call this emergent coherence as "co-emergence communication."

However, co-emergence itself is direct experience involved in self. So, it cannot be simply generalized as the design principle of man-machine system. If this duality is modeled in explicit self, its space will be closed, and cannot overcome the limitation of search paradigm. So, the model of duality should be represented based on the duality of self. In other words, the model is represented in open form including implicit self, as a part of the co-emergence communication between self and the model, as shown in **Fig.2**. Then, designers can have the internal viewpoint of participating in the communication and establish co-emergence process based on the incompleteness of self. Please refer to other papers in the detail [3) 14]. In this background, we think that we have to reconsider the design principle of man-machine system from the viewpoint of the co-emergence interface between self and machine [15].

2.2 New man-machine system

By the way, what is the essential difficulty in realizing the co-emergence system in machine side? It may be the mutual interference between machine and human dynamics by the open interaction through human body. This is because the machine cannot identify and anticipate the environmental change of human on such open dynamical complexity. In other words, designers cannot previously define the state space where machine acts.

The way of dealing with such unpredictable situation can be classified into 2 sorts. One is "uncertainty" where probability is applied. Well, state space is defined, but state transition is not defined. The other is called "indefiniteness" where even the definition of state space is impossible [5]. In the former, the weak action from the environment causes weak disturbance on machine dynamics. This is solved by the existing control technique. In the latter, the strong action form human side as the environment causes the mutual interference between human and machine dynamics. The effective method which deals with this open indefinite situation has not been established, yet.

So, we can say that the existing man-machine system has been constructed in the environment where there is

no mutual interference. And, machine has been controlled based on the optimizing process of internal condition in fixed state space which has weak disturbance from environment. The prototype of this mechanism is seen in Winner's cybernetics [16]. The function design based on the search paradigm in closed function space has been established by developing this mechanism. Its type is seen in master-slave system and server-client model.

This man-machine system corresponds to the situation that the time scale of machine dynamics is much different from that of human as environment, from the viewpoint of dynamical system. For example, when machine changes more quickly than environment, environment can be regarded as constant approximately, so state space and its optimality can be defined only in machine side. When machine changes more slowly than environment, environment is regarded as steady state [17]. On these conditions, since the dynamics of machine and environment can be separated approximately, designers are able to regard machine as closed space. As the result, this caused the endless expansion of function space in machine and the function design unfitted to users' need.

The man-machine system which we propose is expanding to the direction that the time scale of machine is not very different from that of environment, from the viewpoint of the comparison with existent technology. The mutual interference is dominant in this situation, and state space cannot be defined only in machine side. As machine is open to human body and machine dynamics becomes indefinite, the search in closed function space is of no effect. Then, the co-emergence of the relational functions on the basis of open interaction is needed.

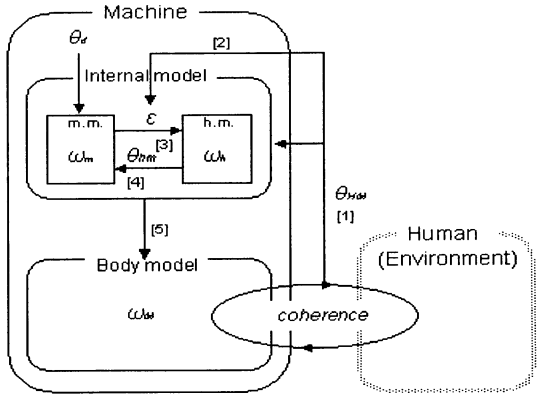
Recently, the communication technique to utilize mutual interference through body interaction has begun to emerge. For example, it is Miwa's approach to "embodiment" [18] and Watanabe's "virtual actor" [19]. In this technique, the mutual entrainment of body motion is used as an example of interaction in open space. The next necessary step in this direction is not only open space, but also duality as connotation relation including closed space. Machine can deal with human duality by this duality. This study can be regarded as the first approach to establish man-machine system based on this co-emergence communication.

We have modeled duality on the basis of this idea and applied it to man-machine system. Especially, we have aimed at the walk support system to establish rehabilitation as an example of co-emergence communication, by generating the cooperative walk as a relational function between human and robot. For example, when we humans walk together, their walk pace is often coincided with each other. This is the mutual entrainment of body motion and is regarded as an example of dual interaction including implicit self [20]. We have already submitted the many reports of such walk support robots [21) 22) 23) 24) 25)]. In this study, we propose the fundamental models concerning their design principle.

3. Duality model

3.1 Overview

As shown in **Fig.3**, we have proposed "duality model" by referring to the duality in co-emergence communication [23) 24)]. This consists of body model and internal model. Body model corresponds to implicit self, meanwhile, internal model corresponds to explicit self. We explain the co-emergence process of self consciousness as mutual constraint process between them. The body model which



(1) In body model, coherent phase relationship (θ_{HM}) is self-organized by mutual entrainment between the machine and its environment.
(2) In internal model, error measure is calculated by the difference between predicted relationship (θ_{hm}) and organized relationship (θ_{HM}), and parameter of internal model (ε) is modified to decrease the measure.
(3) At coherent phase relationship (θ_{hm}) in internal model, original frequency of environment-side (ω_h) which satisfies the organized phase relationship in body model (θ_{HM}) is searched under fixed original frequency of machine-side (ω_m).
(4) At coherent phase relationship (θ_{hm}) in internal model, original frequency of machine-side (ω_m) which satisfies the desired phase relationship (θ_d) is searched under fixed original frequency of environment-side (ω_h) obtained in the above step.
(5) Original frequency of body model (ω_M) is modified based on the searched frequency (ω_m) to realize desired phase relationship.
(6) Return to the first step.

Fig.3 Duality model

establishes the interaction in open space is modeled by the mutual entrainment of body motion, based on the reference to Condon's experiment. Meanwhile, internal model is represented as the search process by using one sided action in closed space, by reference to Poppel's experiment.

3.2 Structure and algorithm

Duality model consists of the following two sub-models and their mutual constraint process. However, the time hierarchy of body model and internal model is assumed on this modeling. Well, the dynamics of body model is embedded in its mutual interference with environment, because its time scale is close to that of environment change. This corresponds to the situation that the system is open to environment. Meanwhile, internal model varies more quickly than environment, corresponding to the situation that the system is closed against environment. This is verified by the fact that the state of being conscious is related to the anticipation of the environment variation [26]. In this study, as shown in Fig.2, we represent duality model as the co-emergence communication between self and the model. So, this model should correspond to the machine side in man-machine system.

(1) Body model has the dynamics of which time scale is close to environment variation, and constructs the space which is open to environment. Particularly, it is possible that it generates the coherent relation through the interaction with environment (human). Mutual entrainment is used as an example of such dynamics, and body model is constructed as a kind of non-linear oscillator.

(2) Internal model has the dynamics which is much quicker than environment variation, constructs the space which is closed against environment. Particularly, it is realized as the coupled non-linear oscillator system to represent machine side model corresponding to body model and environment (human) side model corresponding to environment. And, by decomposing the coherent relation generated in body model into one sided action in internal model, internal state of body model and environment are anticipated by search. This is a kind of reverse problem. Internal model can be regarded as the hypothetical constraint to overwhelm the ill posed situation.

Then, the mutual constraint between these two models is necessary. Both dynamics is separated approximately on the basis of the difference of their time scale. So, mutual constraint is constructed as alternate constraint. In addition, the concrete application of this model is walk support robot, of which goal is the co-emergence of cooperative walk. Concretely, the goal is the coherent state of the walk rhythm between human and machine, and this coherence as a kind of relational function is realized by maintaining the phase relation to the target value.

(1) The coherent relation between machine and environment (human) is generated through mutual entrainment in body model. And, the following steps are started to interpret this relation.

(2) First, the state space for internal model is defined. This is constructed so that the difference between the predicted coherent relation in internal model and the relation actually observed in body model might decrease.

(3) In internal model, the time evolution of the parameter of machine side model is fixed, and the parameter of environment (human) side model to reorganize the observed coherent relation is searched.

(4) In internal model, the time evolution of the parameter of environment (human) side model is fixed to the above searched value, and the parameter of the machine side model to establish the target relation is searched.

(5) On the basis of these two one-sided relations, the internal state of machine and environment (human) are anticipated and body model is modified by this prediction.

(6) Return to the first step.

As temporal hierarchy is assumed on body model and internal model, each dynamics is represented by different time coordinates. And, three time coordinates are used to describe the above mutual constraint process including the time to relate both.

(1) t_{ec}: time to describe body model

(2) t_{ic}: time to describe internal model

(3) t_{md}: time to describe mutual constraint

The first coordinate, t_{ec}, is the continuous time to describe body model and corresponds to the so-called physical time. This time coordinate has its time scale close to environment variation and is embedded in the interaction with environment. This corresponds to the embodied time in the implicit self, on the relation with duality. The next coordinate, t_{ic}, is the continuous time to describe internal model and is used to simulate the interaction between environment and body model. This time is separated from physical time, and is defined virtually, on the assumption that the time scale of internal model is much faster than that of body model. This corresponds to the cognitive

time in explicit self, on the relation with duality. The last coordinate, t_{md}, is the time to describe the mutual constraint process between internal model and body model. Mutual constraint is constructed as alternate constraint approximately, so this time coordinate to represent relation between tec and tic is discrete.

3.3 Body model

Body model constructs open space, so it is expressed as non-autonomous system and the object of its interaction is not represented. In addition, mutual entrainment is assumed as dynamics, body model is constructed by non-linear oscillator. Then, the general formulas are as follows.

$$\dot{x}_M(t_{ec}) = y_M(t_{ec}), \quad (1)$$

$$\dot{y}_M(t_{ec}) = -\omega_M^2(t_{md})x_M(t_{ec}) + \xi f(x_M(t_{ec}), y_M(t_{ec})). \quad (2)$$

x_M and y_M is state variable described on t_{ec}. ξ represents non-linearity and ω_M is the parameter described on t_{md} to define original frequency of body model. This parameter ω M is modified based on the mutual constraint process. Particularly, animal walk is controlled by central pattern generator, and can be modeled as van der Pol oscillator approximately [27]. Then, the following formulas are introduced.

$$f(x_M(t_{ec}), y_M(t_{ec})) = (1 - x_M^2(t_{ec}))y_M(t_{ec}). \quad (3)$$

Since van der Pol oscillator has the stable limit cycle when $\xi > 0$, body model is constructed using this. However, it is regarded as stance phase in walk when $x_M < 0$, and it is regarded as swing phase when $x_M > 0$. The timing of leg grounding is defined as the time that the sign of x_M changes from plus to minus.

Then, the interaction which is established between body model and human walk rhythm as its environment is modeled.

$$\dot{x_M}(t_{ec}) = y_M(t_{ec}), \quad (4)$$

$$\dot{y_M}(t_{ec}) = -\omega_M^2(t_{md})x_M(t_{ec}) + \xi(1 - x_M^2(t_{ec}))y_M(t_{ec}) + g(x_M(t_{ec}), x_H(t_{ec})). \quad (5)$$

$g(x_M, x_H)$ represents interaction, and x_H is the state variable for human walk. Concretely, pulse action is assumed as the interaction through grounding timing of leg, such as footstep.

$$g(x_M(t_{ec}), x_H(t_{ec})) = \begin{cases} -height, & if(t_{ec} - last_H(t_{ec})) \leq length \\ 0, & otherwise. \end{cases} \quad (6)$$

Pulse height and duration is *height* and *length*, respectively. And, $last_H$ represents the latest time of the timings that human leg is grounded.

Although ideally, body model should be modeled on the basis of human body structure, the model of non-linear oscillator is used as the first approximation in this study, because it is thought that the most important character in body dynamics is in the open interaction on the basis of its mutual entrainment.

3.4 Internal model

Internal model is on the hypothesis for open space through body model, and is constructed as closed autonomous system using the coupled non-linear oscillators. Particularly, body model and human walk rhythm can be regarded as limit cycle approximately. So they are represented in the following formulas by the coupled phase oscillator system [28].

$$\dot{\varphi_m}(t_{ic1}) = \omega_m(t_{ic2}) + m(\varphi_h(t_{ic1}) - \varphi_m(t_{ic1})), \quad (7)$$

$$\dot{\varphi_h}(t_{ic1}) = \omega_h(t_{ic2}) + h(\varphi_m(t_{ic1}) - \varphi_h(t_{ic1})). \quad (8)$$

φ_m and φ_h represents the state variable as the phase of machine side in internal model and that of environment (human) side, and ω_m and ω_h is the parameter as each original frequency, respectively. $m(\varphi_h - \varphi_m)$ and $h(\varphi_m - \varphi_h)$ is coupling function and symmetrical coupling is used as the simplest case. And, the following $\varepsilon(> 0)$ is coupling parameter.

$$m(\varphi_h(t_{ic1}) - \varphi_m(t_{ic1})) = \varepsilon(t_{md})\sin(\varphi_h(t_{ic1}) - \varphi_m(t_{ic1})), \quad (9)$$

$$h(\varphi_m(t_{ic1}) - \varphi_h(t_{ic1})) = \varepsilon(t_{md})\sin(\varphi_m(t_{ic1}) - \varphi_h(t_{ic1})). \quad (10)$$

Then, internal model predicts the internal state of body model and its environment by searching for its original frequency parameter. So, dynamics is described with multiple time scales. One is t_{ic1}, the time to simulate the generation of the phase coherence in body model inside internal model, and the other is t_{ic2} to simulate the search process of its original frequency parameter. It is assumed that t_{ic2} changes much more slowly than t_{ic1}. The change of the coupling parameter corresponding to the generation of internal model itself depends on the mutual constraint of body model and internal model, and is established with time scale, t_{md}.

In the above background, the dynamics of mutual entrainment as for phase variable is described with time scale, t_{ic1} [28]. Then, the phase relation between machine side and environment (human) side is defined as follows.

$$\theta_{hm}(t_{ic1}) = \varphi_h(t_{ic1}) - \varphi_m(t_{ic1}). \quad (11)$$

Then, the following dynamics as for the time evolution of phase relation is defined.

$$\dot{\theta}_{hm}(t_{ic1}) = \omega_h(t_{ic2}) - \omega_m(t_{ic2}) - 2\varepsilon(t_{md})\sin(\theta_{hm}(t_{ic1})). \quad (12)$$

This has the following potential function V_1.

$$V_1 = (\omega_h(t_{ic2}) - \omega_m(t_{ic2}))\theta_{hm}(t_{ic1}) - \int_0^{\theta_{hm}(t_{ic1})} (-2\varepsilon(t_{md})\sin(\theta'))d\theta', \quad (13)$$

$\theta_{hm}(t_{ic2})$, the coherent phase relation as the stable state of mutual entrainment is defined as follows.

$$\theta_{hm}(t_{ic2}) = \sin^{-1}\frac{\omega_h(t_{ic2}) - \omega_m(t_{ic2})}{2\varepsilon(t_{md})}. \quad (14)$$

In this case, $-2\varepsilon(t_{md}) < \omega_h(t_{ic2}) - \omega_m(t_{ic2}) < 2\varepsilon(t_{md})$. This (14) is used to search for original frequency parameter with time scale, t_{ic2}, in the next chapter.

3.5 Mutual constraint process

3.5.1 Body model to internal model

In the algorithm mutual constraint, the definition of internal model, the constraint from body model to internal model, and the constraint from internal model to body model are performed in turn. However, we, taking account of the ease of understanding, start from the constraint from body model to internal model and finally explain the definition of internal model.

First, the relation between body model and human walk rhythm as its environment is defined as follows, using phase relation $\theta_{HM}(t_{ec})$.

$$\theta_{HM}(t_{ec}) = 2\pi\frac{\Delta t_{HM}(t_{ec})}{period_M(t_{ec})}. \quad (15)$$

$\Delta t_{HM}(t_{ec})$ is the time difference of mutually corresponding events on the relation between body model and human. In the case of walk, it may be the difference of the timing of leg grounding. And, $period_M(t_{ec})$ is the apparent frequency of body model. The reason why the apparent frequency is used is that the frequency of the non-linear oscillation is different from that of original frequency due to interaction. On this condition, when the variance rate of phase relation is lower than threshold, Ω_{th},

$$|\dot{\theta}_{HM}(t_{ec})| < \Omega_{th}, \quad (16)$$

the phase relation is regarded as coherent state. And the following constraint is defined for internal model.

$$\theta_{HM}(t_{md}) = \theta_{HM}(t_{ec})|_{coherence}. \quad (17)$$

Second, in internal model, as shown in **Fig.4**, the phase coherence established in body model is interpreted on the basis of one-sided relation, and the original frequency parameter to regenerate the phase relation is searched. The following potential function, V_2 is introduced to define the search dynamics.

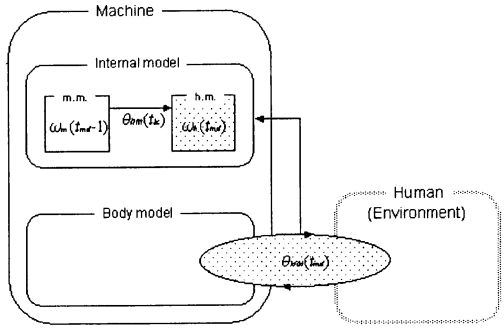


Fig.4 Constraint from body model to internal model

$$V_2 = -\alpha\cos(\theta_{hm}(t_{ic2}) - \theta_{HM}(t_{md})). \quad (18)$$

$\theta_{HM}(t_{md})$ is defined in (17). $\alpha(>0)$ defines the potential shape and search velocity. The search process of original frequency is as follows.

$$\dot{\theta}_{hm}(t_{ic2}) = -\frac{\partial V_2}{\partial\theta_{hm}(t_{ic2})} = -\alpha\sin(\theta_{hm}(t_{ic2}) - \theta_{HM}(t_{md})). \quad (19)$$

The dynamics as for the phase variable in internal model is deleted by the substitution of (14) for (19). So, the time evolution of the original frequency parameter with the time scale, t_{ic2}, is as follows.

$$\dot{\omega}_h(t_{ic2}) - \dot{\omega}_m(t_{ic2}) = -\alpha\sqrt{4\varepsilon^2(t_{md}) - (\omega_h(t_{ic2}) - \omega_m(t_{ic2}))^2} \times \sin(\sin^{-1}\frac{\omega_h(t_{ic2}) - \omega_m(t_{ic2})}{2\varepsilon(t_{md})} - \theta_{HM}(t_{md})). \quad (20)$$

However, the time evolution of two original frequencies cannot be defined with one equation. So, both dynamics is separated. And, the one-sided relation from machine side to environment (human) side is assumed as follows.

$$\omega_m(t_{ic2}) = \omega_m(t_{md} - 1) = const., \quad (21)$$

Then, the following dynamics is defined.

$$\dot{\omega}_h(t_{ic2}) = -\alpha\sqrt{4\varepsilon^2(t_{md}) - (\omega_h(t_{ic2}) - \omega_m(t_{md} - 1))^2} \times \sin(\sin^{-1}\frac{\omega_h(t_{ic2}) - \omega_m(t_{md} - 1)}{2\varepsilon(t_{md})} - \theta_{HM}(t_{md})). \quad (22)$$

This representation means that open mutual relation through body model is interpreted as one-sided causal relationship form machine to human in closed internal model. The original frequency of walk rhythm in human side is predicted as follows.

$$\omega_h(t_{md}) = -\alpha \int_{t_{ic2(0)}}^{t_{ic2(max)}} \sqrt{4\varepsilon^2(t_{md}) - (\omega_h(t_{ic2}) - \omega_m(t_{md}-1))^2} \times \sin(\sin^{-1} \frac{\omega_h(t_{ic2}) - \omega_m(t_{md}-1)}{2\varepsilon(t_{md})} - \theta_{HM}(t_{md}))dt_{ic_2}, \quad (23)$$

The time width of search is from $t_{ic2(0)}$ to $t_{ic2(max)}$, and $\omega_h(t_{md}-1)$ is used as the initial condition of $\omega_h(t_{ic2})$.

As above, in the constraint process from body model to internal model, we fix the original frequency of the oscillator corresponding to machine side, and search for the original frequency parameter of the oscillator corresponding to human side. This means that the human internal state embedded in the phase relation generated through body model is predicted on the basis of the one-sided relation in internal model.

3.5.2 Internal model to body model

Next, we explain the constraint from to internal model to body model. As shown in **Fig.5**, we search for the original frequency parameter to establish the target coherent phase relation. The search dynamics of original frequency is established with the time scale, t_{ic2} by the introduction of the potential function V_3.

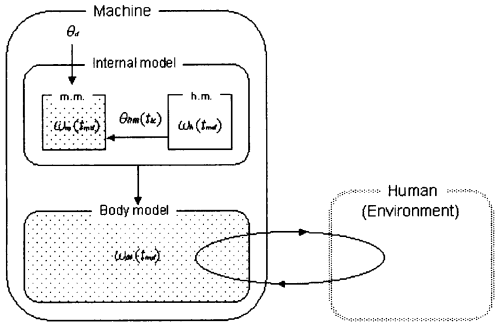


Fig.5 Constraint from internal model to body model

$$V_3 = -\beta \cos(\theta_{hm}(t_{ic2}) - \theta_d). \quad (24)$$

θ_d is the target phase relation. $\beta(>0)$ defines the potential shape and the search velocity. Then, the following search process is defined.

$$\dot{\theta_{hm}}(t_{ic2}) = -\frac{\partial V_3}{\partial \theta_{hm}(t_{ic2})} = -\beta \sin(\theta_{hm}(t_{ic2}) - \theta_d). \quad (25)$$

The time evolution of original frequency parameter with the time scale, t_{ic2}, is defined by the substitution of (14) for (25).

$$\dot{\omega}_h(t_{ic2}) - \dot{\omega}_m(t_{ic2}) = -\beta\sqrt{4\varepsilon^2(t_{md}) - (\omega_h(t_{ic2}) - \omega_m(t_{ic2}))^2} \times \sin(\sin^{-1} \frac{\omega_h(t_{ic2}) - \omega_m(t_{ic2})}{2\varepsilon(t_{md})} - \theta_d). \quad (26)$$

However, the time evolution of two original frequencies cannot be defined by one equation. So, the one-sided relation from environment (human) side to machine side is assumed as follows.

$$\omega_h(t_{ic2}) = \omega_h(t_{md}) = const., \quad (27)$$

Then, the following dynamics is defined.

$$\dot{\omega}_m(t_{ic2}) = \beta\sqrt{4\varepsilon^2(t_{md}) - (\omega_h(t_{md}) - \omega_m(t_{ic2}))^2} \times \sin(\sin^{-1} \frac{\omega_h(t_{md}) - \omega_m(t_{ic2})}{2\varepsilon(t_{md})} - \theta_d). \quad (28)$$

This representation means that the mutual relation through body model is interpreted as the one-sided causal relationship from human to machine in internal model. Then, the original frequency of body model in machine side is predicted as follows.

$$\omega_m(t_{md}) = \beta \int_{t_{ic2(0)}}^{t_{ic2(max)}} \sqrt{4\varepsilon^2(t_{md}) - (\omega_h(t_{md}) - \omega_m(t_{ic2}))^2} \times \sin(\sin^{-1} \frac{\omega_h(t_{md}) - \omega_m(t_{ic2})}{2\varepsilon(t_{md})} - \theta_d)dt_{ic2}. \quad (29)$$

The time width of search is from $t_{ic2(0)}$ to $t_{ic2(max)}$, and $\omega_m(t_{md}-1)$ is used as the initial condition of $\omega_m(t_{ic2})$.

As above, in the constraint process from internal model to body model, the original frequency parameter of the oscillator corresponding to machine side is searched, on condition that the original frequency of the oscillator corresponding to human side is fixed. This means that the original frequency of body model which is required to establish the goal phase relation generated through the body model is predicted on the basis of the one-sided relation in internal model. Then, body model is under constraint of internal model on the basis of the following relation.

$$\omega_M(t_{md}) = \omega_m(t_{md}). \quad (30)$$

As the result, the coherent state which is generated between body model and human walk rhythm decays once, and the new coherent state is regenerated.

3.5.3 Definition of internal model

Finally, we explain the update mechanism of internal model itself corresponding to the constraint condition in this mutual constraint process. Then, we have to note that mutual constraint process is embedded in the open interaction with environment, as the assumption of duality model.

Internal model is the hypothetical model as for the open space through body model, and its relevancy has to be checked by the mutual constraint process of internal model and body model, again. So, as shown in **Fig.6**, internal model has to be modified so that the difference between the phase relation predicted in internal model and the coherent phase relation regenerated with human walk rhythm through body model decreases. And, its error measure is defined as follows.

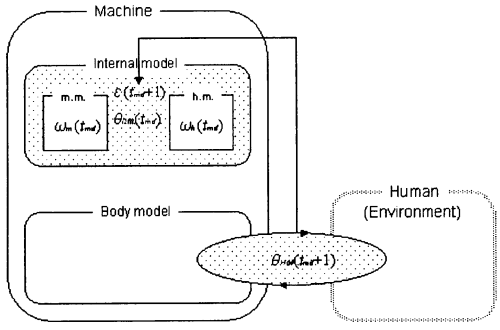


Fig.6 Generation of internal model

$$E(t_{md}+1) = \frac{1}{2}(\theta_{HM}(t_{md}+1) - \theta_{hm}(t_{md}))^2. \tag{31}$$

$\theta_{hm}(t_{md})$ is the coherent phase relation of body model predicted in internal model, as follows.

$$\theta_{hm}(t_{md}) = \sin^{-1}\frac{\omega_h(t_{md}) - \omega_m(t_{md})}{2\varepsilon(t_{md})}. \tag{32}$$

Internal model has to be updated so that the above error measure decreases, on this condition. The coupling parameter in internal model, $\varepsilon(t_{md})$, is modified by the following method, as one example. Then $\eta(>0)$ defines the variance rate of internal model.

$$\varepsilon(t_{md}+1) - \varepsilon(t_{md}) = -\eta\frac{\Delta E(t_{md})}{\Delta\varepsilon(t_{md})}. \tag{33}$$

However, as this error measure includes open interaction between body model and human walk, the variation of this measure is not predictable in internal model. We have to estimate it within the time evolution accompanying the mutual constraint process. As error measure varies with the time delay against the change of parameter ε in this process, (33) is translated as follows.

$$\varepsilon(t_{md}+1) = \varepsilon(t_{md}) - \eta\frac{E(t_{md}+1) - E(t_{md})}{\varepsilon(t_{md}) - \varepsilon(t_{md}-1)}. \tag{34}$$

This is not the search process based on the optimality in closed model, but the emergent process to generate variety in open space. So, internal model should be grasped from historical viewpoint in which only relevancy is defined in the time evolution process of each model.

4. Construction of co-emergence process

4.1 Simulation

We simulate the co-emergence process of duality model in two agent system to research it herein. One example of the process is shown in **Fig.7a-e**. The apparent frequency and original frequency of body model in each agent is shown in Fig.7a. The phase relation between two agents in body model is shown in Fig.7b. The original frequency parameters of both agents which are expected in the internal model are shown in Fig.7c, the error measure is shown in Fig.7d, and the time evolution of coupling parameters in the internal model is shown in Fig.7e. The left arrow shows the start of the interaction between agents, and the right arrow shows the disturbance in each figure. The time axis corresponds to t_{ec}.

As shown in Fig.7a, before interaction, the body models of both agents oscillate with each original frequency, which is identical to each apparent frequency. Both apparent frequencies become close each other after the start of interaction, and become identical at about $30sec$. As shown in Fig.7b, by this mutual entrainment, the coherency that the phase relation between body models becomes stable is generated. So, as shown in Fig.7c, the internal model of each agent predicts the original frequency of both agents to realize the goal phase relation (In this example, the goal phase difference of agent 1 is -$0.5rad$, and that of agent 2 is $0.5rad$). So, as shown in Fig.7a, the original frequency of body model changes, and the coherency of body model temporally decays. However, the coherency is gradually recovered by mutual entrainment, and apparent frequencies of body models become identical at about $40sec$ again. Then, the above process is repeated. As shown in Fig.7a, this process is repeated several times, after that, stable state emerges at about $80sec$. As shown in Fig.7d,e, in this process, the coupling parameter of the internal model changes, so that error measure might decrease. These phenomena correspond

to the mutual constraint process in duality model.

Furthermore, it is observed that these mutual constraint processes synchronize with each other between both agents. As shown in Fig.7a, according to the timing that the original frequency of body model changes, the timing of mutual constraint process in each agents gradually coincide. And, mutual adaptation process between each original frequency can be observed. Furthermore, as shown in Fig.7e, the update timing of internal model in both agents is also synchronized. It is thought that these dynamics correspond to the co-emergence process of relational function.

Then, we change the original frequency of the body model in agent 1 at the time corresponding to the right arrow to clarify the response to disturbance. As the result, as shown in Fig.7a, the original frequency of body model changes in agent 2 as well as agent 1, and the mutual adaptation process is observed again. And, the goal phase relation in each agent is regenerated. Although both agents are embedded in the same environment in this process, as shown in Fig.7e, each time evolution of the coupling parameters of internal model is different between both agents, dependent on the difference of the histories in each agent. This means that both agents interpret the same environment as different internal model, and it indicates the possibility that agents differentiate and generate diversity in co-emergence process.

It is thought that the reason for the convergence of co-emergence process in this simulation is that the simulation is performed in the closed two agent system. Well, the outer indefinite influence on the model is eliminated. Furthermore, it is important that there is no contradiction between the goal phase relations of both agents. We intend to summarize the detail of these factors in the other paper.

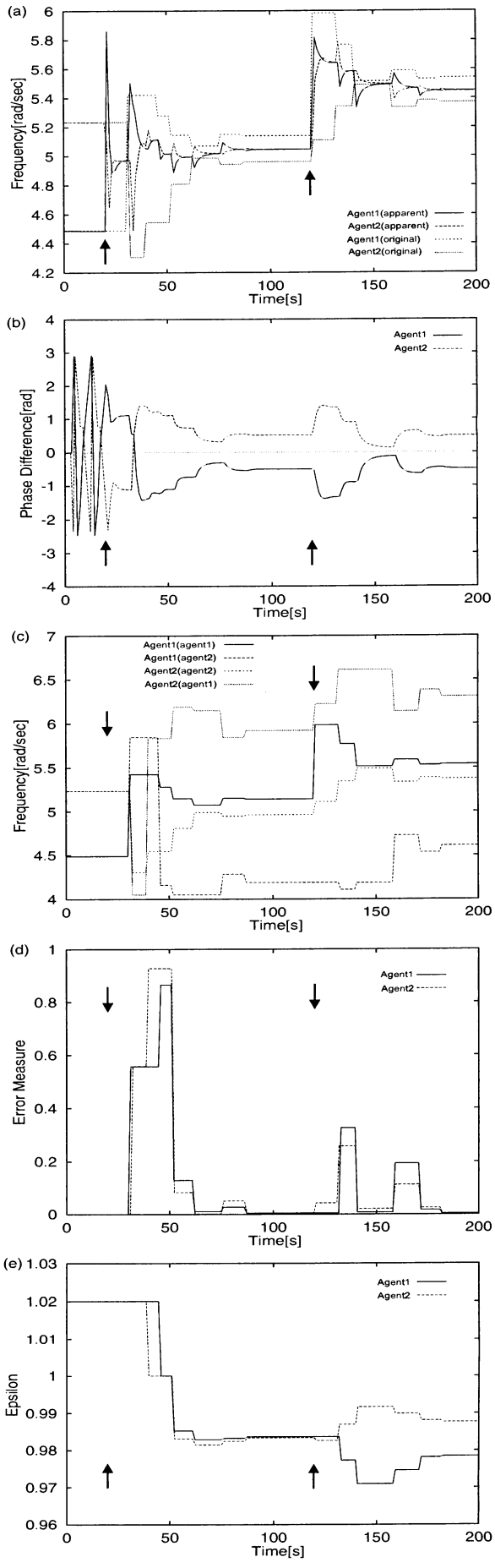


Fig.7 Co-emergence process in two-agents (α=0.6, β=0.5, η=0.02, Δt=0.0005)

4.2 Walk experiment

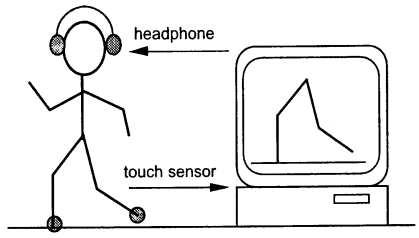
We also construct human-machine system, using duality model. Particularly, the co-emergence process of the relational function between walk robot and human is realized to clarify the possibility for the walk support on the basis of co-emergence communication. The robot as duality model is not real machine but virtual one simulated in computer, and the cooperative walk between human and the robot is realized through the exchange of footsteps.

Concretely, as shown in **Fig.8**, the following experimental device is made up. The timing that human leg is

grounded is detected through the touch sensor equipped on his shoe, and the signal is sent to the simulator. Meanwhile, duality model is calculated in the simulator, and the above signal is input in the body model. And, the timing of leg grounding in body model is composed as footstep and is transmitted to human through headphone. This device is constructed as wearable system using personal computer [25].

Fig.9a,b shows the walk period of human and robot (corresponding to the reciprocal of the apparent frequency of body model) and the phase relation generated between them (corresponding to the phase relation of body model). The left and right arrows mean the start and stop of interaction, respectively. Although both walk with each original period (corresponding to the reciprocal of the original frequency of body model) before interaction starts, their walk periods become close each other after interaction starts. And, the phase relation converges on the target value (0 *rad* of the phase difference in this example). However, when interaction stops, their walk period returns to their original period, and their original period shows the mutually adapted value which is different from the value before interaction. This mutual adaptation process corresponds to the simulation result in the former chapter, and this indicates the possibility that duality model is established in human side. Furthermore, this indicates that co-emergence process is established between this model and human. Recently, we analyze the walk of human side from the viewpoint of duality, and find that the time evolution corresponding to mutual constraint process is observed there.

In this experiment, human walk is unstable by the weight (12 kg) put on human leg. So, as shown in Fig.9a, the period of human walk largely fluctuates before his interaction with robot. However, the fluctuation of period is remarkably decreased and walk becomes stable by the co-emergence of corporative walk during interaction. Particularly, the development of the walk pattern in human side is observed in this mutual adaptation process, and this indicates the possibility that the co-emergence process of the relational function on the basis of duality model is applicable to walk support and rehabilitation. Furthermore, we supplement that space sense and time sense in self consciousness is affected by this device. This means that duality model can be represented as the co-emergence communication between self and machine. We intend to summarize the detail of this walk support robot in the other paper.



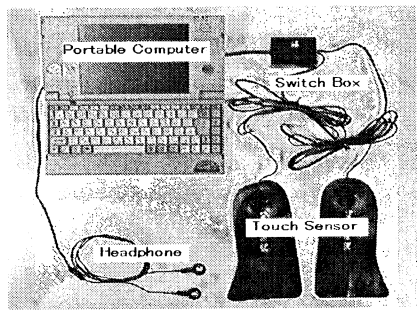


Fig.8 Walk support robot

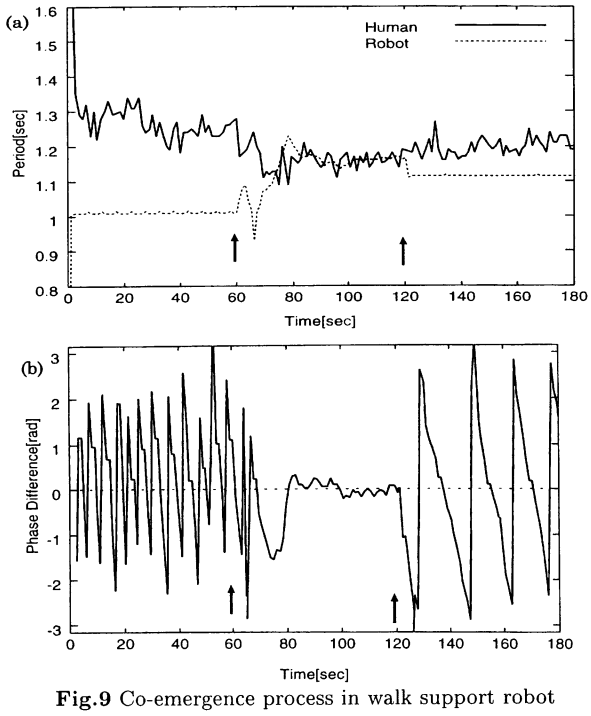


Fig.9 Co-emergence process in walk support robot

5. Conclusion

In this study, we aimed at establishing the new design principle for the relation between human and artifact, of which idea is that humans generate the relational functions in real time through their communication. And, we proposed duality model and human-machine system as co-emergence communication that human and artifact generate their functions together is constructed.

As the result, co-emergence process can be simulated in two agent system using this duality model, and we found out the possibility that the developing process of human

walk is supported by this co-emergence process realized in walk support robot. These results show that this model is applicable to co-emergence communication process of humans and indicates its effectiveness. In this background, we are expecting this framework can be extended into the human-machine-human system to support human communicability, exceeding the usability of human-machine system.

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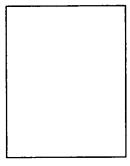

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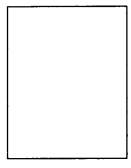

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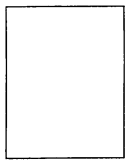

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Translated from Trans. of the SICE vol.37, no.11, 1087/1096 (2001)