The 21st Century COE Program for
Research and Education on Complex Functional Mechanical Systems
— New Front of Mechanical Engineering Inspired by Science of Complexity —

Kyoto University

Graduate School of Engineering
Dept. of Mechanical Engineering
Dept. of Precision Engineering
Dept. of Engineering Physics & Mechanics
Dept. of Aeronautics & Astronautics

Graduate School of Informatics
Dept. of Applied Analysis and Complex Dynamical Systems

International Innovation Center

Program Overview

Mission and Scope of the Program

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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 (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".

Our objective in education is to foster and develop innovative young researchers that will become leaders in these novel fields of study. The COE program provides significant opportunities for such development on the job, promoting these young scientists' broad perspectives, creativity, and a strong will in preparation for their entrance into the global research community.

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.

Research and Education Objectives

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Introduction

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 questions 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 complex 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. The recent trend of global warming has demanded the development of a model for an atmosphere-ocean system that enables the long-term prediction of global climate change. To be comprehensive and highly reliable, such models must be designed based on an explicit, comprehensive theory. The elementary processes that play crucial roles in this model have been well studied in Mechanical Engineering. For example, in the field of Fluid Mechanics, research on heat transfer through turbulent structures has been a focus of interest, resulting in numerous significant findings. This turbulent convective heat-transfer phenomenon is exactly what plays an essential role in processes such as long-term climate change. Building a model of an atmosphere-ocean system based on such knowledge is an important research subject for this Complex Systems Mechanical Engineering. With such a phenomenon as global climate change, new difficulties arise in regard to the uncertainty in prediction that naturally accompanies such a large system. Development of new analytical and modeling procedures to deal with these problems is an important item on the COE’s agenda.

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.

As always, education is a top priority at Kyoto University. Through guidance on-the-research training framework, which has long been a staple of the education system here, we will develop young researchers with profound prospective, broad vision, and highly specialized skills who will actively create novel research fields and continue to work at the frontiers of science.

Research program

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. 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.

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.

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.

Education program for young researchers

One of the primary roles of the 21st Century COE Program is to develop superior young researchers in those fields. In this program, we will employ Kyoto University's tradition of on-the-research training to develop young researchers with broad perspectives and highly specialized skills who possess the ability and courage to act as trailblazers in a novel field of study. Various new systems and programs will be prepared for this purpose.

Joint Interdisciplinary research program

To improve the research capabilities of those in the doctoral course, instead of a traditional education style of unidirectional communications relying on lectures, we will prepare and broaden a system to promote education as a joint act of the teacher and student in conducting research, examining a variety of viewpoints, and deciding upon experimental objectives and procedures. In addition to the joint research that has occurred in the past under the tutelage of a single instructor, a new system designated as the Apprenticeship program is being established. In this system, a student is allowed to participate in joint research unrelated to the department or course to which he or she belongs, including overseas research projects, for a set period of time. In addition, the student will be given opportunities to interact with instructors in other disciplines and participate in their research.

Fellowship program

Young researchers, post-doctoral research fellows and graduate school doctoral students, will be provided with comprehensive support for their research activities, including expenses for research, travels associated with joint study, and domestic and international conferences, so that they will be able to focus on their high-level research as independent researchers.

Public education program

The field of Mechanical Engineering is currently undergoing a paradigm shift, from mechanical systems that emphasize efficiency alone, to those that take a balance between harmony with environments and high productivity. Thus, engineers are now being asked to understand mechanical engineering in the context of complex systems. The COE will offer a recurrent course, open to the public, entitled "Complex Systems Mechanical Engineering." This course will be offered in several cities throughout Japan. The courses will present a simple description of Complex Systems Mechanical Engineering, and provide training opportunities for researchers and engineers who are struggling with relevant problems and seeking a systematic new understanding of mechanical engineering. This program will collaborate with the alumni organization for mechanical systems courses, which have long been active in community outreach.

Research Program for Complex Fluid Mechanics Research Group

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Introduction

We live in an environment surrounded by fluids and encounter a variety of fluid flow phenomena on a daily basis. The scales of these fluid flows vary widely in the range from microns, as seen in the blood flow of living organisms, MEMS (Micro Electromechanical System) or microreactors, to meters in industrial equipment, and to km in the atmosphere or ocean. These fluid flows are caused not only by pressure force, but also by buoyancy, gravitation, centrifugal force, electromagnetic force and other external forces. In most fluid flows, not only momentum transfer, but also heat and mass transfer, chemical reactions and various other factors are involved, which make the fluid flow phenomena highly complex. Accordingly, to understand fluid dynamics in practical flow fields and develop useful fluid technology, we have to identify each of the various factors that constitute complex fluid phenomena and study their basic properties.

Our fluid mechanics research group in the 21st century COE program "Mathematical Modeling and Design Theory of Dynamic Functional Mechanical Systems," involves eight laboratories which belong to three different departments, Mechanical Engineering, Physics and Mechanical Engineering and Aeronautics and Astronautics, and our group together forms a collaboration devoted to the study and modeling of complex fluid flow phenomena. Each member of the group promotes unique fundamental research on complex fluid phenomena and publishes his/her research results through international leading journals and academic exchange. The group also develops two research projects, Turbulence Control System and Atmosphere-Ocean System, related to complex fluid flow phenomena that go beyond the framework of conventional fluid and thermal engineering research. Such themes are most challenging for our mechanical engineers who have a deep knowledge of simultaneous transfer of momentum, heat and mass in fluids. Both researchers in this core group and other visiting researchers from Japan and abroad will take parts in the exciting projects.

Objectives of the complex fluid mechanics research group

Building a true sense of COE for complex fluid mechanics research

Our fluid mechanics research group is not simply a group of researchers engaged in special research projects. Our ultimate objective is to become a legitimate internationally recognized center of excellence for fluid mechanics research that retains a high level of researchers or scientists and provides the latest advanced information of fundamental researches to the world, as well as to invite many excellent researchers from both Japan and abroad. To attain this objective we set the following three targets:

(1) We will actively engage in fundamental researches on complex fluid flow phenomena and present these results in leading international peer-reviewed journals. In this context, we will focus especially on the development of young excellent researchers, nurturing them in the global research community and helping them to get grants to support their researches.

(2) We will host international conferences, invite foreign researchers and dispatch our researchers, to organize collaborations and other international exchange projects to strengthen complex fluid mechanics research, and we will provide new findings to the international community.

(3) In order to establish an interdisciplinary fundamental fluid mechanics research body in our university, we will collaborate with researchers from the Advanced Institute of Fluid Science and Engineering which involves more than 30 staffs in 6 departments of our graduate school of engineering, Kyoto University. We intend to increase the international visibility of Kyoto University complex fluid mechanics research group, aiming that it is recognized as a leader in the international academic field of fluid mechanics.

Research projects of the complex fluid mechanics research group

Current research subjects of the eight laboratories that belong to the complex fluid mechanics research group are summarized as follows:

1) Molecular gas dynamics and its application to complex flows with phase transition
2) Complex two-phase flows by the lattice Boltzmann method
3) Plasma-surface interactions on planar and microstructural feature surfaces in space and industrial plasma environments
4) Dynamical roles of elementary vortices in heat and mass transfer in turbulence
5) Turbulent transport phenomena in environmental and industrial flows
6) Transition to turbulence in shear flows. Analysis on complex thermal convection in rotating systems and its application to turbulence control.
7) Complex fluid phenomena with thermal radiation and/or phase changes
8) Complex thermofluid phenomena in microthermal systems

To exploit maximally the research specialties of each laboratory, our group has focused on two subjects: 1) development of turbulence control system, and 2) modeling of atmosphere-ocean system. These two projects are briefly introduced below.

Development of turbulence control system

For the optimum design of transportation machines such as airplanes, vehicles, and ships and energy equipment such as gas turbines and chemical reactors, it is important to fully understand the turbulence structure near the wall and to develop technology for controlling this turbulence. Particularly important are reduction of the friction drag acting the transportation machines, the efficient promotion of mixing and reaction in reactors, and the control of heat exchange rate in combustors. Resolution of these issues requires clarification of complex fluid flow phenomena associated with heat and mass transfer. Furthermore, surface treatment of the wall at the nano-level may be required to reduce friction drag or to promote heat and mass transfer. Accordingly, the main focus of our project is on the elucidation of these complex turbulence phenomena and integration of all the information obtained through such investigations, to provide knowledge useful for developing turbulence control technology. Therefore, this project is clearly distinct from the empirical trial and error researches currently used to develop such systems. Figure 1 illustrates the specific aspect of turbulence control system which some members of our fluid

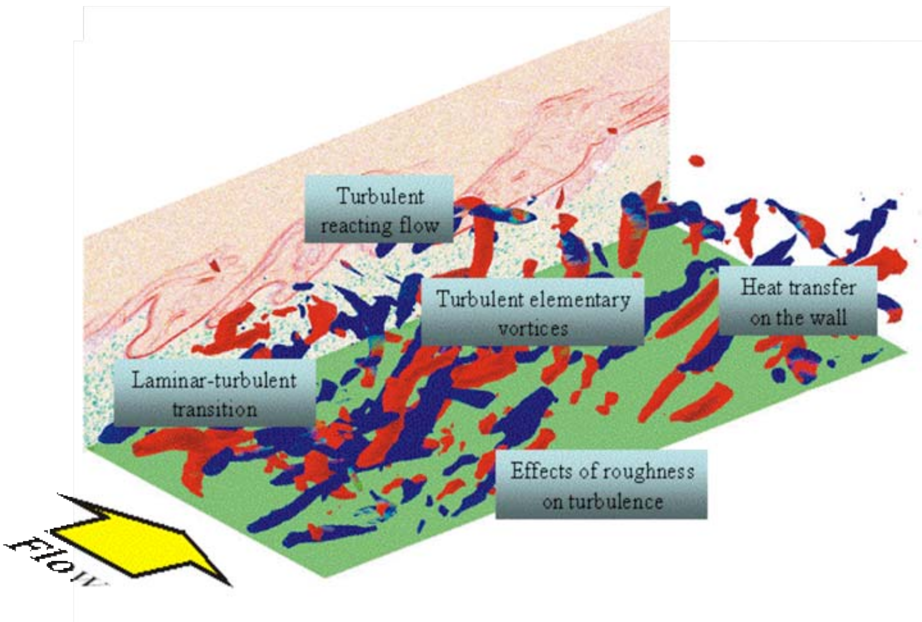

Figure 1. Research project on turbulence control

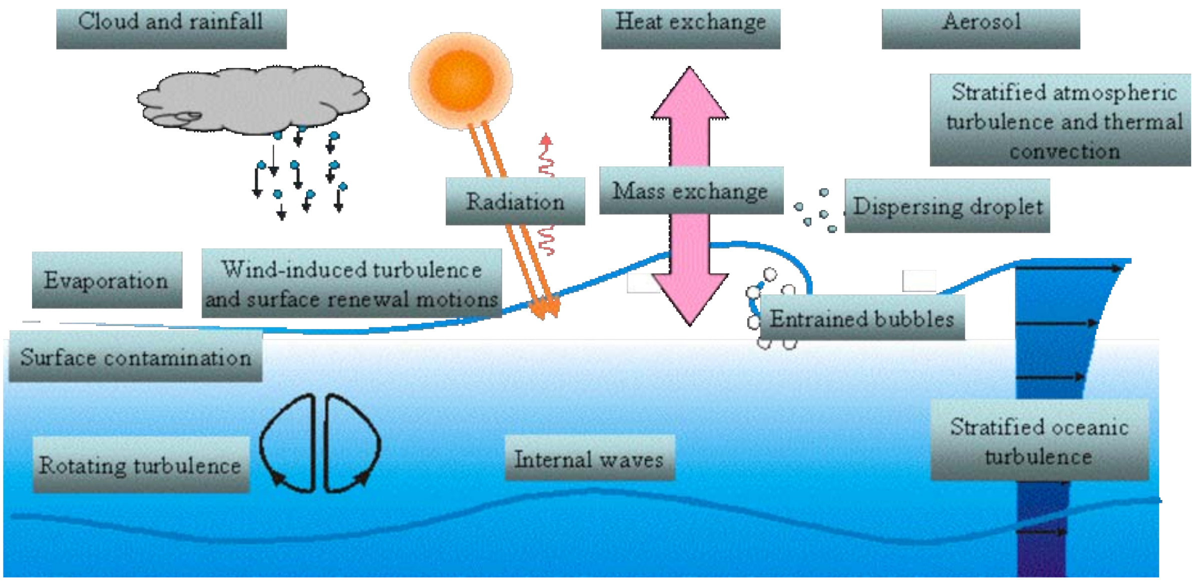

Figure 2. Research project on atmosphere-ocean system

mechanics research group are focusing.

Modeling of atmosphere-ocean system

Global warming is mainly caused by carbon dioxide (CO_2) generated in the course of fossil-fuel burning. It is an important issue for environmental researchers to precisely forecast the greenhouse effect, resulting in the promotion of large-scale national projects such as the "Earth Simulator". This global warming forecast has been conducted using a General Circulation Model (GCM), composed of various sub-models that represent the complex turbulent transport phenomena associated with heat, mass and momentum transfer occurring in atmosphere and oceans. The numerical simulation by the GCM based on the sub-models provides future scenarios on global warming. This simulation method can be used not only for this application, but also for forecasting several unusual climate changes such as localized torrential downpours, droughts, heat island and so on. However, the specific physical sub-models used for the current GCM have not been fully examined, and so there remains a risk of significant errors in forecasting global warming and local climate changes. The reliability of the sub-models for estimating heat, mass and momentum transfer at the air-sea and air-land boundaries is especially poor. When we look at the method used in the GCM for estimating exchange rate of mass (CO_2, etc.) between the atmosphere and ocean, for example, heat and mass flux is expressed simply by the product of concentration difference between the atmosphere and ocean and the mass transfer velocity (referred to as the mass transfer coefficient in engineering field). The mass transfer velocity is, however, strongly influenced by several factors, including the turbulence structure near the air-sea interface, the density stratification, the entrained air bubbles and dispersed droplets due to intense wave breaking, surface contamination and others. If the transfer velocity model does not accurately express these effects, an estimate of mass exchange rate between the atmosphere and ocean may easily result in the error of about 1 PgC per year. That is, even if we integrate the mass flux over the whole ocean surface and evaluate the global mass exchange rate between the atmosphere and ocean, the predicted scenario for global warming will be far from reality, unless the sub-models used as their bases are reliable. Furthermore, to estimate the mass exchange rate between the atmosphere and land is even far more difficult than that between the atmosphere and ocean, due to the influence of land-based vegetation. We can only indirectly estimate the land uptake by taking the mass balance of carbon between ocean uptake and absorption into atmosphere. Therefore, it is of great importance to precisely estimate the atmosphere-ocean flux, in order to accurately forecast the global warming.

Currently, researches related to such global warming forecasts are considered to fall under the category of atmospheric or marine science, and only geophysicists who specialize in meteorology or oceanography are conducting such studies. However, complex fluid transport phenomena in atmospheric and oceanic turbulence are important research subjects that can and should be addressed by mechanical engineers, who can easily treat simultaneous momentum, heat and mass transfer. A number of phenomena, including heat and mass transfer between atmosphere and ocean and between atmosphere and land, turbulent heat and mass transfer with evaporation and radiation in the atmosphere and ocean, the effects of clouds, rain and aerosols on heat and mass transfer, the density stratification effects on turbulent eddy motions in the atmosphere and ocean, interact with one another, together composing the complex atmospheric and oceanic system. Our fluid mechanics group members are specialized at investigating these complex fluid flow phenomena. To create a reliable model for this atmosphere and ocean system, we will study in detail the underlying turbulence and transport phenomena using the most advanced techniques available in the present thermal and fluid engineering. The first two or three years of our project will be devoted to the study on the heat and mass transfer mechanism between the atmosphere and ocean. The project developing component models on which a more reliable climate model can be built is clearly distinctive in comparison to the current research underway, which only conducts global numerical forecasts based on unreliable component sub-models. Figure 2 illustrates the elemental fluid flow phenomena in the atmosphere and the ocean system that individual laboratories of our complex fluid mechanics research group can treat.

Research Program for Complex System Control and Design Group

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Introduction

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. To this end, we have focused on the following three key subjects:

(1) To elucidate adaptive system structure and dynamics;
(2) To elucidate adaptive system structure principles; and
(3) To develop an adaptive system.

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 3) 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.

Objective: To establish the concept of control design based on dynamical

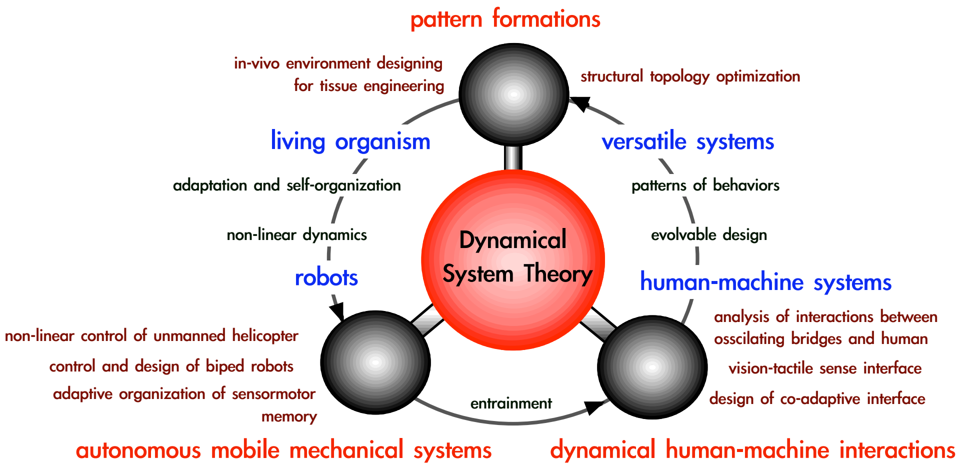

Figure 3. An overview of the group

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 4). 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.

Outline of research programs of individual subjects

In this section, we briefly explain our group's research programs.

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

The stability of motion in multi-dimensional dynamical systems represents a mechanism in which their behaviors are compressed into low dimensional dynamics through interaction among their constituent elements. In autonomous mobile mechanical system design, the degree of freedom is compressed in the manner that even involves a degree of freedom of the environment in addition to that intrinsic to the robot, which creates qualitative stability (isomorphism) of motion patterns. At the same time, by generating versatility within, adaptation to the environment is created. Alternate repetition of the order-structure-formation phase and collapse phase underlies the adaptation of an autonomous mobile mechanical system, which we consider to represent a complex system.

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. The group develops this mechanism further into one that can create voluntary movements. As an example, the group has shown that by demonstrating the robot's motion and posture control when turning to an intended direction over various turning radii.

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-

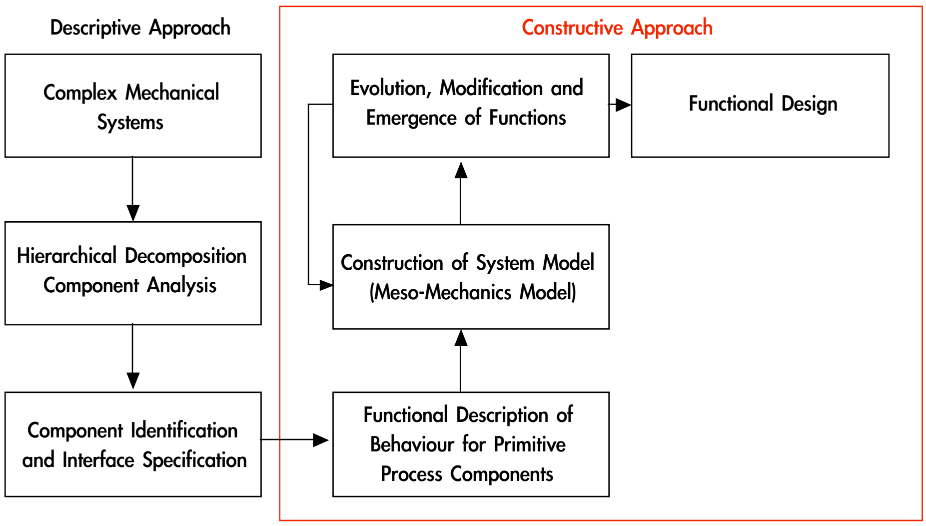

Figure 4. Constructive approach

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. However, true social behavior in robots is probably not possible, given the limitations on abilities to construct and use an objective external environment model to forecast accurately the behavior of other people. 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. In this way, the robot can trace and keep an object in its line of vision by way of adaptive body movement, and learn new strategies for doing so through experience.

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, and have also performed mechanical model analysis of the dynamics of the interactions involved in the synchronization.

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. Furthermore, through the analysis on the velocity profile of hand and finger movement in grasping motion on a virtual platform, they aim to elucidate the general principles on the selection and combination of degrees of freedom depending on the object type, as well as the segmentation of motions.

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, and to share "isomorphism of tasks" through mutual adjustment of their individual behavior.

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. It is an extremely important challenge to elucidate the dynamics governing the process in which a macroscopic order emerges and disintegrates controlling the degrees of freedom in such an organization or group consisting of multiple elements. Such knowledge may be utilized for the design of a dynamic and functional mechanical structure system.

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. In an initial experiment to observe the structure and function of cartilage cells and tissues without imposing any dynamic environment conditions, ES cells did not differentiate into cartilage cells; however, the group aims to confirm that, when a dynamic state of the environment is altered, morphology and function are enhanced to organize and adapt to the environmental changes. 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 emergence of hierarchies in the interaction fields, and 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. It is, therefore, suitable for structures that cannot be composed entirely of rigid structures. 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. They also have developed this theory into multi-stage design optimization with the intention of designing a method of the functional mechanical structure system for multi-physics phenomenon that deals with the physical coupling phenomena.

PROPERTIES OF MATERIALS WITH COMPLEX STRUCTURE

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Introduction

From the viewpoint of conventional "complex science", the subject of our group may give a feeling that something does not in a place. Among four groups in the COE program, fewest research works have been done on the mechanical behavior of materials in terms of the conventional "complex science". However, the "modeling of materials" requires the concept of "complexity" because the rich behavior stems from its "compound understructure". In this program, we will discuss the modeling of materials on the basis of "complex science in a broad sense". We do not confine our activity in the conventional research subject on the materials behavior in the mechanical engineering in order to reconstruct the fundamentals for future development in the materials science.

Materials science in mechanical engineering

The study targeted here is centered on the modeling of materials system (including behavior based on the quantum mechanics), which gives the fundamental idea on the design, production, service, and disposition (recycling) of "machine".

In this COE program, "the complex machine systems" are defined as:

(A) Systems that constitute numerous elements with complex interaction, and/or

(B) Systems that shows various structures under environmental influences.

In other words, "complexity" can be construed as various phenomena and structures that arise through interaction of numerous elements under an external environment. Generally, materials that constitute a machine have their own internal structures. Therefore, in the "complex science", material is regarded as a system made up with "elements forming an internal structure" and through "interaction of the elements".

Figure 5 shows research subjects on materials behavior in the mechanical engineering. The subjects are classified

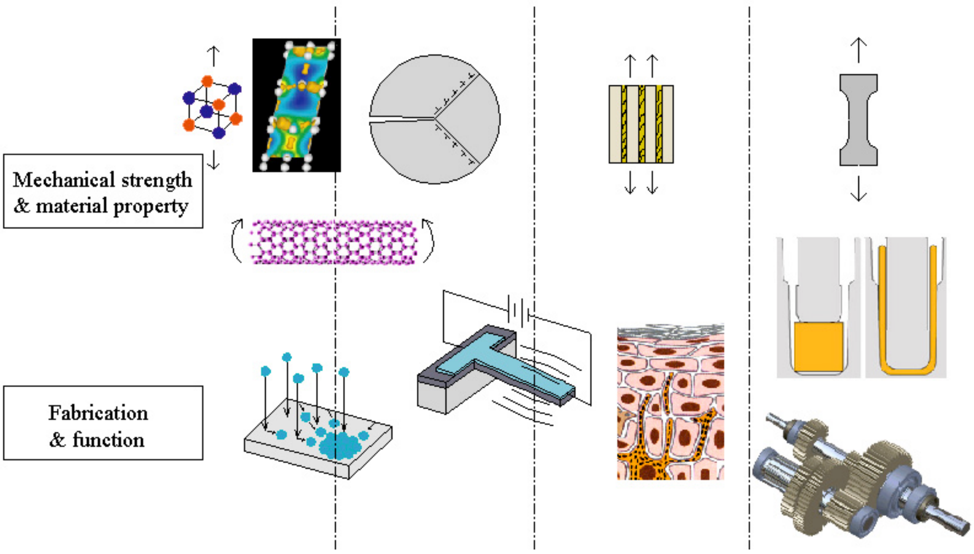

Figure 5. Research subjects on materials behavior

into 4 levels, (1) atomic, (2) lattice, (3) cell (grain), and (4) structure levels, according to the dimension of elements. While the basic behavior is illustrated in the upper column, the fabrication process and function of components are shown in the lower column. Although the focus is put on the mechanical strength in the conventional mechanical engineering, other physical properties (piezoelectric, magnetic, electric ones and so on) become important in the development of advanced machines and devices. Our group is investigating the multi-physical aspects of materials behavior. Since the variety of the behavior stems from the understructures, the material itself should be understood as a complex system consisted of multiple elements (microstructures). In view of the rapid progress in computers in recent years, fundamental knowledge obtained by experiments and analyses is integrated in the modeling of system, which gives us insight of not only scientific information but also wisdom for the design and control of industrial products.

As pointed out by the project leader, to comprehend the "complexity" consists of two processes, to identify the elements and to make clear their interaction. Focusing on the atomic level, the modeling and simulation based on the concept are briefly explained below.

At the atomic level, the element is an atom, and the interaction is governed by the quantum mechanics. The active research works are conducted on the low-dimensional nano-structured components such as nano-dot, nano-wire, and nano-film. The numerical simulation are conducted by the methods of molecular dynamics, molecular orbital, Metropolis (Monte Carlo) on the basis of the first principle. The large-scale simulation based on empirical interatomic potential is included in this level.

As the reader can understand from the example of atomic level, the key point in this project is to understand the complex substructure from the viewpoint of the elements and their interaction. This clearly contributes to enhance the multi-scale understanding of materials.

Research plan

As mentioned above, a complex materials study has a wide range of themes. If all the themes are targeted in this program, it may cause desultory results. Therefore, considering the future of mechanical engineering and the past specialization areas of members in the group, the subjects are selected.

The major frontier in the mechanical engineering can be found in the nano- and micro-meter scales. In this program, therefore, we will focus on the research works at the atomic, and cell levels. Table 1 and Figure 6 summarize the young researchers selected and their subjects in 2003 fiscal year supported by the frontier research program. It clearly shows the key areas of this program. This year, we focus on:

(1) Analysis of mechanical strength and physical properties on the atomic level;
(2) Formation of functional thin film and its application to structure;
(3) Analysis of mechanical strength of composite materials.

The emphasis on (3) will be reduced next year and the emphasis will be shifted to

(4) Biomechanics and regenerative medicine.

Accordingly, in the entire program (five years), the main targets will be (1), (2) and (4) in the diagonal line from the upper left to the lower right of the figure. Every year the researchers and themes for the frontier research will be evaluated. Furthermore, as the program progresses, meetings to exchange information in the materials group are planned, and should develop joint research and cooperative relationships among researchers. Cooperation beyond fields and scales is expected *e.g.* piezoelectric materials -> Formation of thin film -> Structure -> Application to living organisms.

On the other hand, to strengthen cooperation with foreign researchers, exchanges (dispatch/ invitation) and joint research are planned.

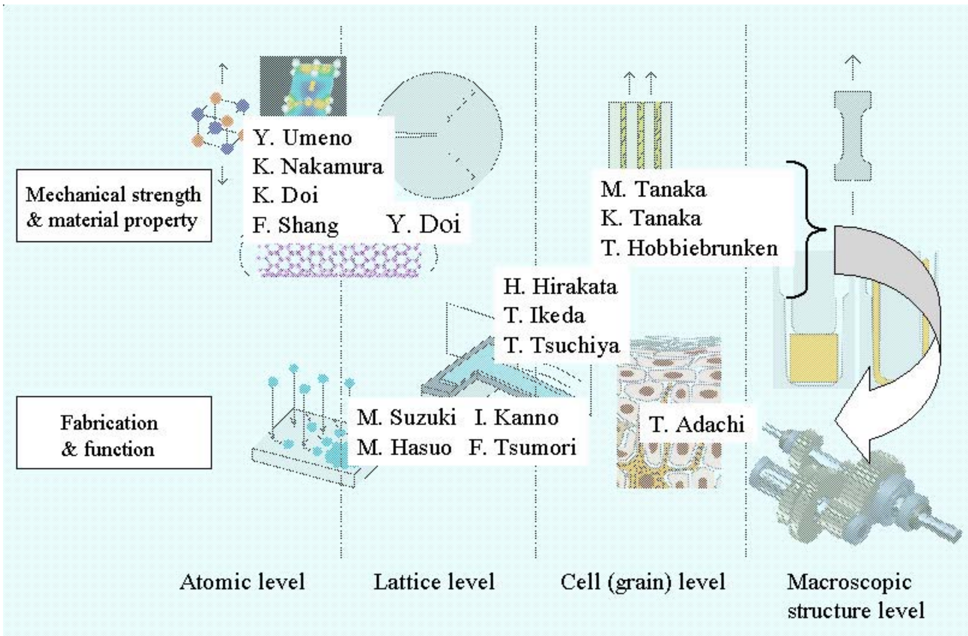

Figure 6. Researchers in frontier research project

Conclusion

Mechanical engineering has a long history and as the field can be regarded as a mature, but "machines" are transforming themselves day by day. Currently, machines (systems) that by definition didn't exist yesterday are being continuously produced. Materials constituting machines form the foundation of the present time and it is indispensable for a deep understanding of the complicated internal structures (systems) that materials themselves have in order to correspond to functional demand. The first-stage objective

Researcher	Theme
Y. Umeno	Analysis on unstable deformation of solids by collective motion of atoms
M. Tanaka	Establishment of Complex System Simulation for Fracture Behavior of Fiber Reinforced Composite Materials
I. Kannno	Manipulation of droplets for molecular tapestry
M. Suzuki	Control of nano-morphology and mechanical properties of compound thin films using dynamic oblique deposition
K. Tanaka	Development of testing method for environmental mechanical properties of composite materials and evaluation of the localized environmental effects
M. Hasuo	Photo-induced changes of semiconductor thin films on TiO_2
F. Tsumori	Microstructure Design of Powder Particles under Magnetic Field with Discrete Element Method
H. Hirakata	Strength of microstructured small components
K. Nakamura	Analysis of Vibrational Behavior in Solid Materials by Perturbational Approach to Electronic Wave Function
K. Doi	Theoretical study on electronic states of bulk, surface, and interface under external fields in electronic devices
T. Hobbiebrunken	Mesoscopic Failure Prediction of Composite Materials A Multi-scale Analysis
F. Shang	Molecular Dynamics study on the internal stress problem of piezoelectric thin films
Y. Doi	The fracture of materials due to energy localization with lattice scale
T. Tsuchiya	Development of high-cycle fatigue tester and mechanical properties database for MEMS/NEMS materials
T. Adachi	Multi-scale modeling and simulation of bone regeneration/functional adaptation as a complex biological system

Table 1. Themes in frontier research project

of this program is to grasp the nature and properties of materials that have internal structures by clarifying elements and their dynamical interaction. The second stage to develop a comprehensive and systematic understanding of "Mechanics of materials": Raw material => member => structure (physical properties -> function). One goal is to establish a common basis for dealing with "complexity" by reconsidering deformation/fracture and function from an atomic level and understanding the influence of inhomogeneity. The third stage is to develop fields in cooperation with other groups, while recognizing the internal structure of each field. We hope that this program will show a new direction for "Materials science in mechanical engineering".