Research and Education on Complex Functional Mechanical Systems
— New Front of Mechanical Engineering Inspired by Science of Complexity —

Tetsuo Sawaragi* and Kazuo Tsuchiya**

Graduate School of Engineering, Kyoto University.

Yoshida Honmachi, Sakyo, Kyoto 606-8501, Japan.

* Complex System Control and Design Group Leader of the COE   ** Project Leader of the COE

Email: sawaragi@prec.kyoto-u.ac.jp

Abstract – Fundamentals of complex functional mechanical systems are macroscopic phenomena of complex systems consisting of microscopic elements, mostly via nonlinear, large-scale interactions. Such phenomena can be observed or created in every aspect of modern science/technology. They typically present collective behavior such as self-organization, pattern formation, learning etc., which does emerge out of interactions among individuals with an ability of creating variabilities. Our COE program aims at clarifying fundamental principles in such phenomena as well as utilizing and synthesizing the knowledge derived out of them to realize the adaptability of the mechanical artifacts to the environmental disturbances. A group of control and design of complex mechanical systems is one of the four groups making up the program. In this manuscript, an overview of our group's ongoing works is presented including the design and analysis of novel control mechanisms for autonomous robots, biological systems, mechanical artifacts and more general human-in-the-loop systems.

I. INTRODUCTION

The 21st Century COE (Center of Excellence) Program is an initiative taken by the Japanese Ministry of Education, Culture, Science and Technology (MEXT), aiming at supporting universities to establish international centers for education and research and to enhance to be the world's apex of excellence in the specific research areas. Our program of "Research and Education on Complex Functional Mechanical Systems" is awarded the grant for carrying out advanced research and education as Centers of Excellence in the field of mechanical engineering in 2003 in a domain of mechanical and civil engineering (five-year project), and is expected to be a leader in research and education both in Japan and worldwide. Our objective in research is modeling, analysis, and control of phenomena and design theory geared specifically for complex mechanical systems, and is to form the basis of a novel field of study to be known as "Complex Systems Mechanical Engineering".

To this end, we will establish high-level joint teams combining specialized scientists and engineers from the four departments of Graduate School of Engineering (Department of Mechanical Engineering, Department of Engineering Physics and Mechanics, Department of Precision Engineering, and Department of Aeronautics and Astronautics), one department of Graduate School of Informatics (Department of Applied Analysis and Complex Dynamical Systems), and Kyoto University International Innovation Center. Research will be conducted using the facilities of the five departments on Yoshida campus, and it will also be carried out at Katsura Intec Center, our interdisciplinary joint research facility. In this article, we briefly introduce an overview of the program.

II. RESEARCH OBJECTIVES

Mechanical Engineering concerns modeling and analysis, and the control and design of mechanical systems. It is traditionally thought of as a mature field; however, there remain within it, and at its intersections with other fields, a number of problems that remain unresolved. One such field of study is “Complex Mechanical Systems”. In our COE program, we have applied novel methods for analyses and recent discoveries regarding pattern formation and the emergence of function acquired in Complex Systems Science to study and explore complex mechanical systems. By determining universal laws that govern phenomena and emerge on complex mechanical systems and principles that control behaviors of complex mechanical systems, we aim to gain a deeper understanding of complex mechanical systems as well as to form the basis for the novel field of “Complex Systems Mechanical Engineering”.

Here, “complex mechanical systems” refer to mechanical systems that comprise a number of non-linear interacting elements, and form a variety of structures under the influence of the external environment. At present, in many fields with which Mechanical Engineering is associated, there are urgent demands, both explicitly and implicitly, to study complex mechanical systems.

Nonetheless, Mechanical Engineering has traditionally sought to maximize efficiency, precision and speed progressively; however, these paradigms have shifted and expanded, such that the field is becoming increasingly concerned with how machines can function in concert with its *environment*. However, such machines cannot be made in the context of conventional rigid, inflexible mechanical systems, but instead require the development of soft and flexible mechanical systems that can change their structure according to the external environment. In the field of control engineering, we target mechanical systems that have complex internal structures and that exhibit a variety of behaviors in response to external environment and elucidate control principles and formulate design theories.

In our COE program, we aim to create a novel field of Mechanical Engineering, “Complex Systems Mechanical Engineering” by elucidating laws that govern the way in which large numbers of interacting components generate the behavior of such complex mechanical systems, and by developing design methods that can control them. The program consists of the following four research groups;

(1) Mathematical Analysis of Complex Systems
(2) Analysis and Modeling of Fluids
(3) Control and Design of Complex Mechanical Systems
(4) Analysis of Behaviors of Mechanical Materials with Complex Structures

Systems with a great deal of element and non-linear characteristics that include self-organization, fractal and chaos upon interaction with the environment, are known as complex systems [1, 2]. Such systems have been the focus of much of the recent research in all fields of science. These studies have made it clear that complex systems spontaneously form coherent structures under the influence of the external environment; as a result, such systems can perform higher function through these ordered structures. We believe that novel methods for analyses and recent discoveries regarding pattern formation and emergence of function acquired in the field of Complex Systems Science will become important tools and concepts in the study of complex mechanical systems; to this end, we have engaged in modeling and analysis, and control and design of complex mechanical systems by establishing an effective joint research team comprising of both mechanical engineers and complex systems scientists. The following is an overview of the program's goals.

A. Modeling and analysis of universal laws governing the dynamic behaviors of natural and artificial complex mechanical systems

We develop novel methods of analysis, fractal analysis, etc., for phenomena that conventional methods cannot treat due to their large size and structural complexity, and analyze the dynamic behaviors of basic physical processes such as thermal diffusion over fractal structure and wave propagation. The modeling of the atmosphere-ocean system has long relied upon phenomenological methods. We plan to develop a new model that is faithful to phenomena, comprehensive, and highly accurate. To that end, we have analyzed turbulent structures and formulated an accurate model of turbulent convective transfer, an important element of the atmosphere-ocean system, based on an analysis of a structural organization of turbulence, and then used a constitutive procedure to model the atmosphere-ocean system. We model and analyze the mechanical characteristics of materials that have complex structures with the aim of applying them to practical use; a fine example material is bone. By constructing a mathematical model based on physiological data of adaptive processes undergone by bone in response to a dynamic environment, we are likely to develop more lifelike artificial bones.

B. To elucidate and formulate control principles which make possible the practical application of complex systems

A complex system comprises a number of unstable elements with non-linear characteristics and interactions; thus, conventional control theories cannot treat it adequately. For such systems, we aim to develop novel control methods based on dynamical systems theory and autonomous distributed systems theory. We have revealed that flow fields of a certain type of turbulence are governed by an unstable limit cycle, and based on these discoveries we aim to develop a control algorithm of turbulence by the use of chaos control theory. We aspire to develop mechanical systems that have complex internal structures and that exhibit a variety of behaviors in response to external environment and elucidate control principles and formulate design theories.

III. RESEARCH PROGRAM FOR COMPLEX SYSTEM CONTROL AND DESIGN GROUP

In the following, we focus on the introduction of the research overview of Complex System Control and Design Group, one of the four research groups making up the entire program.

The focus of research on a future mechanical system needs to be changed from the machine itself as an entity that is highly accurate and highly efficient to a whole integrated system, which involves the environment that surrounds the machine and a human who operates it. In general, there are limited numbers of systems in which entire functions are accomplished by machines alone. In most cases, the interactions between human and the external environment accomplish the original functional purposes of mechanical systems; however, the theory for its system design and control has yet to be established.

Essentially, autonomous and proactive processes, typically seen in living systems, are not steered only by external forces. Instead, they can autonomously change the relationships among the internal elements that constitute themselves, while taking in external disturbances and adapting themselves to them. In this way, the internal dynamics of each element and the interactions among these elements form a mutual feedback system. Our research group will perform mathematical and experimental analysis of these adaptation processes of internal dynamic systems, and develop a system design theory using those process models.

We will cope with the problems inherent in a design of autonomous mobile robots, a design of man-machine systems and a systemic functional emergence arising from the interactions among organic cells and non-linear material elements. We will carry out our research through active and progressive collaboration among all the group members, focusing on the following three subjects (Figure 1) and seeking the possibility of fusion and integration between these disparate research topics:

1. Design of autonomous mobile robots that adaptively generates behaviors through physical interactions with the environment;
2. Analysis and design of dynamical human-machine interactions and its interface design; and
3. Environmental design for a pattern formation out of interactions among elements.

A. *Objective: To establish the concept of control design based on dynamical system theory*

Complex mechanical systems can be defined as mechanical systems that consist of multiple elements with their complex interactions and that form a variety of structures and behaviors being affected by an external environment. Each element has its own *internal dynamics*, and these internal states encounter the competition between two contradicting trends: “stability,” which is associated with the extent of autonomy maintained inside, and “adaptability,” which represents plasticity for adaptation to the environment and surrounding elements. Furthermore, interactions between the elements underlie a further level of dynamics that allows the evolution of complex behavior, and at the same time, a rational functional design is realized by selecting a nominal option, while other versatile options are suppressed.

Our group aims to clarify the principles with which systems dynamically and autonomously form orders and emerge new functions, and apply our findings to the design of mechanical systems in which functional elements constituting the system transform their nature in response to their environment. This innovative approach to mechanical system design is rooted in the evolutionary and adaptive principles found in life systems that are characterized by its nature of *plasticity* and *loose-couplingness* present among components and their interactions. Since complex systems are defined not by any fixed relationships, but by the evolving interactions between its constituent elements, conventional analytical methods are insufficient. We augment them by using constructive approaches, in which we develop a simulation model, and compare its dynamics with experimental observations (Figure 2). In other words, we build up our understanding of a phenomenon by combining several basic processes using an elementary model, aiming to acquire a constructive understanding of nature. Although quantitative forecasts will be difficult to make using such analytical methods, this approach will play a significant role in the qualitative prediction and comprehension of phenomena of universal behavior classes. In this way, we hope to make complex subjects comprehensible and applicable for practical development.

Major directions we aim at in this project are summarized as follows;

1. **Self-organization and Pattern Formation**: to use the *natural* dynamics of the system to create structures and functions.
2. **Evolutionary and Adaptive Dynamics**: to utilize structural and/or functional change of the complex systems for *evolvability* design with high complexity for desired function.
3. **Collective Behaviors and Decision-making**: to find out interdisciplinary principles governing a variety of domains including biological evolution, socio-economic systems and societies of electronic agents.

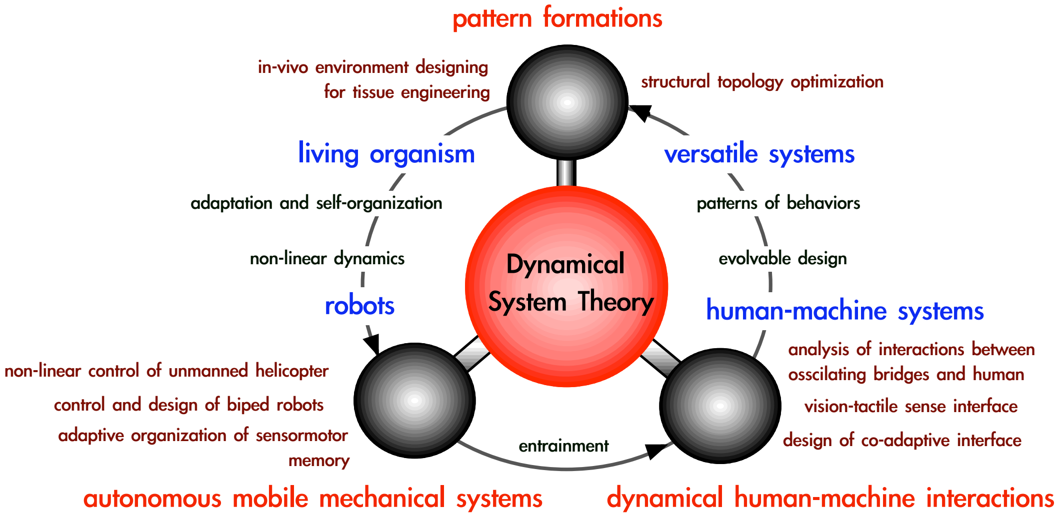

Fig 1. An overview of the group

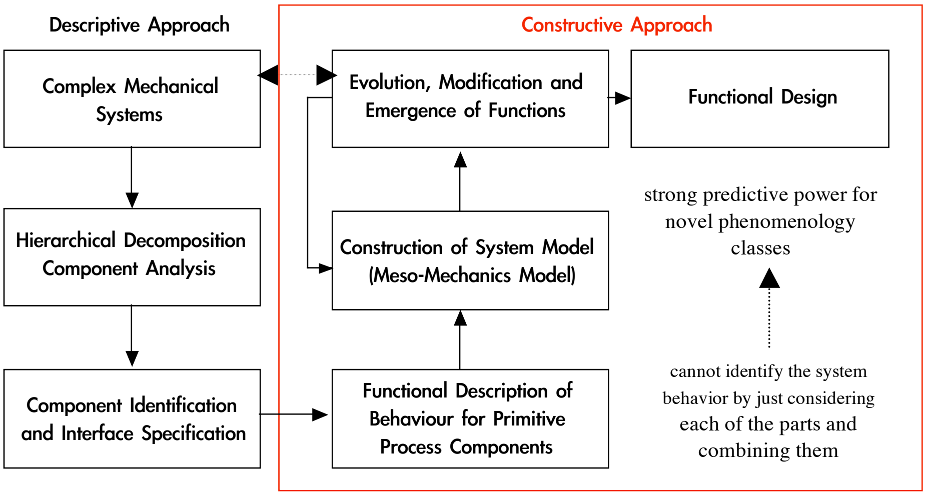

Fig.2. Constructive approach

(4) **Paradoxes of Complex Systems**: how to let the competitive criteria coexist within a system such as altruism and selfishness, cooperation and competition, and stability and adaptability.

B. Outline of research programs of individual subjects

To design an environmentally adaptive autonomous mobile mechanical systems that exploits versatility

The group of Tsujita and Aoi (the Tsuchiya laboratory) carries out research on the control and design theory of biped robots, taking self-organization and phase transition by control parameters as the principle of motion control. In this research, the nervous system, which is capable of generating voluntary activity patterns related to locomotion, draws in and strongly couples the actions while interacting with a body that is in physical contact with the environment. This results in a mechanism that can generate versatile and adaptive walking motions. The group designs quadruped and biped robots that incorporate this motion control system, which autonomously forms and affects four types of locomotion patterns (walk, trot, bounce, and pace) according to changes in its environment, such as floor inclination, walking speeds and loads.

Nakanishi studies the design of systems that would dynamically control adaptation in response to complex changes in dynamic characteristics, in order to deal with unanticipated changes in an environment or in a model. In this research, he uses an unmanned helicopter to explore control system design using a neural network as an adaptive component. By combining off-line learning on a simulator and on-line learning in the actual environment, he demonstrated robust adaptation to the problems encountered by actual machines such as model learning errors, changes in environment such as ground effects and gusts, and changes in dynamic characteristics. As a control method with versatility, he adds multiple modules that can adapt to environmental changes and pursue control system design in which individual modules selectively learn adaptations to complex environmental changes and function together as a coherent system.

For social robots that perform social interactions with people using body motions, motion learning is an important technical issue for a robot to enhance its autonomy by adaptively organizing its pre-existing internal structures and to elicit human responses. Here, learning should be focused on the process of transforming the robot itself, rather than model the environment. Through its interaction with others and its internalization, robots define a new reality, then constantly change and optimize their behavior. Taniguchi in the Sawaragi laboratory studies the ability of face robots to trace moving objects. He has proposed an adaptive organization mechanism that allows the robot to organize tracing motions intrinsically, without external instruction signals in learning in the sensorimotor system.

To analyze man-machine dynamics and design its interface

Complex phenomena generally occur at interfaces where antagonistic heterogeneous effects coexist. At the interface of man-machine systems, multiple peripheral influences interact and interfere with intrinsic properties to generate such complex phenomena.

Such behaviors often exceed design specifications. For example, on a footbridge, the rhythm of a human and that of the rolling oscillations of the bridge interact with each other, and human rhythm unconsciously synchronizes with the movement of the bridge and thus the rolling becomes amplified. The research group of Utsuno in the Matsuhisa laboratory carries out research on the interaction of such rolling oscillations of bridges with body motion governed by the nervous system that works as a rhythm generator. They analyze these complex behaviors observed at the time of human locomotion on a light and flexible structure such as a pedestrian bridge. They have found that this phenomenon of entrainment of a human's walking pace can be experimentally reproduced by the use of a trapezoid pendulum model.

Yokokoji and Saida in the Yoshikawa laboratory describe the importance of coherence of vision and tactile sense at vision-tactile sense interface to the virtual environment. Specifically, they are investigating a bi-directional motion transfer based on the concept of mechano-media, where a mechanical system takes charge for mapping of human action beyond spatial and temporal aspects. This knowledge, they hope, will enable the design of robots that perform these motions with human-like flexibility, with all the multiple degrees of freedom they entail.

Horiguchi in the Sawaragi laboratory conducts studies based on an assumption that the interactions occurring in a human-robot collaboration and the strength of their global association are determined by a specification of an interface design connecting these autonomies. The group has found that these properties manifest themselves in the dynamics of both autonomous and collaborative behavior of human and robot. Often, they have observed that mutually adaptive behaviors become coordinated, thus optimizing the work output of a human-machine combination. Finally, the group has been investigating interface design for tele-operation robot, which is intended to promote the bi-directional exchange of intentions by equivalent and semi-independent parallel loops between a human and a robot.

Environmental design for pattern formation of element groups in the interaction field

To understand the behavior of a living organism, it is essential to elucidate the organic behavior of aggregated as well as single cells. In a life system, there is inherent diversity at the individual level, but at the group level, there is also an inherent mechanism that becomes increasingly more stable and deterministic.

Yamamoto, in the Tomita laboratory, studies medical engineering focusing dynamics of organisms and their environments in terms of hierarchy in a biological system in the context of interactions among cells and between cells and tissues. To investigate the dynamics of this system further, specifically the functional and structural adaptations that constituent units undergo, the group has developed an ES cell-cartilage regeneration simulation model using cellular automata.

In order to create microstructures that simulate living organisms, the pattern formation mechanism in view of topological changes of such functions ought to be elucidated. Compliant mechanisms that actively exploit the structural flexibility of a mechanical structure can realize the mechanical function as the structure itself by adding required flexibility to an appropriate position within the structure. Nishiwaki, in the Yoshimura laboratory, investigates new topological design optimization in structure design of compliant mechanism. To date, this type of optimization has only been conducted empirically; this group intends on studying it analytically, and is focusing especially on vibrating structures.

IV. DYNAMICAL AND COMPLEX BEHAVIORS IN CONTROL SYSTEMS AND HUMAN-MACHINE CO-ADAPTIVE SYSTEMS

A. Complexity in Human-in-the-Loop Systems

The conventional division between human beings and machines should be modified in the context of thinking about *evolutionary* engineering processes. Human beings and the technologies including computers, communication devices, electronic networks, etc. should all be understood to be part of the system. Wherein, changes in the individual parts may take place through introducing alternate components, and all of these changes are part of the dynamics of the system. Sometimes such changes may be too complex for a designer to predict the behaviors emerging out of those. Engineering efforts should be on change to the system as a whole, rather than just on change to the small parts. In the following of this section, we introduce our framework that one of the authors, Sawaragi, is developing in this COE program.

B. Harnessing: A Novel Control and Design Principle for Complex Systems

Today's advanced automation might be indeed experts in solving/performing particular tasks, but have no means of relating to human users. Thomas Sheridan at MIT has called this “autistic automation”[3]; “autism” represents those humans who seem to have lost their skill of becoming engaged, being embedded in a situation, a sense of belonging to the world and to their partners. Actually, such an aspect is becoming an origin of a new type of human errors caused by some mismatch between a human and machine autonomy (e.g., a well-known *automation-induced surprise* in aviation [4]). As a concept of human-centred automation [5] reveals, automation needs to behave "socially"; automation should learn a variety of powerful social rules which minimize interference and maximize group (i.e., human-automation) benefit and automation systems should be designed from the perspectives of "relations" and "processes" that may emerge out of the interactions between the automation and the human user.

In order to enrich the interactions between a human and machine autonomy and to let such a friendly and social relationships emerge through those interactions, we should abandon the conventional straightforward “control” doctrine and develop a novel principle for human-machine interactions. We think that a promising idea as an alternative to that is “harnessing”, whose characteristics are described as follows.

(1) External input only gives direction for the path and its strength is kept as small as possible.

(2) Minimize the control input and let the system move by its own dynamics with reasonable resolution (i.e., not seeking for preciseness).

Machines to which this harnessing capability is embedded are assumed to generate a human-friendly mechanical behavior and as well as to present biological significance. For this purpose, machines should be evolvable though experiencing the interactions with a human, who is allowed to interact with a machine demonstrating a human competency.

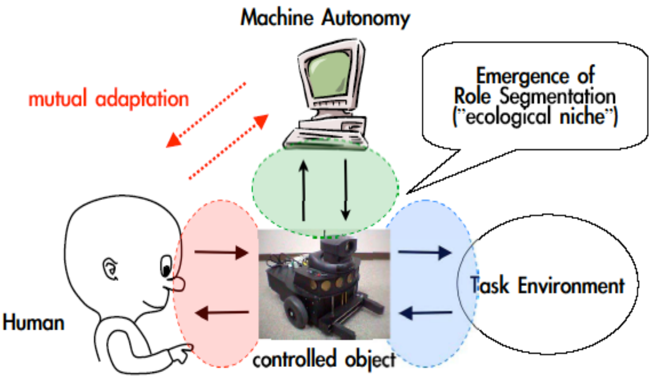

Fig.3.Tele-operated mobile robot

C. *Shared Autonomy between Human and Machine*

As a testbed for constructing a human-machine collaborative system, we deal with a tele-operation system for a mobile robot as shown in Fig.3. We characterize this system as a shared autonomy system, meaning both machine autonomy and human autonomy must be shared. A main focus of a conventional simple tele-operation system has been attended to design an interface so that it could transfer an operator's control intentions and commands to a robot exactly as well as it could show a robot's behavior to a human as transparent as possible. Wherein, an ideal interface is the one that can establish a *morphological* mapping between a human task and a robot's task.

On the other hand, in a shared autonomy system both a human and a machine have their own autonomies, whose intentions are sometimes competitive and conflictive at least at the initial time. Through experiencing those conflicts and introspecting those competitions, both a machine and a human should be able to mutually adjust their judgments with each other and to find their own "niche" to perform collaboratively.

D. *A Generic Model for Co-Adaptation between Two Heterogeneous Autonomous Agents*

As a generic model for such a co-adaptive process emerging in collaboration by two autonomous entities, we construct a model shown in Fig.4 as a pair of autonomous entities, each of which is a self-organizing system consisting of hierarchical structures simultaneously undergoing a variety of distinguishable activities. Different sets of variables and parameters are appropriate to a state space description pertaining to these activities taking place at the individual levels. Wherein, independence of descriptions of state spaces between the two entities is essential, and just a physical channel interconnecting them is shared. We do not assume that neither any "symbols" nor any "meanings" can be transferred on this channel, since symbols should be constructed and grounded by the autonomous entities by themselves in a self-enclosed way rather than by a system designer's ad hoc definition. We just assume that what can be shared between them should be restricted to information of an *object* level in terminologies of Pierce's classical idea of *semiosis*.

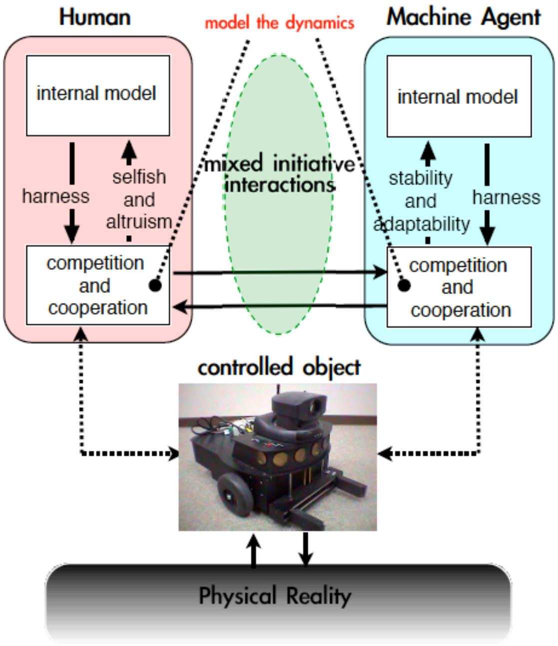

Fig.4. Human-robot Co-adaptation

As mentioned in section III.A, one of the key concepts of complex systems is a paradox that more than two competitive criteria may co-exist within a single entity as well as within an organization and/or team of them. This characteristic is making the behaviors generated both at a single agent level and at an organizational level dynamical and complex. That is, they cannot be implemented as a simple input-output function and is quite different from a classical stimulus-response model proposed in conventional behavioral psychology. Rather, a complex system behavior is characterized by the key properties of "open" systems, where flows of matter, energy and information can occur across their boundaries, and this makes them undergo spontaneous transformations of structure and functionality within and among entities. Successive instabilities occur each time that existing structure and organization fail to withstand the impact of some new circumstance or behavior. When this occurs, the system re-structures and becomes a different system, subjected in its turn to the disturbances from its own non-average individual entities and situations. It is this interaction between successive systems and their own inner richness that provides the capacity for continuous adaptation and changes.

For realizing such a dynamics between two heterogeneous autonomous agents (i.e., a human and a machine agent), a hierarchical structure consisting of two layers is essential. Lower layer deals with the basic competitive and cooperative dynamics, and upper layer called an internal model maintains macroscopic status of its internal states evolving at lower layer from meta-level perspectives. In each of the autonomous entities, this basic architecture enables a reciprocal and bidirectional interactions. In the bottom-up direction some kind of ☒ order parameter constructed from the lower level is viewed as a representation of the internal model at a higher level, related with some macroscopic behavior ranging between two extremes of “autistic” and “social”. In the top-down direction, on the other hand, only a few instructions and/or simple parametric commands are sent to a lower level intermittently, and then ongoing non-equilibrium statistical mechanics at the lower level may be affected indirectly and another equilibrium phase transitions may occur. In a word, the upper level takes a role of “harnessing” a dynamic behavior at the basic level by just adjusting a single parameter governing the dynamics at the lower.

In our framework, dynamics at lower level is implemented as non-constant-sum, nonnegotiable "Paradoxical" games in order to implement an “Ego” drifting between “selfishness” and “altruism” [6]. This game is well-known as a Prisoner’s Dilemma (PD) game and Chicken game (CG). In this model, each of the two players (agent 1 and 2) takes either of cooperation (C) or defeat (D) on the partner, thus their state is one of the four possible states of CC, CD, DC, or DD. For each state, payoffs that each of the players can get are defined as illustrated in Fig.5. In CC (both players take a cooperation), both of them can get a payoff of 1.0, but when either of the player takes defeat and the other takes cooperation, the payoff of a defeating player is ξ, while the payoff of a defeated one is - ξ. If both of them take defeat, the payoffs of the both players are reduced to -1.0 and this paradoxical outcome leads to “behavioral paralysis”. If the payoff for DD is increased from -1.0 to -2ξ, then the state DC and CD become local equilibria since DD state is too expensive for the players to afford (“Chicken game”).

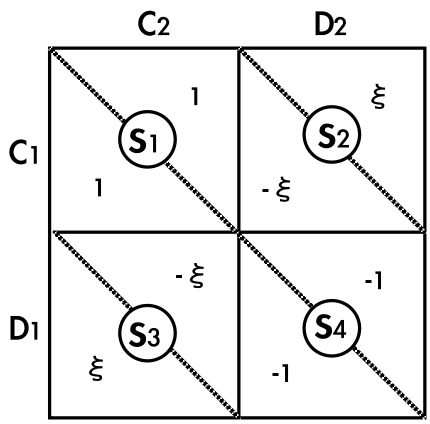

Fig.5. Payoff table for dynamics

By assuming the games are played in iteration, learning takes place, which means that the time evolution of the propensities is governed by a system of two first order non-linear differential equations; the time derivatives of the propensities are proportional to the gradient of the expected payoffs with respect to that propensity. This is illustrated in Fig.6, in which a parameter ξ is set to a particular value. This figure shows; when two agents start from particular initial values of the propensities to keep taking cooperation, they get to be converged into one of the four states through iterating the games. Thus, this illustrates the internal dynamics of a *single* autonomous agent, in which competition and cooperation with its partner coexist. This Markovian kinetics providing the basic dynamics at the lower level do not evolve under a fixed ξ (i.e., a game type), but the changeover between game types might be possible within each individual when the expected payoff with the previous game seems to be reaching local plateaus, and this changeover may be adjusted by changing a parameter ξ from the upper layer.

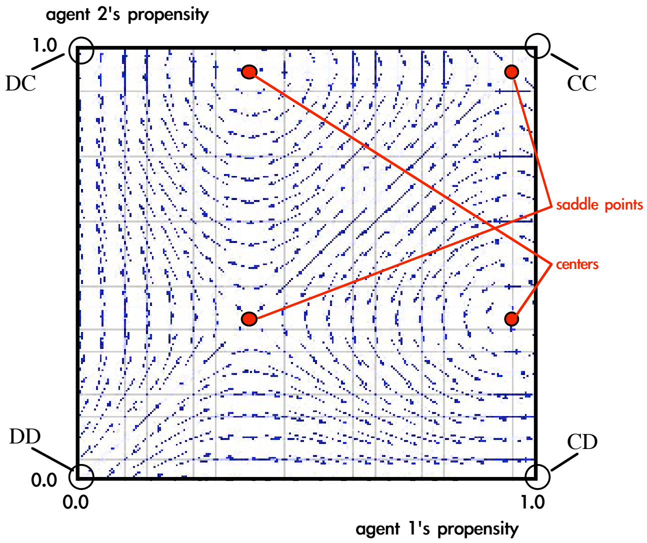

Fig.6. Evolution of transients of internal states along learning

Then, how and when does this parameter of ξ should be adjusted from the upper level? It depends both on;

(1) Its own state: how consistent so far within itself (i.e., entropy of the state occupancy) that drives transitions of states at the higher level towards autistic attitude.

(2) Its partner’s state: how consistent so far with its partner’s (i.e., cross-correlation with the partner’s behaviors) that drives transitions of states at the higher level towards social attitude.

Communication channel between the two autonomous agents is used for calculating the above cross-correlation. In other words, neither of any explicated intentions nor symbolic information is transmitted on it, but just cues that indirectly affect on both of the dynamics are transferred. Interpretation of those and how they are transformed into the adjustment of the parameter ξ are done in a self-enclosed

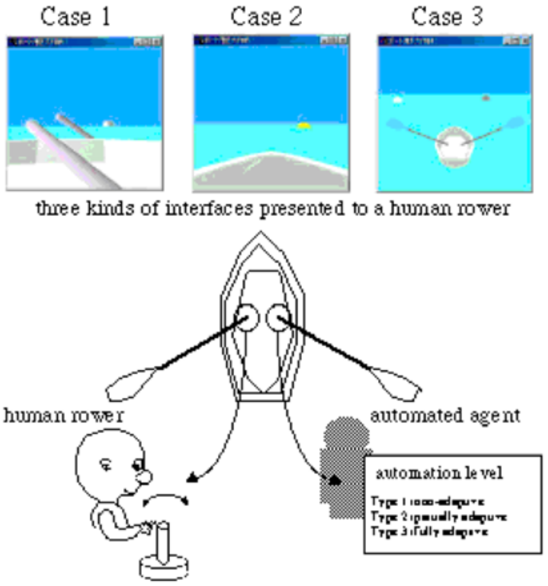

Fig.7. Boat rowing simulator

way within the individual agents according to the above rules (1) and (2).

D. *Constructive Approach to Design and Control of Human-Machine Co-Adaptive Systems*

Based on the generic model for co-adaptation mentioned in the previous subsection, we are now taking a *constructive* approach to design and control of a variety of human-machine co-adaptive systems [7]. Constructing and simulating this model, we compare the model output with the reality. Based upon the above co-adaptation model, we are investigating into design of human-machine interface for tele-operated mobile robot and human-agent collaboration for a task of simulated boat rowing.

The former study aims at a new design framework for combining and capitalizing on both advantages of the human- and the mechanized automatic controls into their joint activity (i.e., shared control), wherein their well-coordinated collaboration is achieved through the interaction of dynamic and mutual shaping function allocations among them. Implementations of shared communicational modality between a human and a machine autonomy is realized by letting the intention of the robot autonomy transfer onto the joystick using the feedback force and by letting the operator's and the autonomy's input actions be mutually restricted through that joystick. Through experiments of a navigating problem of a mobile robot in a simple corridor environment, we identify the difference of cue-utilization style between human operator and robot autonomy. Developing an algorithm of machine autonomy’s adaptation, we verified that a human and a machine get to find their own niche; they get to take different roles and to construct their own control policies through experiencing the interactions.

The latter study deals with a micro world simulation testbed for human-agent collaboration as shown in Fig.7. Wherein, a human and an automated agent take parts of rowing individual oars to steer the boat to the destination. The difficulty in this collaborative task is that this task requires balanced rowing of both oars. Here, our interest lies in what kinds of information in the display of the simulator the human is using as cues needed for the collaboration with the automated agents that row the oar in three different autonomous ways. Wherein, a human and an automated agent are, at least initially, two independent judges making individual judgments within the common task ecology of the boat-rowing system. To see the effects of an agent’s autonomy on a human, we design the cues available to an agent in three different ways. Moreover, in order to investigate into the relationships among the human-agent-environment we design a number of displays by changing the perspectives of the ongoing task within the virtual display of the simulator, and thus by changing available cues to a human rower. We change the parameters of the co-adaptation model and compare the results with the actual data obtained in the experiments using the boat-rowing simulator.

V. CONCLUSIONS

In this article, we gave an overview of the 21st Century COE (Center of Excellence) Program of "Research and Education on Complex Functional Mechanical Systems" that is ongoing at Kyoto University. For more detailed information, please refer to the following home page of our program; http://www1.mech.kyoto-u.ac.jp/coe21/.

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