System Design Methodology Based on Concept of System Life

Kazuo Yoshida
Department of System Design Engineering, Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama, 223-8522 Japan
yoshida@sd.keio.ac.jp

***Abstract*—The artifact-systems created by humans generate a deep and huge interaction with the surrounding natural world, and reflect a large-scale influence on our human lives. The most creditable concept to this critical issue of scientific and technological development seems to be "System Life" that is an innovative competence to be embodied into any artifact-systems for creating harmony in the world of the natural entities and artifacts-systems interacting each other. The system life is defined as a seamless fusion system of sensing, processing, activating and expressing mechanisms governed by system life information. This paper introduces a design approach of intelligent systems possessing the system life. First, this paper presents the concept of system life comparing with the conventional design methodology. Second, this paper introduces an intelligent control methodology using the cubic neural network that the author developed in order to cope with unpredicted failures. Finally, this paper presents various intelligent robots, a skiing robot, autonomous soccer robots, a game playing robot and so on as new concrete artifact-systems designed by the system life concept.**

I. INTRODUCTION

In 2003, the Center of Excellence proposed by Keio university and titled "System Design: Paradigm Shift from Intelligence to Life" was selected and started. This COE aims at establishing a global collaborative and educational research center of excellence based on the system design engineering which was initiated by KEIO University. In this COE, an important role will be played in the mechanical and architectural fields of engineering by leading in the 21st century the paradigm shift to life for the engineering developed historically from high-performance technology to intelligence technology in the 20th century. In order to create harmony in the world of the natural entities and artifact-systems interacting each other, this COE focus on the characteristics of life as a system as well as various life functions and creates a new design methodology of mechanical and architectural systems which are enabled to be interactive among inner components and outer systems by embedding design information including rules of interaction.

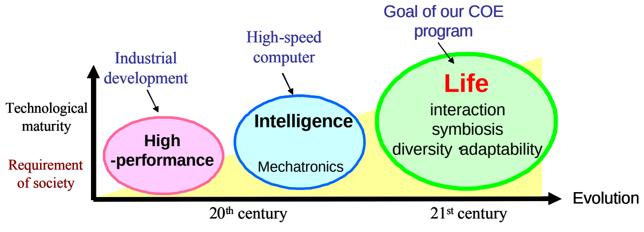


Fig. 1 Evolution of technology

In order to achieve the objective of this COE, the system design engineering will be further developed as a backbone of the COE and several product innovations with respect to architecture, robotics, bio/energy system and so on will be explored.

The artifact-systems created by humans generate a deep and huge interaction with the surrounding natural world, and reflect a large-scale influence on our human lives. The most creditable concept to this critical issue of scientific and technological development seems to be "System Life" that is an innovative competence to be embodied into any artifact-systems for creating harmony in the world of the natural entities and artifacts-systems interacting each other. The system life is defined as a seamless fusion system of sensing, processing, activating and expressing mechanisms governed by system life information, as shown in Fig.2.

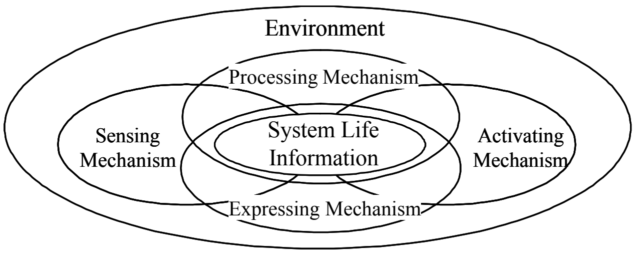


Fig. 2 Concept of System Life

This paper introduces a design approach of robots possessing the system life. First, this paper presents the concept of system life comparing with the conventional design methodology. Second, an intelligent control methodology using the cubic neural network that the author developed will be introduced in order to cope with unpredicted failures. Finally, this paper presents various intelligent robots, a skiing robot, autonomous soccer robots, a game playing robot, an autonomous running bicycle robot and so on as new concrete artifact-systems designed by the system life concept.

II. CONCEPT OF SYSTEM LIFE

There has been no concept of life on artifacts except for artificial life and computer virus. Who uses a machine is a human and a machine is regarded as a tool for a human. However, programmed intelligent machines play more influential roles than human expects and human has become to be strongly influenced by machines. This trend will become stronger and we will face the limitation of conventional design approach and procedure.

There is a natural principle that the more intelligent animals are, the more complex expression they have. In the design of current intelligent machines we have not necessarily such a principle. Therefore, current intelligent machines cause various conflicts with human, since there is little communication between human and machine. As a matter of fact, there have been many problems on the interaction between human and machine. For instance, there is a case that it is regarded as a human error problem if inconsistent operation happens because human does not interpret the intention of a machine: a typical example is a fall accident of China Airline in 1994 and this is novel in our memory.

Furthermore, to solve the environmental problems, it is necessary to design machines considering those decomposition and disposition, and paying attention to the influence to the environment. In other words, "Birth and Death" of machines are important and it is necessary to design a machine as a life system in order to realize the symbiotic design with nature. As before-mentioned, the system life is defined as a seamless fusion system of sensing, processing, activating and expressing mechanisms governed by system life information. What we have to learn form bio-systems is function of life and also life itself as a system. The concept of system life is an indispensable concept for techno-humanity society.

In the natural systems, the information on environment is embedded into the information of gene through the evolution and adaptation. In the gene the following information is accumulated and embedded.

- Species
- Adaptation
- Evolution
- Environment
- Optimality

These kinds of information play the role of design information and possess the information on the existence and evaluation. Figure 1 shows an adaptation of bones by the experimental result after cutting pig bone. This fact indicates that the bone was recovered at least so as to support the load on the bone because of difficulty of extending the bone. The natural system does not have the information on what or how accident or damage is, but possesses the information on generation and function. This fact is much meaningful and might follow that the bone possesses its essential role and recover itself according to the information of gene. In the design of machines, accident and damage are a priori supposed and for example failure mode is presupposed. Thus, the current design procedure of artifacts is quite different form the natural system and should be shifted to a design methodology particularly for the machines working and existing in open environment.

The natural system possesses the balance as a life system by adapting to the environment in real time and past long time. On the other hand, there are not few machines that do not have good balance, since they are designed by making a particular function intelligent. As a matter of fact, although the designer, that is human possesses the design information, but the machines do not have it. In the same manner as the natural system, the design information should be embedded into machines and products that we design.

The features of natural systems and artifacts are as follows:

- Natural systems have balance as a life system through adaptation to nature.
- Mechanical systems have a problem on system balance because a part of function is made intelligent.
- Some common base is necessary to realize consistency between natural systems and artifacts.
- Machines that are utilized in open environment will increase in 21st century.
- Interaction of artifacts with human or natural system will increase in future.

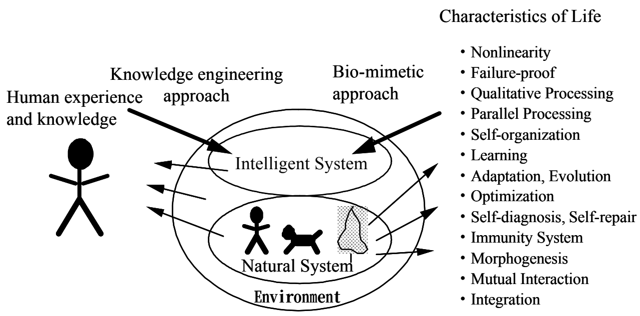


Fig 3 Knowledge engineering and bio-mimetic approaches

From the above-mentioned viewpoint, it is considered to be necessary to embed the information similar to that of natural system into artifacts so as to have the common base with natural system. Thus, the concept of system life was proposed. As shown in Fig. 3, in the knowledge engineering approach, an intelligent system is designed by embedding human experience and knowledge into artifacts, and in the bio-mimetic approach, by embedding some function of natural system into artifacts. In the both approaches, consideration on the total balance of the designed system is often lacking. The natural system from which we learn is a system, but attention is paid to only some aspects of the natural system. There are possibilities that we realize each aspect of a natural system, for instance, by virtue of a computer, human champion of chess game will be defeated. However, human as a system is an everlasting and ultimate target of design. As a first step, it is necessary to design an artifact considering the balance of the system by realizing not only one aspect, but also other some aspects as shown in Fig. 4, for the artifact to be consistent with a natural system.

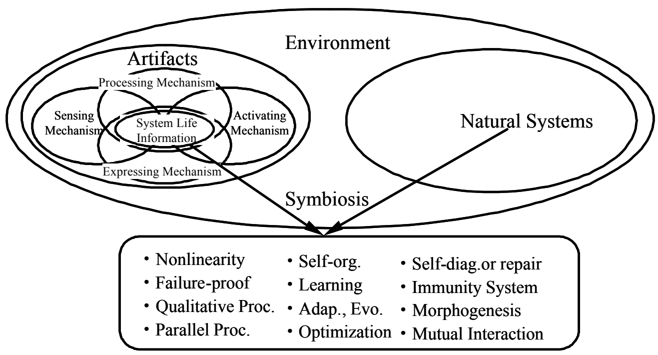


Fig. 4 Symbiosis between artifacts and natural systems

III. DESIGN OF INTELLIGENT SYSTEM

In the previous chapter, the features of life are characterized from their functions. Here, if it is characterize from the side of the biology, the following features are described.

- Autonomy
- Metabolism, Immunity
- Self-organization
- Homeostasis
- Adaptation to Environment
- Stability to Disturbance
- Storage of Information
- Learning, Memory
- Generation, Self-reproduction
- Heredity
- Evolution, Growth Ability
- Aging, Apoptosis
- Death

The above features are also nothing but aspects of life phenomena. The common information on various aspects is embedded in gene. In other words, the governing principle realizing each aspect in well-balanced condition is important and indispensable. Such governing principle or rule is also important for an artifact. In the concept of system life, it is embedded into a system as system life information. In the concept of system life, the gene information corresponds to the system life information of an artifact. In this chapter, construction approaches of intelligent system are described by classifying them into 4 categories as follows:

- Qualitative and quantitative failure-proof control
- Intuitive and logical parallel processing
- Action control based on objective evaluation
- Morphogenesis approach for adaptation

A. Qualitative and quantitative failure-proof control

In this section, a quantitative and qualitative parallel control methodology will be introduced. Human uses different levels according to the situation. In order to realize such action, the author proposed the Cubic Neural Network (CNN) shown in Fig. 5 for an intelligent control method. The effectiveness of the integrated CNN controller for a nonlinear and multipurpose control problem has been ever verified [1][2]. In the method, a qualitative controller is designed by abstracting a quantitative controller through a fuzzy neural network, as shown in Fig. 6.

In order to demonstrate the effectiveness of the CNN intelligent control method, the CNN is applied to a control problem of a swung up and inverted double pendulum mounted on a cart. In order to swing up and stabilize the double pendulum, two controllers at each equilibrium point should be integrated taking account of the influence of various uncertainties and the physical limitations, especially the limited length of the track. In this method, an NN-based nonlinear switching hyper-plane is designed based on the dynamical energy principle. By embedding the energy principle of the pendulum into the integrator shown in Figs. 7 and 8 as system life information, a more robust switching hyper-plane taking account of the nonlinearity of the pendulum is designed. In order to verify the performance of the integrated CNN controller, computer simulations and experiments on a real apparatus were carried out for the cases of parameter variation and sensor failure. As a result, it was demonstrated that the integrated CNN controllers can stand up the double pendulum for the case of arbitrary initial condition of pendulum angle. In addition, the robustness and the fault-tolerance of the proposed CNN controller were verified experimentally for the abnormal situation that the sensor amplifier becomes wrong, as shown in Fig. 9.

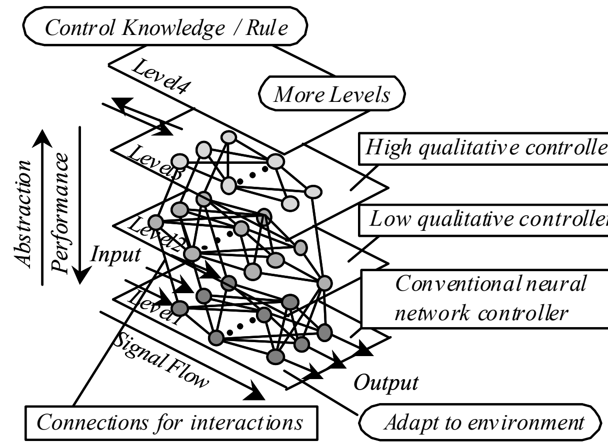


Fig. 5 Cubic Neural Network Control Method

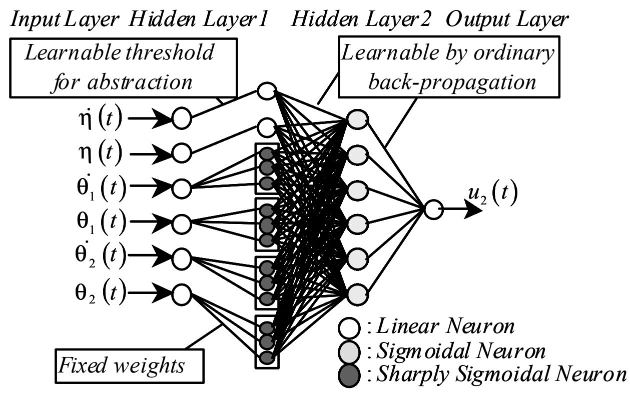


Fig. 6 Abstraction using a Fuzzy Neural Network

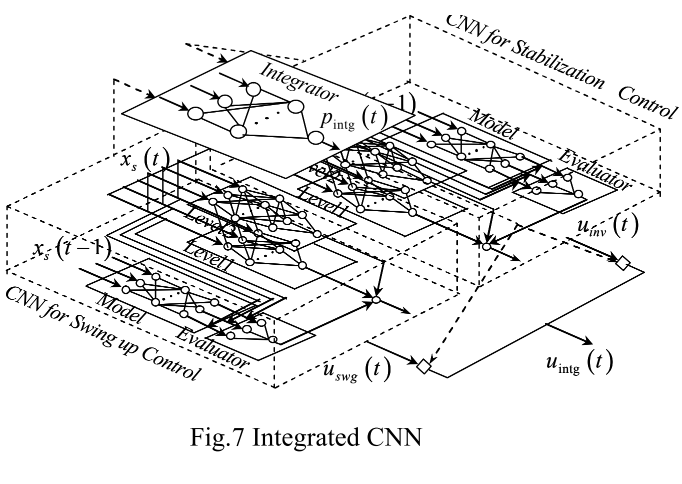


Fig.7 Integrated CNN

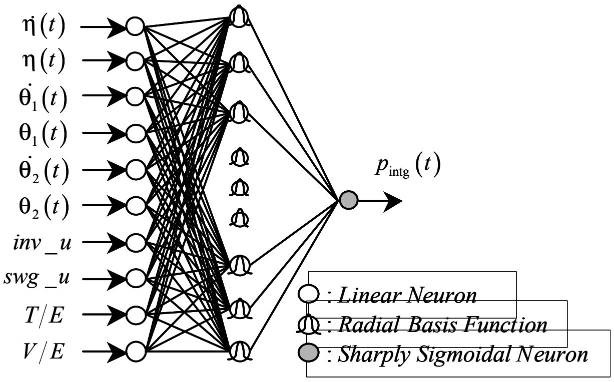


Fig.8 Integrator Neural Network

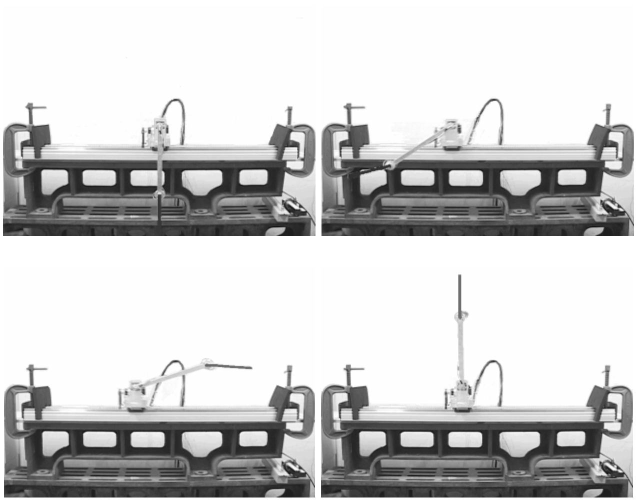


Fig.9 View of Cart-Double Pendulum during Swinging up and Stabilizing Control

B. *Logical and intuitive parallel processing*

Conventional learning algorithm is useful under static and simple environments such as chess and Othello games, but its algorithm has no ability of processing under dynamical environments. So it is important for a system possessing learning algorithm to make an accurate and quick processing under a dynamical environment which has restriction of time like real world. In order to improve this learning algorithm to adapt to real environment, its algorithm should have not only a processing of searching out the optimum action with search tree, but also a flexible processing system with environment adaptation and accurate processing for a changing environment. Therefore, a new intelligent system capable of quick and accurate processing under dynamical environment is introduced, imitating human brain which performs logical and intuitive processing.

The information processing of human brain is divided into logical and intuitive kinds of processing. These two kinds of processing cooperate each other and enable accurate and well balanced processing in real-world.

A new intelligent information processing system with logical and intuitive performance is presented as shown in Fig.10, and in order to investigate its effectiveness, it is applied to a robot playing a Tetris game which requires accurate and quick processing.

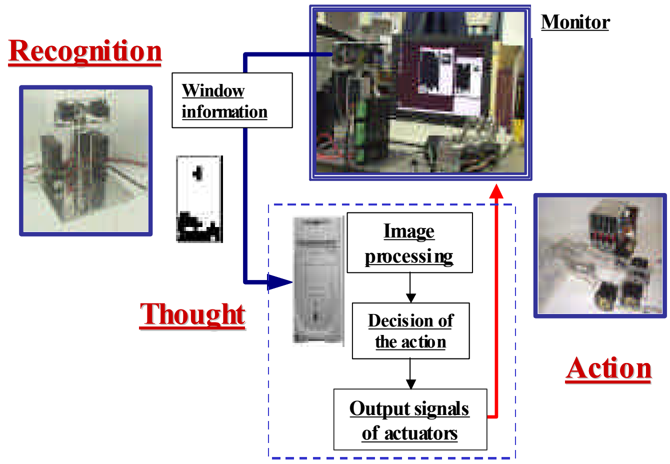


Fig. 10 System of Tetris playing robot

Cooperation between logical and intuitive processing enable a versatile view of the object of the problem, and make it possible to construct compensating and cooperative system as shown in Fig. 11, making use of strong point and compensating bad point of each system.

This cooperative system consists of systems of logical and intuitive processing including the function of learning and compensating with each other. As the learning proceeds, this system has ability of not only extending logical and intuitive personal skills also improving the whole system ability (accuracy and quickness of processing). Next, logical and intuitive processing are shown in detail.

The logical intelligent processing is composed of two function algorithms in order to realize accurate actions and perform trial and error. One of them possesses minimum rules carrying out the task of the subject and consists of fuzzy inference with neural network.

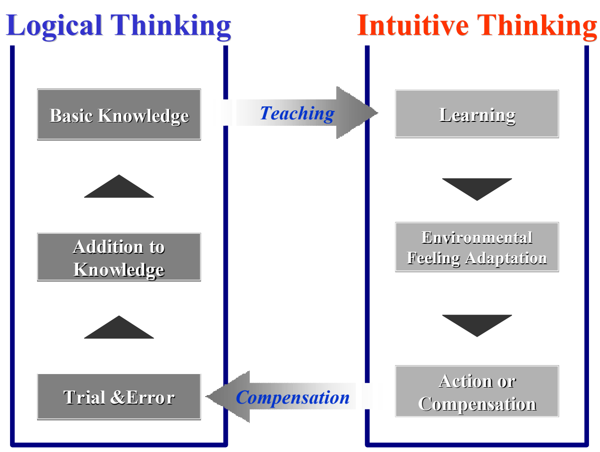


Fig. 11 Relation between Logical and Intuitive Systems

In order to apply logical system to Tetris game, the system of existing knowledge and the system of knowledge acquisition with trial and error are set up. Basic knowledge is set by the minimum knowledge to play the game. In Tetris game, the basic knowledge is the difference of the block space, block bump and deleted lines between the state before actions and after actions.

In order to store plenty of information effectively, the intuitive system has nineteen neural networks for each appearance of the Tetris blocks in the game. The input is set by the block bumps in the game screen. The output is set by the teaching signal obtained by logical system. The intuitive system is shown in Fig. 12. This figure indicates that there is only one best action and no candidate action. The intuitive system acts directly, but there are some candidate actions, this system provides this information to the logical system, and logical system decides the optimum action judging always from acquired information.

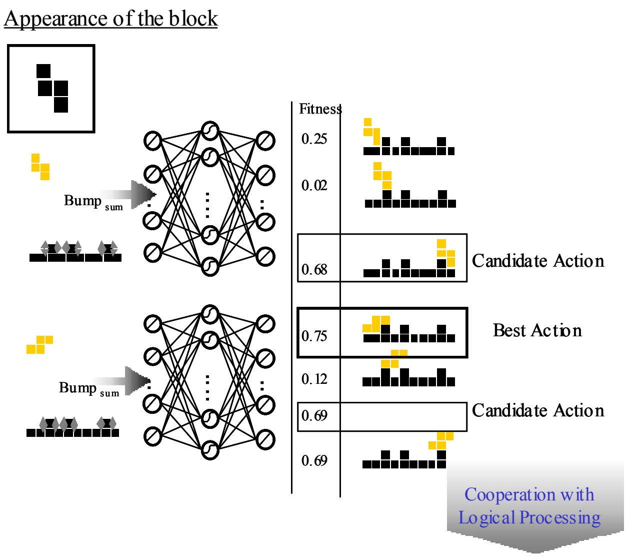


Fig. 12 Intuitive System combined with Logical System

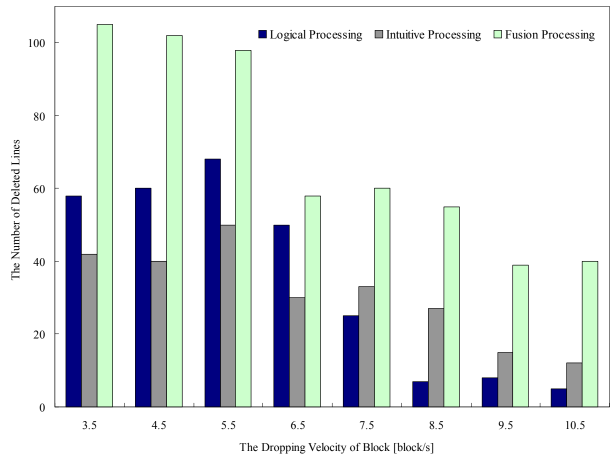


Fig. 13 Comparison between learning algorithm for each difficulty level

Figure 13 indicates the efficiency of the every information processing for changing the dropping speed. In the easy phase of this game, the logical processing can play well, but in the difficult phase, the logical processing can not act well because of the restriction of action time.

In order to investigate the effectiveness of each processing, the result of comparing in each difficulty level of this game is indicated in Fig. 13. In the case of easy level, the logical system needing the long processing time has ability of acting well, but as increasing the difficulty level, the deleted lines of logical system becomes lower than intuitive processing. Finally in the most difficult level 10.5 [block/s], only the fusion system has an ability of acting well. These results indicate that the fusion system can behave under the dynamical environment. In this research the effectiveness of the architecture of a new intelligent information processing system was verified for the changing state of environment.

C. Action control based on objective evaluation

It is expected that autonomous mobile robots will be used in dynamical environment. There have been considerably many researches on the design methods and adaptation to dynamical environment for autonomous mobile robots. In such classical planning methods as sense-model-plan-action framework, the environment was supposed to be static [4]. Working in dynamical environment is very hard for autonomous robots. For achieving intellectual action in dynamical environment, it is necessary to use such decision making based on sensory information as Subsumption Architecture [5] and [6]. The System-Life Information (SLI) is provided for designing well-balanced artificial systems, so that an effective behavior control can be achieved.

The soccer robot system as shown in Fig. 14 is designed to play soccer game on the field of RoboCup Middle-Size League. The system consists of Sensing, Processing, Activating and Expression mechanisms. The sensing mechanism recognizes environment in real-time. The processing mechanism selects the most appropriate behavior with environmental information. The activating mechanism drives actuators. The expression mechanism is a communication system to realize cooperative behavior. The system life information comprises environmental model, memory, estimated state, purpose, and self-evaluation. Figure 15 shows the scheme of the System-Life architecture, for the robot.

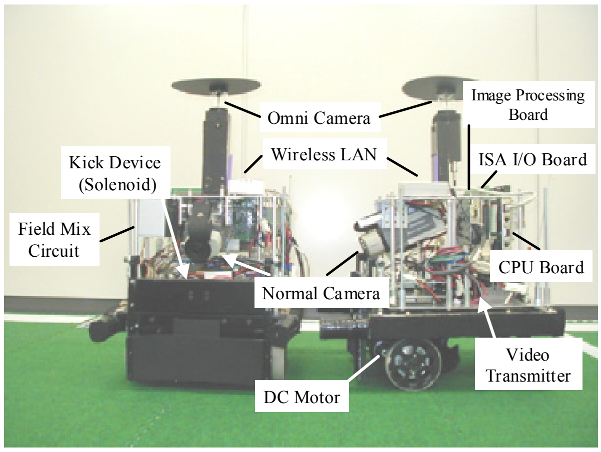


Fig. 14 Field player robot

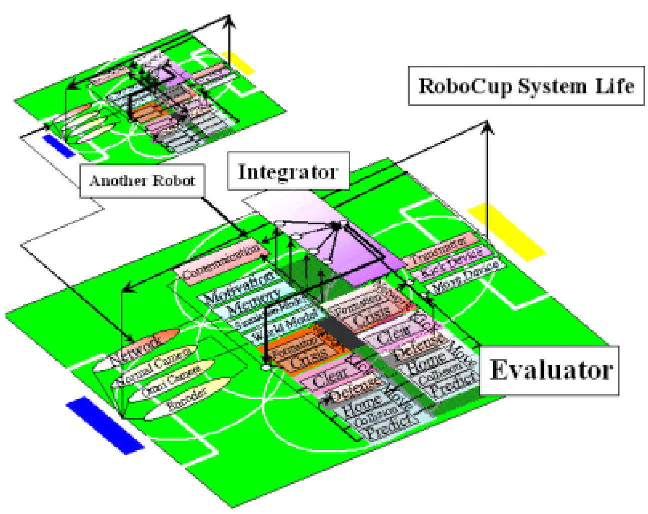


Fig. 15 Architecture of action control

Figure 16 shows the action selection concept mainly for keeper robot. The feature of this control method is to employ an integrator and an evaluator. The integrator selects an action module in each frame. The action module is designed as the action for midterm objective. The midterm objective is achieved by selecting the action modules continuously. The evaluator estimates the output of the integrator according to the environmental information and the result is employed for the action selection in next term. Additionally, it also has characteristics of the robustness against lacking image information from the sensing mechanism. This is obtained by compensating missing information using short-term memory [7]. In this method, the short-term memory is constructed based on the Atkinson and Shiffrin model [8] and the forgetting curve by Brown Peterson Paradigm [9], [10]. The compensated information is utilized or not according to the evaluation of the information stored in short-term memory and estimated information. As well as the keeper robot, the field player robots perform cooperation by communicating each other the achievement and evaluation index of the total objective of the robot systems [11], as shown in Fig. 17. The flexible objective selection is realized by using the method of the qualitative information about own achievement level of the objective and the evaluation about team achievement level of the objective calculated based on the summation of the respective self-evaluations of each robot. This method enables robots to change appropriately the multi-agent system behavior with keeping the high autonomy of each agent. The experiments demonstrate that the field players and the goalkeeper can cope with the dynamical environment and the proposed method is effective. Furthermore, the validity of the proposed method in dynamical environment was demonstrated through the world champion at RoboCup 2002 in Fukuoka and RoboCup 2004 in Lisbon.

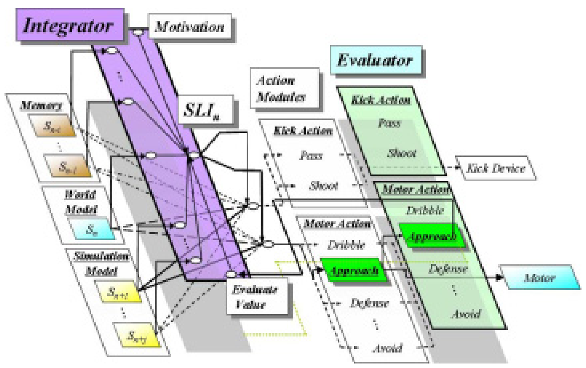


Fig. 16 Action selection scheme

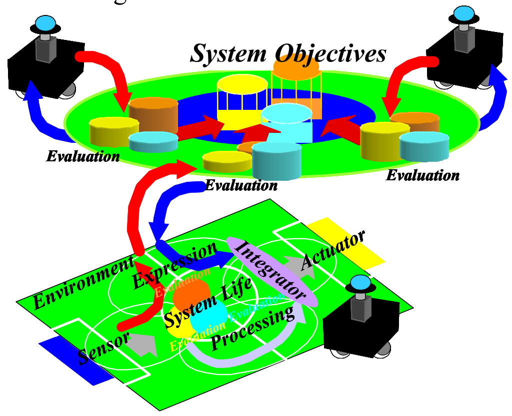


Fig. 17 Cooperative control method using index on purpose and evaluation

D. *Morphogenesis approach for adaptation*

Here, a robot design concerning Morphogenesis for adaptation is introduced by presenting the development and the experimental results of an aerial ski robot, which can perform a somersault coupled with twist motion in the air. Two degree-of-freedom joint is necessary for a robot to perform a somersault. The robot which was developed as shown in Fig. 18 is composed of three rigid links and two rotational joints driven by DC motors and contains control devices so that cone motion can be performed in the air as shown in Fig. 19. To plan the motion of the robot, Fourier Basis Algorithm (FBA) is applied, which approximates the optimal joint trajectories by the finite terms of the Fourier basis. The joint trajectories to perform a twisting somersault from FBA were inputted to the robot, and the flight experiment was carried out. As the result, the robot achieved one backward somersault with half twist, as shown in Figs. 20 and 21. From these figures, the validity of the analytical model and the motion planning method was shown.

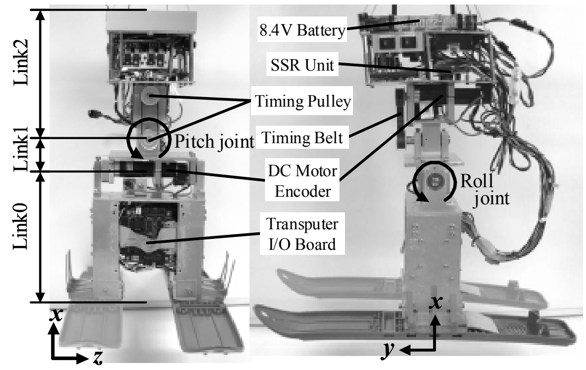
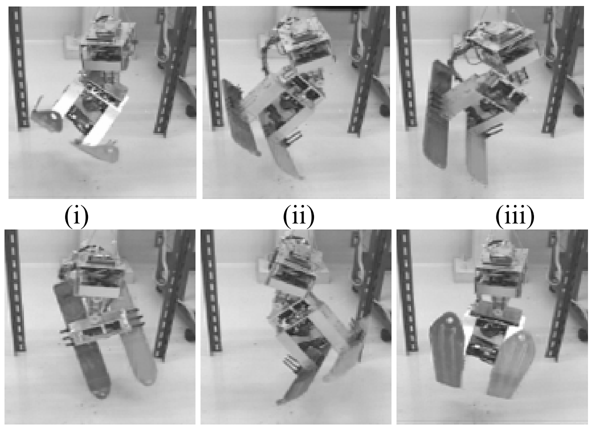


Fig. 18 Developed aerial ski robot



(i) (ii) (iii)

(iv) (v) (vi)

Fig. 19 Cone motion

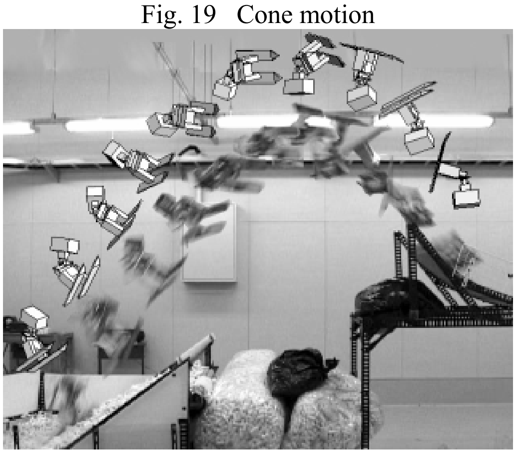


Fig. 20 Sequential pictures of the performing robot in the flight experiment in side view

Fig. 21 Sequential pictures of the performing robot in the flight experiment in front view

IV. CONCLUSION

This paper introduced the concepts of system life and the system design methodology of various robots and intelligent systems based on the concept. Particularly, the importance of integration method of various aspects was indicated. Our challenge is still primitive and only the first step to the system design aiming at paradigm shift from intelligence to life. We have to keep learning system integration methodology from natural systems, since life is not a function, but a system. We explore a systematic approach of system integration methodology.

ACKNOWLEDGMENT

The paper is grateful to the ministry of education and science for the support of the COE program titled "System Design: Paradigm Shift from Intelligence to Life. Additionally, this work is supported in part by Keio University Special Grant-in-Aid for Innovative Collaborative Research Projects.

REFERENCES

[1] H. Kidoshi and K. Yoshida, "Intelligent Control Method Using Cubic Neural Network (Intelligent Nonlinear Control of Pendulum from Swing up to Stand up)", JSME Int. J., vol.63, 613, 1997, pp.3160-3167.

[2] K. Yoshida and K. Hatano, "Intelligent Control Using Cubic Neural Network", JSME Int. J., vol.43, no.3, C, 2000, pp.612-617.

[3] M. Takahashi T. Narukawa and Kazuo Yoshida, "Intelligent Control Using Destabilized and Stabilized Controllers for a Swung up and Inverted Double Pendulum," Proceedings of 2003 IEEE Inernational Symposium on Intelligent Ccontrol (ISIC2003), Texas, USA, 2003-10.

[4] R.E. Fikes, and N.J. Nilsson, "TRIPS: A New Approach to the Application of Theorem Proving to Problem Solving," Artificial Intelligence, Vol.2, pp,189-208, 1971.

[5] R.A. Brooks , "Robust Layered Control System for a Mobile Robot," IEEE Robotics and Automation, Vol2, No.1, pp.14-23, 1986.

[6] S. Rosenshein, "Formal Theories of Knowledge in AI and Robotics," New Generation Computing, Vol3, No.4, pp.345-357, 1985.

[7] H. Fujii, N. Kurihara and K. Yoshida, "Intelligent Control of Autonomous Mobile Soccer Robot with Inputation," Proceedings of the 21st Annual Conference of Robotics Sosiety of Japan, CD-ROM (3J35), 2003 (in Japanese).

[8] R. C. Atkinson, R. M. Shiffrin, "Shuman memory: A proposed system and its control processes," in K. W. Spence, J. T. Spence (Eds.), The psychology of learning and motivation: Advances in research and theory. Vol. 2. New York: Academic Press, 1968.

[9] J. Brown, "Some tests of the decay theory of immediate memory", Quarterly Journal of Experimental Psychology, Vol.10, pp.12-21, 1958.

[10] L.R. Peterson, M. J. Peterson, "Short-term retention of individual verbal items", Journal of Experimental Psychology, Vol.58, No.3, pp.193-198, 1959.

[11] H. Fujii, D. Sakai and K. Yoshida, "Cooperative Control Method Using Evaluation Information on Objective Achievement," Proceedings of the 7th Int. Symp. on Distributed Autonomous Robotic Systems (DARS 04), 2004 (to appear).

[12] T. Hashieda and K. Yoshida, "Online Learning System with Logical and Intuitive Processings Using Fuzzy Q-Learning and Neural Network, " Proceedings of IEEE Int.Symp. on Computational Intelligence in Robotics and Automation, 2003.

[13] S. Shirokura, R. Fukushima *and* K. Yoshida, "Development of an Aerial Ski Robot Performing a Somersault Coupled with Twist Motion," Jounal of the Robotics Society of Japan, Vol.21, No.2, 2003, pp.172-177 (in Japanese)