Intelligent Control System Taking Account of Cooperativeness Using Weighting Information on System Objective

Masaki TAKAHASHI
School of Science for Open and Environmental Systems, Keio University
Yokohama, Kanagawa 223-8522, Japan

and

Kazuo YOSHIDA
Department of System Design Engineering, Keio University
Yokohama, Kanagawa 223-8522, Japan

ABSTRACT

This study considers an intelligent control system to integrate flexibly its components by using weighted information where the system evaluation is reflected. Such system evaluates the information flowing through the components and converts them by weighting depending on the degree of importance. Integration of components based on the system evaluation enables a system consisting of them to realize various, flexible and adaptive control. In this study, the intelligent control method is applied to a swing up and stabilization control problem of a number of cart and pendulum systems on a restricted straight guide. To stabilize the pendulum in a restricted environment, each system should realize not only a swing-up and stabilization control of the pendulum, but also a position control of the cart to avoid collision or deadlock. The experiment using a real apparatus demonstrated that the controller learning light interaction acquires egoistic character, the controller learning heavy interaction behaves altruistically, and the controller equally considering self cart and another cart becomes cooperative. In other words, these autonomous decentralized controllers can acquire various characters and flexibility for cooperation.

Keywords: Intelligent Control, Autonomous Decentralized System, Cooperativeness, Inverted Pendulum.

1. INTRODUCTION

As applicable scope of control becomes more widespread, the demand for robust performance and flexibility increases. Recently, it has been desired that control systems deal with unexpected situations in a dynamic environment. Many researchers have been studying an intelligent control method as one of approaches for establishing flexible and adaptive control method. Some hierarchical intelligent control structures referring the human behavior have been proposed [1]-[6]. Recent works have focused on designing a hybrid intelligent control system by combining a number of artificial intelligence-based technologies such as fuzzy logic, neural networks, evolutionary algorithms, case-based reasoning, expert systems and so on [7]-[10]. Especially, variety of intelligent control systems has been proposed in the fields of mobile robots [3]-[6], [11]. An intelligent robot requires the ability to sense the change of environment, and to make decisions, and then to generate new control actions to achieve task in dynamic environments. In multi-agent system, to achieve own control purpose, each agent has to take cooperative actions by taking account of the interaction dynamics between the robots and its environment. As the above-mentioned cooperative actions, collaborative activity to achieve a joint goal and cooperative activity generated as a result of collision or deadlock avoidance to achieve own purpose are considered.

This study considers an agent which acts autonomously based on sensory information to achieve the control objective in dynamic environments. An intelligent control system taking account of system evaluation by giving added weight to observational and explicit information is proposed. The proposed intelligent control system has the ability to adapt to changes in its environment depending on the evaluation of observational information and to take cooperative actions according to the evaluation of explicit information with communication. Such system evaluates the information flowing through the components and converts them by weighting depending on the degree of importance. Integration of components based on the system evaluation enables a system consisting of them to realize various, flexible and adaptive control. In this study, the intelligent control method is applied to a swing up and stabilization control problem of a number of cart and pendulum systems on a restricted straight guide. To stabilize the pendulum in a restricted environment, each system should realize not only a swing-up and stabilization control of the pendulum, but also a position control of the cart to avoid collision or deadlock. The experiments using a real apparatus demonstrate that the controller can acquire various characters and flexibility for cooperation.

2. INTELLIGENT CONTROL SYSTEM USING WEIGHTING OBSERVATIONAL AND EXPLICIT INFORMATION

This study proposes an intelligent control system using weighted observational and explicit information. The structure of the proposed method is shown in Fig.1. In general, the system consists of sensing, processing, communicating and activating elements. These elements of system are designed based on each local system objective individually. In the method, the connection among these elements using weighted observational and explicit information enable the system to take various and adaptive actions. Figures 2, 3 and 4 show the following three elements for weighting information.

1) Observational cooperation at channel between sensing and processing elements (S. to P. channel).
2) Explicit cooperation at channel which connects among sensing, processing and communicating elements (S. P. to C. channel).
3) Integration of several controllers at channel which connects among sensing, processing and activating elements (S. P. to A. channel).

These elements are constructed by combining a number of artificial intelligence-based technologies such as fuzzy logic, neural networks, evolutionary algorithms, case-based reasoning, expert systems and so on.

S. to P. channel

The agent has to take flexible actions according to the situation to achieve control purpose in dynamic environments. However, the controllers at processing element are designed to carry out each local control purpose. It is not easy to realize flexible and adaptive control to deal with unexpected situations in dynamic environments because of its restricted function. At channel between sensing and processing elements, observational cooperation is carried out. In the proposed method, the system evaluates information observed at sensing element and senses the change of environment. By weighting information depending on the degree of importance, inputs to the controller are converted to suitable targets for achieving system objective. By this means, the system realizes flexible and various controls according to the situation in a dynamic environment.

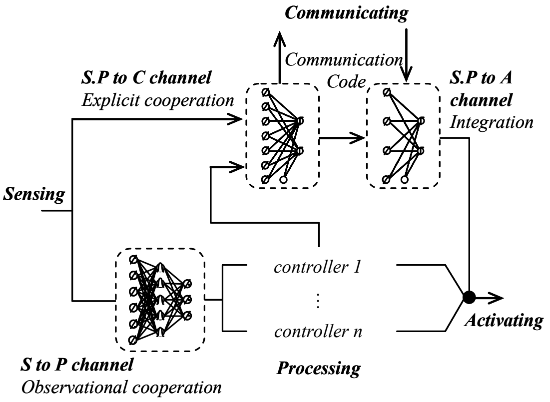


Fig.1 Structure of the proposed method.

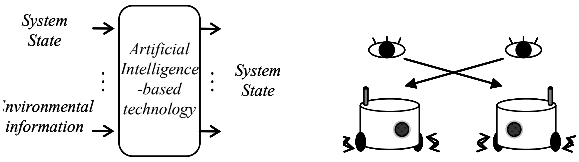


Fig.2 Observational cooperation at S. to P. channel.

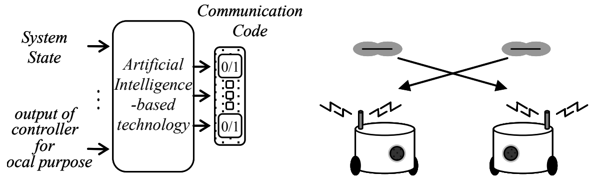


Fig.3 Explicit cooperation at S. P. to C. channel.

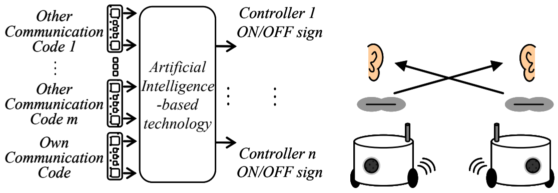


Fig.4 Integration of controllers at P. C. to A. channel.

S. P. to C. channel

In a restricted environment, each agent acts autonomously without respect to interaction and competes with each other. To navigate the multiple agents to their goals without competition, each agent should make the connection between behavior and environmental effects including other agents. In this case, each agent should communicate with each other as shown in Fig.3 [12]-[14]. The agent needs an explicit means of communication to interact with other agents [15]. In the method, the abstracted information where system internal states are expressed as bit code is generated by weighting observational information and output of the controller at S. P. to C. channel which connects among sensing, processing and communicating elements. This code is called communication code.

S. P. to A. channel

In multiple mobile agents, each agent has own goal or position and should take action autonomously. Additionally, to navigate the multiple agents to their goals without collision, it is desired to establish control techniques to make the most of interaction among them. At S. P. to A. channel which connects among sensing, processing and activating elements, the communication codes are weighted to achieve the system objective. Based on the communication code receiving from other agent, the agent judges whether cooperative behavior is carried out according to the situation. By this means, the irrelevant information for achieving the system objective is inhibited. When other agent's communication code is recognized as meaningful information, each agent builds cooperative relationships with each other.

In the method, the agent evaluates information flowing through these elements and weights information depending on the degree of importance. Whereby, each agent senses the change of environment, makes decisions, and then generates new control actions to achieve task in dynamic environments. As a result of weighting information by taking account of interaction, cooperative action is generated without changing the construction of control system.

3. APPLICATION TO SWINGING UP AND STABILIZING PENDULUM

Control Problem

In this study, the proposed intelligent control method is applied to a coordination control problem of a number of cart and pendulum systems on a restricted straight guide as shown in Fig.5. In case that each cart acts autonomously to swing up and stabilize the pendulum, they compete with each other. Therefore, each agent should realize not only swing-up and stabilization control of the pendulum, but also position control of the cart to avoid collision or deadlock as shown in Fig.6. In case shown in Fig.6(c) that one agent reaches the limit of

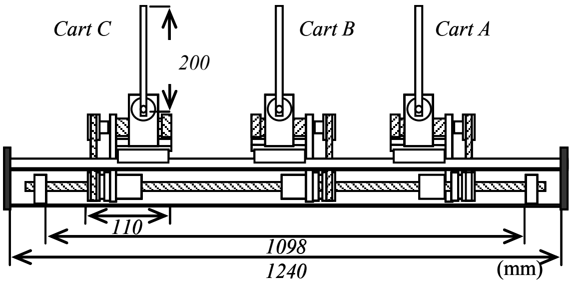
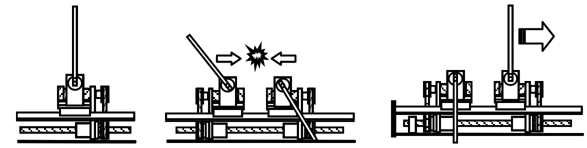


Fig.5 Schematic view of experimental equipment.



(a) Stabilization (b) Collision (c) Deadlock

Fig.6 Control problem.

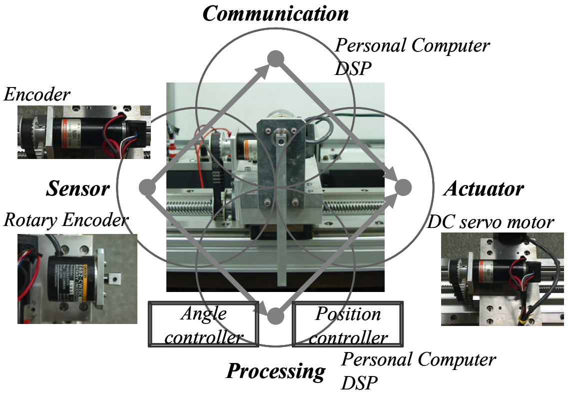


Fig.7 Controlled Object.

straight guide, the left cart should stay in current position to avoid collision until the right cart moves to right free space. On the other hand, the right cart should sense the risk of collision by left cart's action and move to right free space. To solve such problems, each agent should take autonomously action taking account of interaction even if stable state is released. The control problem dealt with in this study is how to design a flexible and various controller for the coordination control problem to achieve own control objective without collision and deadlock.

System Architecture

The model of the cart and pendulum system is shown in Fig.7. The system possesses sensing, processing, communicating and activating elements. The sensing element has the function to measure the displacement of cart and the pendulum angle and to calculate the interval between carts. The processing element consists of cart position and pendulum angel controllers based on sensory information. The communicating element has the function to transmit and receive a message. The cart is driven through the rotary nut which is rotated by the DC servo motor through timing belt.

4. DESIGN OF CONTROLLER

This section demonstrates an example of design methods of the proposed autonomous decentralized controller. Figure 9 shows the structure of the proposed intelligent control system. The system consists of four components and three channels of information among these components. Each component is designed individually to carry out local system object.

Processing Element

The position controller is a regulator to converge the target cart position. The angle controller consists of an unstabilizer to destabilize the pendulum at stable equilibrium point and a stabilizer to stabilize the pendulum at unstable equilibrium point. The unstabilizer is designed by unstable pole assignment at stable equilibrium point. The stabilizer is realized as a state-space controller with the feedback gain vector K, which is calculated according to the linear-quadratic regulator (LQR) design method. In order to swing up and stabilize the pendulum, the integrator neural network shown in Fig.8, which switches automatically a suitable controller according to the situation, is designed.

S. to P. channel

At S. to P. channel, Control actions are represented by knowledge as if-then rule. As for weighting observational information at S. to P. channel, the following three rules are provided.

$$\text{IF } R>0.40 \text{ and } L>0.40 \text{ THEN } x_{ref}=0.0 \quad (1)$$

$$\text{IF } R<0.40 \text{ or } L<0.40 \text{ THEN } x_{ref}=(R+L)/2 \quad (2)$$

$$\text{IF } R<0.40 \text{ and } L<0.40 \text{ THEN } x_{ref}=\dot{x}_{ref}=\theta_{ref}=\dot{\theta}_{ref}=0.0 \quad (3)$$

Where, R and L represent the right and left intervals between the carts respectively. x_{ref} indicates the target position of the cart.

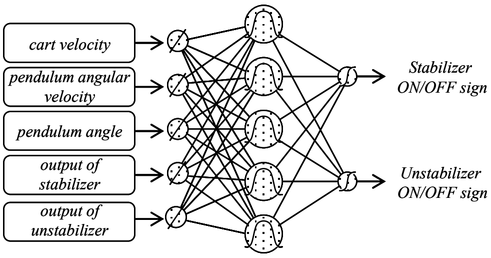


Fig.8 Integration of Stabilizer and Unstabilizer.

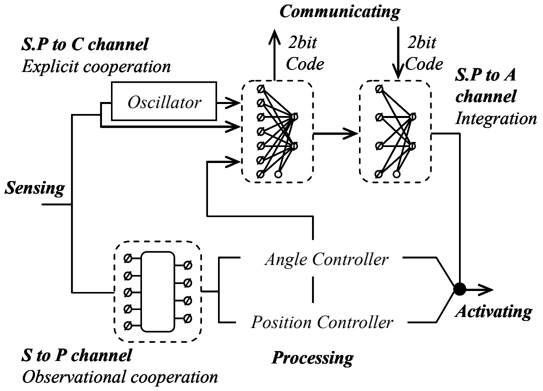


Fig.9 Structure of the proposed method.

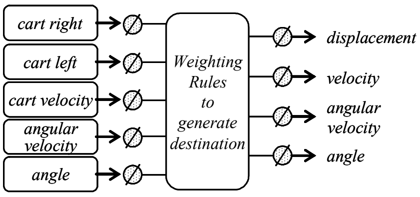


Fig.10 S. to P. Channel.

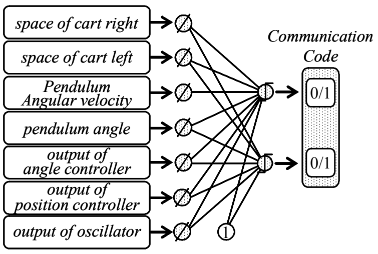


Fig.11 S. P. to C. Channel.

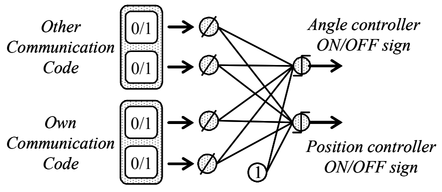


Fig.12 P. C. to A. Channel.

Learning of S. P. to C. and S. P. to A. channels

The S. P. to C. and S. P. to A. channels are constructed by multilayer neural networks shown in Figs. 11 and 12 respectively. Since output of each neural network is affected each other, the weights of two neural networks are learned as a connected weights. The neural networks acquire the adequate weighting for information flowing through these elements to maximize the following fitness factor based on system evaluation by the genetic algorithm.

$$J=\frac{1}{\sum_{t=0}^{n}\sum_{i}\left[a\left\{\left|\theta_i(t)\right|\right\}+b\left\{\left|penalty\left(R_i(t),L_i(t)\right)\right|\right\}\right]+1} \qquad (4)$$

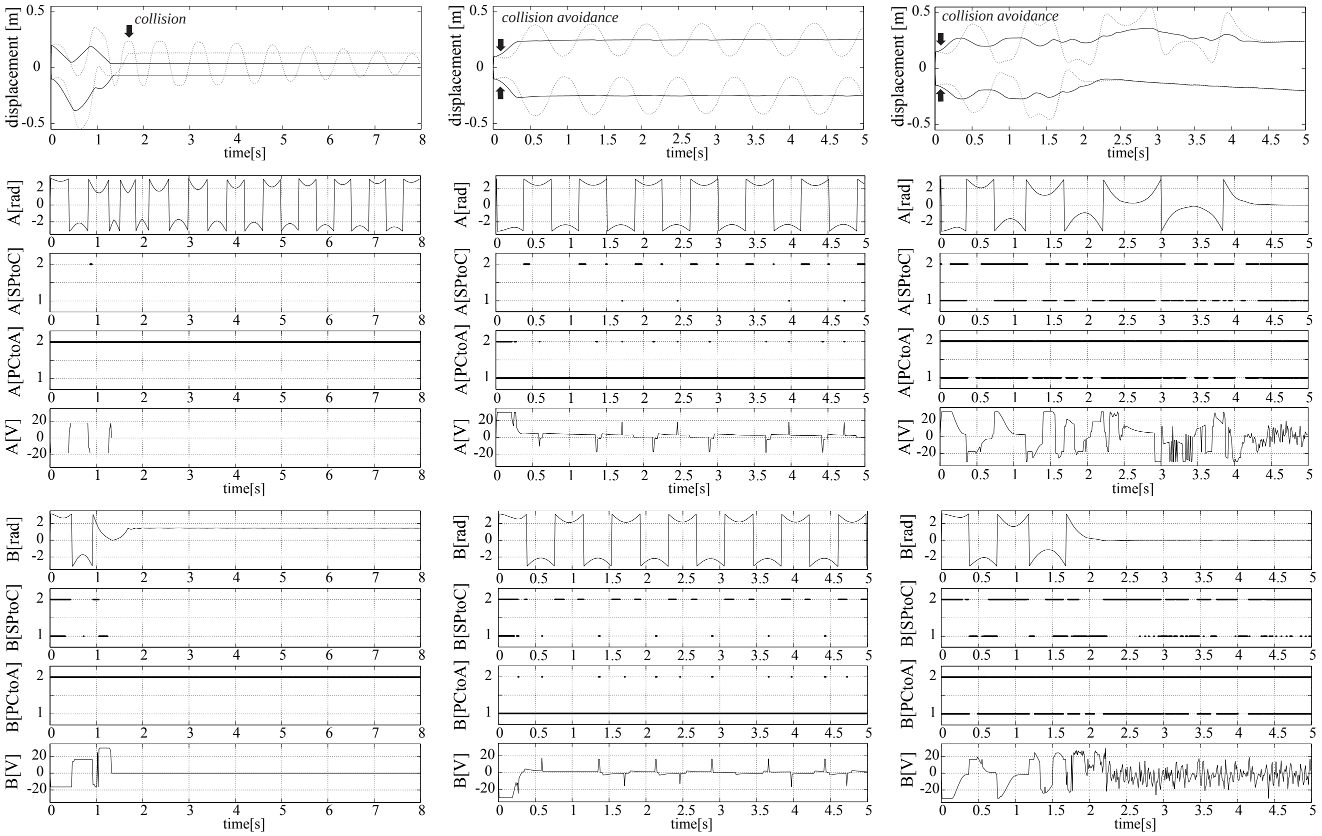
$$penalty\left(R_i(t),L_i(t)\right)=\begin{cases}0.5 & \left(\left|R_i(t)\right|<0.4\ \ or\ \ \left|L_i(t)\right|<0.4\right)\\ 0 & (else)\end{cases} \qquad (5)$$

where, $n=t_a/dt$ and t_a and dt represent the simulation period and the sampling period respectively. $penalty(R_i(t), L_i(t))$ indicates the penalty function on the cart position limit. In this approach, the pendulum control of one cart affects another cart. The neural networks are learned on three different cases depending on the degree of interaction: TYPE-1) light (a=1, b=0); TYPE-2) heavy (a=0, b=1); or TYPE-3) medium (a=1, b=1).

5. EXPERIMENTAL RESULT

Characteristics of Intelligent Controller

The controller designed based on the above-mentioned three types of the fitness factor is applied to the coordination control problem of a number of cart and pendulum systems on a

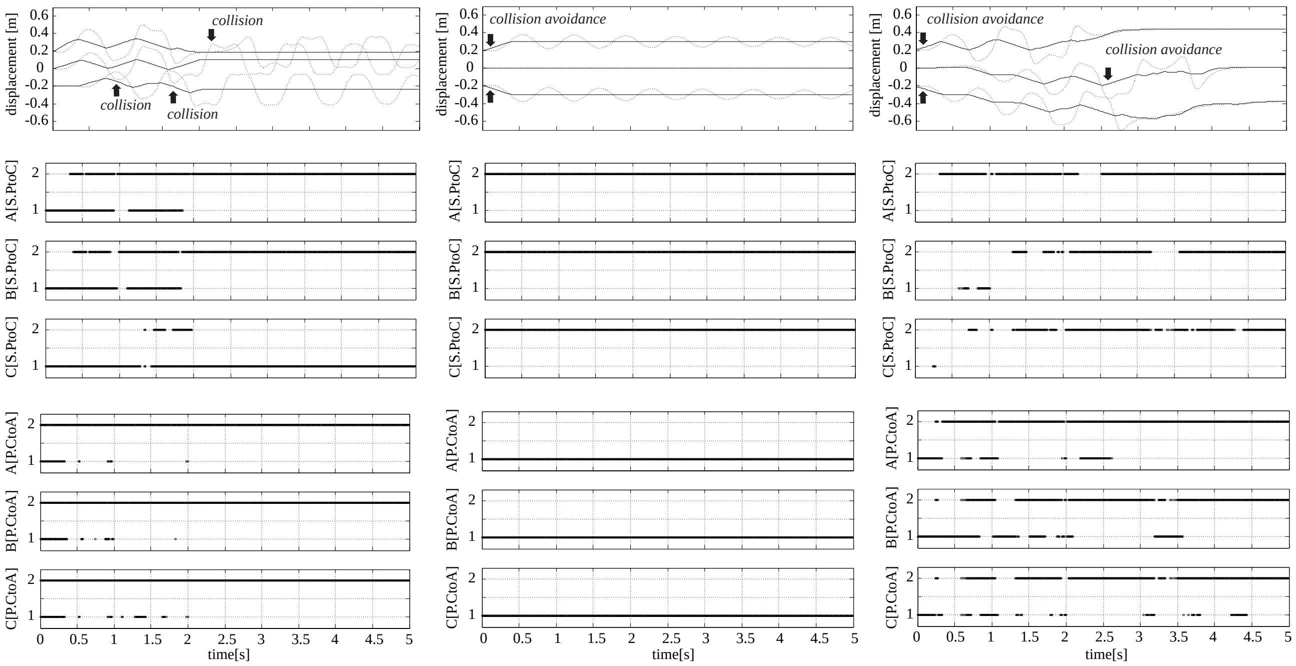


(a) TYPE-1 (Egoistic controller).

(b) TYPE-2 (Altruistic controller).

(c) TYPE-3 (Cooperative controller).

Fig.13 Experimental result for the case that $x_A = 0.10$ m, $x_B = 0.10$ m, $\theta_A = \pi$ rad, $\theta_B = \pi$ rad .



(a) TYPE-1 (Egoistic controller). (b) TYPE-2 (Altruistic controller). (c) TYPE-3 (Cooperative controller).

Fig.14 Experimental result.

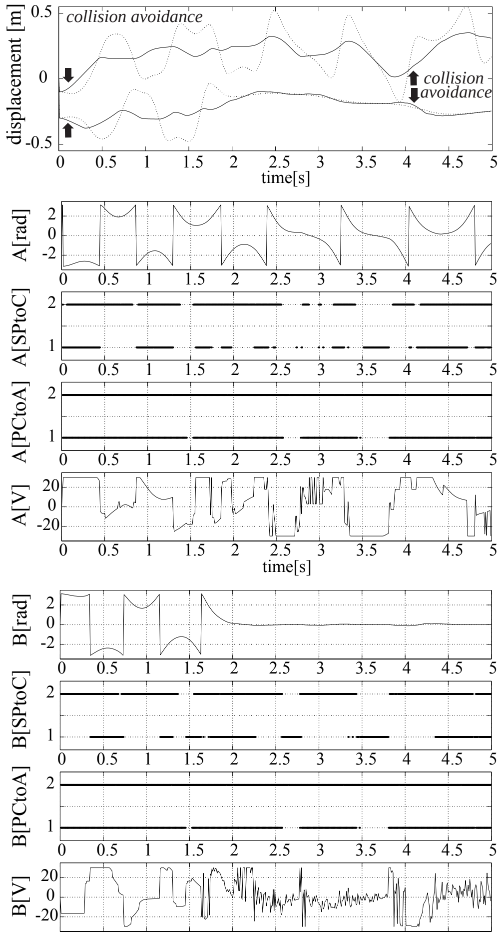
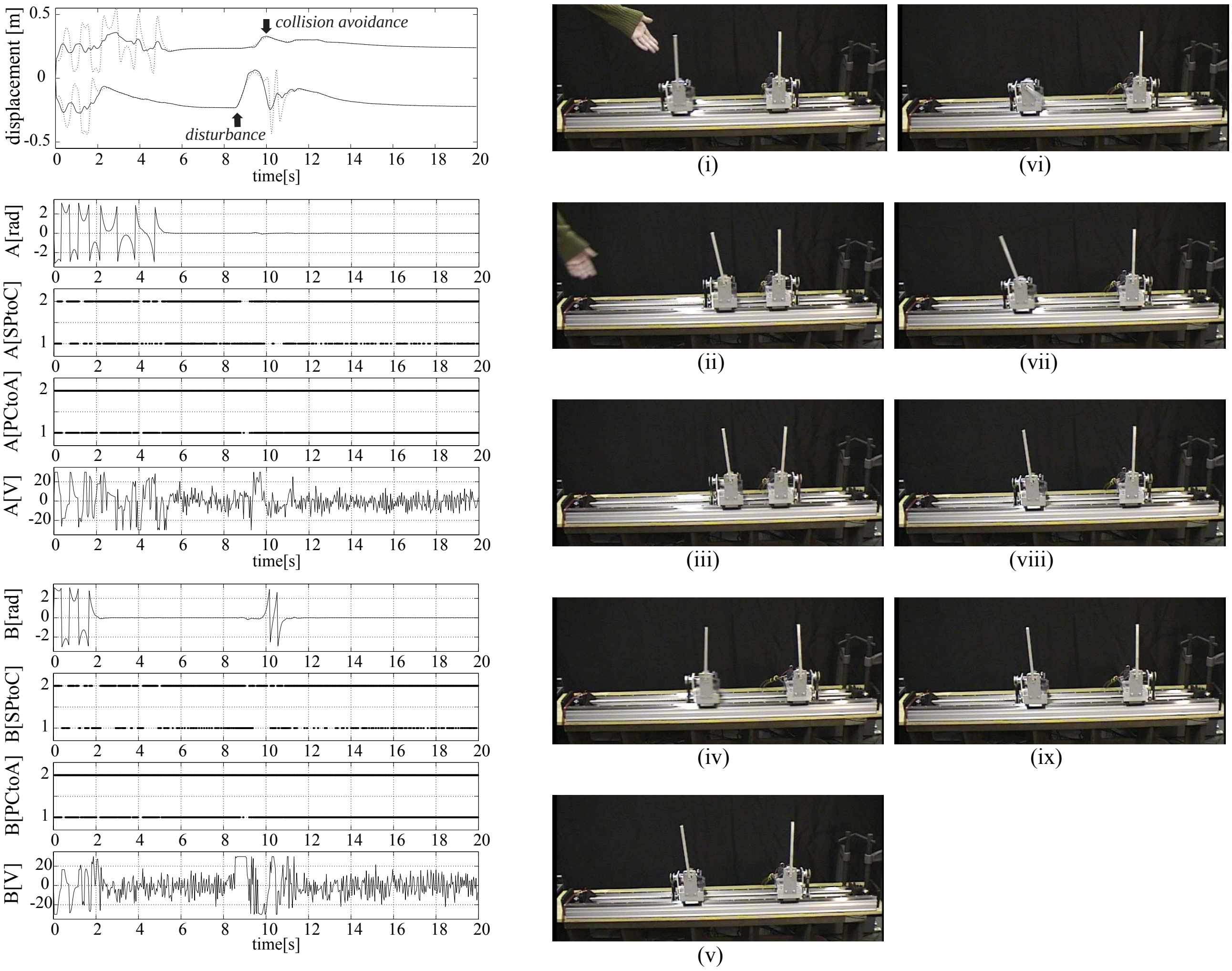


Fig.15 Experimental result (Cooperative controller).

restricted straight guide. In order to verify the characteristic of each autonomous decentralized controller, experiments using a real apparatus for the initial condition that $x_A = 0.10$ m, $x_B = -0.10$ m, $\theta_A = \pi$ rad, $\theta_B = \pi$ rad were carried out. Figure 13 shows that the time histories, in order, the displacement of the cart, the edge displacement of the pendulum, the angle of the pendulum, the outputs of the S. P. to C. and the P. C. to A. channel and the control input. It was demonstrated as shown in Fig.13 (a) that each cart using the controller learning light interaction moves from side to side in order to stabilize the pendulum and collides with each other. It was demonstrated as shown in Fig.13 (b) that though each cart using the controller learning heavy interaction moves without collision, any cart cannot swing up and stabilize the pendulum. Figure 13 (c) shows that the controller considering equally interaction can stabilize the pendulum without collision by selecting autonomously optimum controller. The experiment results demonstrated that the controller learning light interaction acquires egoistic character, the controller learning heavy interaction behaves altruistically, and the controller equally considering self cart and another cart becomes cooperative. The proposed method is extended to cases in which the number of the cart and pendulum systems is three. As shown in Fig.14, the experiments get the same results as the two carts. That is, these autonomous decentralized controllers can acquire various characters.

Cooperative Autonomous Decentralized Controller

In order to verify the usefulness of the cooperative autonomous decentralized controller, experiments were carried out. Figure 15 shows the result of the experiment for the initial condition that $x_A = -0.10$ m, $x_B = -0.30$ m, $\theta_A = \pi$ rad, $\theta_B = \pi$ rad . The cart A transfers to right open space to avoid collision with the cart B and moves from side to side in order to stabilize the pendulum. On the other hand, the cart B swings up and stabilizes the



(i) (vi) (ii) (vii) (iii) (viii) (iv) (ix) (v)

Fig. 16 Experimental result TYPE-3 (Cooperative controller).

pendulum by using open space. It was demonstrated as shown in Fig.15 that both carts can stabilize the pendulum without collision. Figure 16 shows that the experimental result in the case that the stabilized pendulum of the cart B is disturbed by tapping on it. Since the disturbed pendulum gets into unstable, the cart B moves to stabilize the pendulum and then the interval between two carts is narrow. In the case that the cart B moves close in on the cart A, each cart moves automatically in the opposite direction to avoid collision. In order to transfer to open space, the pendulum of the cart B automatically falls down once. However, the cart B stabilizes the pendulum by using open space again. From the experiments, it was demonstrated that these autonomous decentralized controllers can acquire flexibility for cooperation.

6. CONCLUSIONS

This study considers an agent which acts autonomously based on sensory information to achieve the control objective in dynamic environments. An intelligent control system taking account of system evaluation by using weighted observational and explicit information was proposed. To verify the performance of the proposed method, it was applied to a swing up and stabilization control problem of a number of cart and pendulum systems on a restricted straight guide. The experiment using a real apparatus demonstrated that the controller learning light interaction acquires egoistic character, the controller learning heavy interaction behaves altruistically, and the controller equally considering self cart and another cart becomes cooperative. In other words, these autonomous decentralized controllers can acquire various characters and flexibility for cooperation.

7. REFERENCES

[1] J. Rasmussen, "Skills, Rules and Knowledges; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models", **IEEE Transactions on Systems, Man and Cybernetics**, Vol. 13, No. 3, 1983, pp. 257-266.

[2] G. N. Saridis, "Toward the Realization of Intelligent Controls", **Proceedings of the IEEE**, Vol. 67, No. 8, 1979, pp. 1115-1133.

[3] G. N. Saridis, "Intelligent Robotic Control", **IEEE Transactions on Automatic Control**, Vol. 28, No. 5, 1983, pp. 311-321.

[4] R. A. Brooks, "A Robust Layered Control System for a Mobile Robot", **IEEE Journal of Robotics and Automation**, Vol. 2, No.1, 1986, pp.14-23.

[5] J. A. Albus, R. Lumia, J. Fiala and A. Wavering, "NASREM the NASA/NBS Standard Reference Model for Telerobot Control System Architecture", **Proceedings of 20th ISIR**, 1989, pp.1-7.

[6] T. Shibata and T. Fukuda, "Hierarchical Intelligent Control for Robot Motion", **IEEE Transactions on Neural Networks**, Vol. 5, No.5, 1994, pp. 823-832.

[7] L. H. Tsoukalas, "Neurofuzzy Approaches to Anticipation: A New Paradigm for Intelligent Systems", **IEEE Transactions on Systems, Man and Cybernetics**, Vol. 28, No. 4, 1998, pp. 573-582.

[8] S.-F. Su and S.-H. Hsieh, "Embedding Fuzzy Mechanisms and Knowledge in Box-Type Reinforcement Learning Controllers", **IEEE Transactions on Systems, Man and Cybernetics**, Vol. 32, No.5, 2002, pp. 645-653.

[9] B. Lazzerini, L. M. Reyneri and M. Chiaberge, "A Neuro-Fuzzy Approach to Hybrid Intelligent Control", **IEEE Transactions on Industry Applications**, Vol. 35, Np.2, 1999, pp. 413 -425.

[10]L.-H. Chen amd C.-H. Chiang, "New Approach to Intelligent Control Systems with Self-Exploring Process", **IEEE Transactions on Systems, Man and Cybernetics**, Vol. 33, No.1, 2003, pp. 56-66.

[11]T. Fukuda and N. Kubota, "Learning, Adaptation and Evolution of Intelligent Robotic System", **Proceedings IEEE International Symposium of Intelligent Control**, 1998, pp.2-7.

[12]M. Hoshino, H. Asama, K. Kawabata, Y. Kunii and I. Endo, "Communication learning for cooperation among autonomous robots", **IECON 2000. 26th Annual Conference of the IEEE Industrial Electronics Society**, Vol. 3, 2000, pp. 2111-2116.

[13]T. Fujii, Y. Arai, H. Asama and I. Endo, "Multilayered Reinforcement Learning for Complicated Collision Avoidance Problems", **Proceedings of 1998 IEEE International Conference on Robotics and Automation**, Vol. 3, 1998, pp. 2186-2191.

[14]Y. Yanli, M. M. Polycarpou and A. A. Minai, "Opportunistically cooperative neural learning in mobile agents", **Proceedings of the 2002 International Joint Conference on Neural Networks**, Vol. 3, 2002, pp. 2638-2643.

[15]Y. Abe and M. Yoshiki, "Collision Avoidance Method for Multiple Autonomous Mobile Agents by Implicit Cooperation", **Proceedings of 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems**, Vol. 3, 2001, pp.1207-1212.