Overview of the Research Activity of the COE

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1. Prolog- In Search of "*Soft Machinery*"

Modern society needs machinery that harmonizes and coexists with the environment rather than conventional machinery, which focuses on achieving good efficiency. Machinery that harmonizes and adapts to the environment is called "Soft Machinery". Complex systems science has provided an understanding of complex systems, which are composed of numerous elements that non-linearly interact with each other to spontaneously create their behaviors to adapt to a changing environment. Actually, this "Soft Machinery" is just such a complex system, which exhibits various behaviors depending on the environment. The 21st Century COE Program for Complex Functional Mechanical Systems employs mathematical models and design methodology to conduct fundamental research on "Soft Machinery" in collaboration with engineering and science. This collaboration involves three mechanical departments within the Faculty of Engineering (Department of Mechanical Engineering and Science, Department of Micro Engineering, and Department of Aeronautics and Astronautics), the Department of Applied Analysis and Complex Dynamical Systems of the Graduate School of Informatics, which boasts excellent research achievements in complex systems science, and the Kyoto University International Innovation Center.

2. Mechanical Engineering from a "*Complexity*" Viewpoint

Mechanical engineering is an academic field with a long history, which encompasses established fields such as materials engineering, micromechanics, thermal engineering, fluid dynamics, systems engineering, and control engineering. Each of which has active research activities. By rethinking mechanical engineering from a "complexity" point of view, our Center aims to further develop mechanical engineering to an even more attractive research field, which incorporates soft machinery as well as environmental issues and social systems as important research targets. Below is a description of some of our research projects.

Flow is everywhere such as water flowing in a creek and a windy breeze. A slow and calm flow changes into a turbulent flow, which is an irregular and complex flow, as it gains speed. Thus, a long-standing issue of fluid dynamics is to control this turbulent flow to make it a regular flow. The first thing necessary to control a turbulent flow is to understand the features of turbulent flow as a complex system. In other words, the temporal-spatial structure behind complex motions - a structure that gives a skeleton to the turbulent flow - must be understood. However, because turbulent motion is a complex motion, discovering the structural skeleton of the turbulent flow has been extremely difficult. In a recent study at our Center, an unstable periodic motion, which was embedded in the turbulent motion such as a turbulent Couette flow, was discovered. This discovery revealed that this unstable periodic motion controls the temporal-spatial structure and the statistical properties of the turbulent flow. A research project, which is a complete departure from conventional turbulence control research, has been undertaken in collaboration with control engineers in order to control turbulent flow by stabilizing the unstable periodic motion (Fig. 1).

One of the most important tasks for engineers is to devise a technological solution to global warming. It is well known that the increase of carbon dioxide in the atmosphere is the cause of global warming, and the most significant factor for determining the total amount of carbon dioxide in the atmosphere is the carbon dioxide inclusion into seawater through turbulence at the interface between the ocean and the atmosphere. In order to develop a program to reliably forecast long-term climate change, which is a large-scale complex phenomenon, it is essential to build reliable models of the major contributing

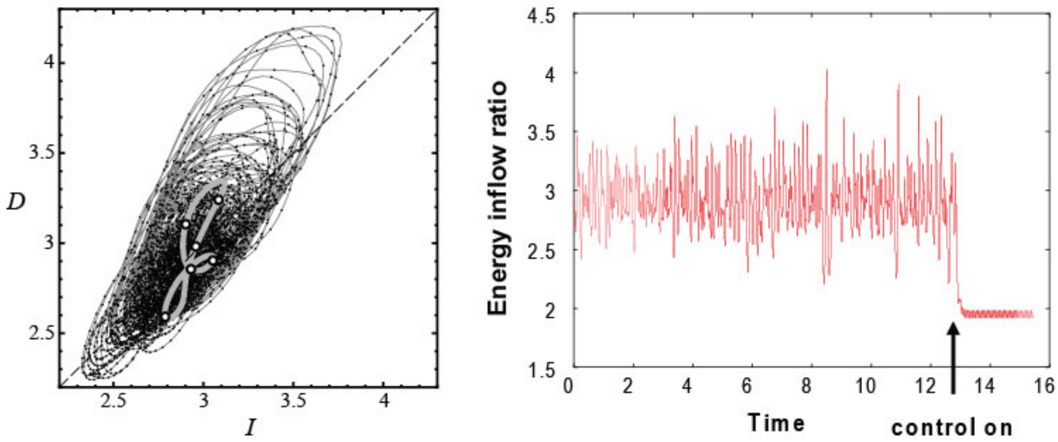

Figure 1: Unstable periodic orbit embedded in a turbulent flow and its control. (a) Unstable periodic orbit embedded in a turbulent flow. When turbulent flow is drawn on a two-dimensional plane, it shows a complex trajectory with an unstable periodic orbit embedded within. (b) Control of turbulent flow. When an unstable periodic orbit is controlled and stabilized, turbulence is suppressed, and a regular flow is realized.

factors. We have been actively conducting research in the field of fluid dynamics on turbulent structures as well as heat and mass transfer at the gas-liquid interface, and much knowledge has been accumulated. Our Center has leveraged this knowledge to gather detailed experimental data in order to build a precise model of the carbon dioxide transport coefficient through turbulence transportation. This new model provides a more reliable forecast value for carbon absorption from the atmosphere to the ocean than the conventional phenomenological model. Additionally, in collaboration with meteorologists, we are currently developing a long-term climate change prediction program that incorporates this new model.

Another goal of mechanical engineering is to build a robot capable of mimicking sophisticated movements similar to real animals. An animal moves in a very sophisticated manner according to changes in its environment. For instance, a four-legged animal naturally switches from walking to trotting as its walking speed changes. Neurophysiology has discovered that the neural circuit in the spinal cord spontaneously generates a rhythmic command, which moves the four legs. However, a thorough understanding of the mechanism for this sophisticated movement, which is generated through the interactions between the neural circuit and the musculoskeletal system, has yet to be obtained. Our Center has developed a walking control system that drives a reciprocating movement of the legs using nonlinear oscillators, which then regulate the movement of the legs using a signal from the sensors at the tips of the toes. We have developed a four-legged robot equipped with this control system, and achieved sophisticated walking such that its leg movement automatically switches from walking to trotting as its walking speed increases. Our Center is currently conducting joint research between robot engineers and physiologists in order to understand the control mechanism of animals' sophisticated movements (Fig. 2).

3. Systematization of *Complex Systems Mechanical Engineering*

Our Center is planning to *systematize complex systems mechanical engineering* based on the specific aforementioned research results. We define *complex systems mechanical engineering* as a cross-disciplinary research field within mechanical engineering, which addresses complex mechanical phenomena and mechanical systems from a *complexity* viewpoint. Our research objectives are to understand and use *complexity* (Fig. 3). These objectives will be achieved by (1) comprehending universal principles and core structures behind complex behaviors, and clarifying the mechanisms for spontaneous formulation of structures, and (2) developing a methodology to control complex and unstable behaviors by

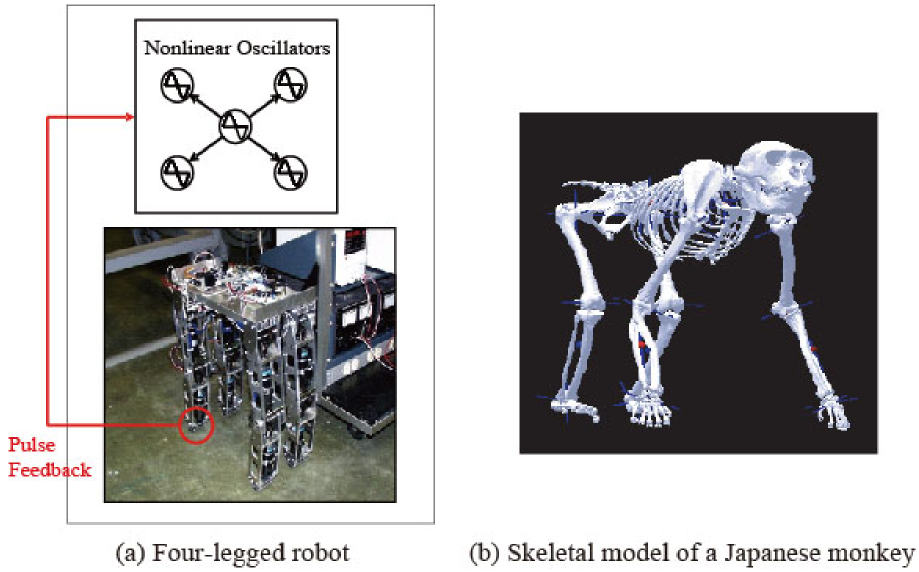

Figure 2: Walking motions of an animal and a machine. (a) Four-legged robot. Leg motions automatically change from walking to trotting as the walking speed increases. (b) Skeletal model of a Japanese monkey. Neural circuit model and a muscle model are combined to analyze the mechanism of walking.

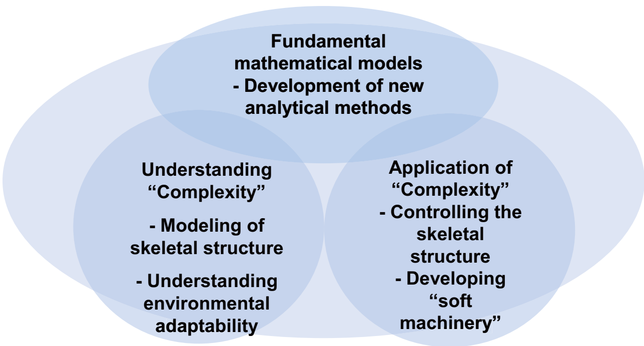

Figure 3: Complex Systems Mechanical Engineering

manipulating the core structures as well as developing a design methodology for "soft machines", which are capable of adapting to a changing environment by altering their internal structures.

4. Center of Collaborative Research for Fundamental Studies

One of our goals is to create an environment such that researchers of various mechanical systems, spanning fluid dynamics to system engineering, spontaneously develop organic collaborative relationships, while individually and freely pursuing their unique research. A mode of research activities where participating researchers conduct their research individually and freely, but are aware of common issues is called a *collaborative research for the fundamental study*. In our Center, these collaborative relationships should develop awareness of the common issue of *complexity*, and thereby form the cross-disciplinary mechanical engineering field of *Complex Systems Mechanical Engineering*. To create this type of environment, it is crucial to provide abundant opportunities for researchers from different fields to interact with each other. To this end, we routinely host seminars to encourage information exchange among researchers through our enhanced visiting researcher system. Moreover, over the last three years, we have invited over 100 researchers from abroad. Furthermore, we are regularly holding a symposium series of the 21st Century COE Program, "Mathematical Models and Design Methodology for Dynamic

Figure 4: Katsura Int'tech Center is interdisciplinary research facilities with five advanced research institutes, and is located on the Katsura campus

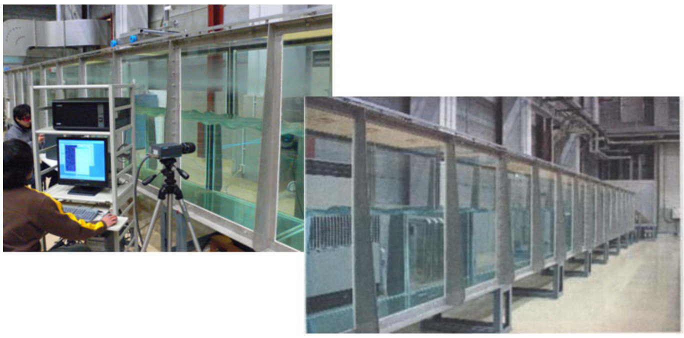

Figure 5: Wind-wave tank (30 m long and 0.6 m wide) installed at the Fluid Dynamics Advanced Research Institute. This tank is used to study turbulent structure and heat and mass transfer at the gas-liquid interface.

Functional Mechanical Systems", which is designed as a forum of research exchange for researchers at our Center. In addition, we are promoting interdisciplinary research among different departments and different faculties within Kyoto University with our interdisciplinary research facilities, Katsura Int'tech Center, as the focal point. At the Katsura Int'tech Center in collaboration with two of its Advanced Research Institutes, we have established large-scale experimental facilities for collaborative research projects that span across different departments and faculties (Figs. 4 and 5).

Furthermore, we are conducting our research activities internationally through our overseas center, the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, which is an international research center operated jointly by eighteen countries from around the world. Every year, we hold 21st Century COE International Workshop, and invite prominent researchers from around the world to impart information on our activities and to have our activities evaluated by these invited researchers. The results of this workshop are published across the globe as an IIASA Report (Fig. 6). We are also actively engaging in research exchanges with overseas research institutes, which support *Complex Systems Mechanical Engineering*. Moreover, we hosted a workshop on control engineering with the Technical University of Munich (Germany) in October 2005 and a workshop on fluid dynamics with the University of Birmingham (UK) in September 2006.

Figure 6: First IIASA - Kyoto University 21st Century Seminar held on June 28 - 29, 2004. This photo was taken at the International Institute for Applied Systems Analysis where the seminar was held.

5. On-The-Research Training – About Training Young Researchers

Another goal of our Center is to train young researchers capable of pioneering new research fields. One of the most effective training methods to reach this goal is to let young researchers initiate network-building for their research exchanges by taking leadership roles in their activities at our Center Specifically, to this end, we have implemented the Frontier Research Assistance Program, which is a competitive research grant system for young researchers. This program provides financial assistance to young researchers who take an initiative in their research, and approximately 40 to 50 % of our annual budget is allocated for this program. We strongly encourage young researchers to use this research assistance pro-

Figure 7: 21st Century Frontier Seminar held as part of the Ph.D. program. Discussions were conducted in a form of a debate between participating groups, and everyone voted on the winner. (AV Hall at a Kyoto University Library, December 21, 2006)

gram to participate in international conferences and to make presentations to prominent research groups abroad on their current research projects so that these young researchers obtain advice and build an international research network. Moreover, we ask visiting researchers, who are part of our visiting researchers program, to provide plenty of opportunities to directly meet with our Ph.D. students for discussions and to provide advice. Furthermore, we offer a lecture series on *Complex Systems Mechanical Engineering* in the Ph.D. program as well as regularly schedule a recurring lecture series on *Complex Systems Mechanical Engineering* for engineers and scientists in industry. The latter lecture series strives to convey to young researchers and engineers the vivid atmosphere of frontline research in *Complex Systems Mechanical Engineering*, which is a developing research field. The 21st Century COE Frontier Seminars, which are part of the Ph.D. Program, are seminars where several students assemble a team, form their own research plan on a predetermined topic, present their results, and these results are evaluated (see Fig. 7). With these seminars, we strive to cultivate not only the ability to pursue a research project, but also the ability to collaborate with other researchers as well as to provide opportunities to give presentations. With their future international activities in mind, all discussions are conducted in English. Furthermore, Ph.D. students must take the initiative to plan and execute their own research exchange tours at universities and research institutes abroad in order to present their research and build networks. To date, young researchers have held research exchanges in the field of micromechanics with three universities: University of Freiburg (Germany), University of Michigan (U.S.A), and Kyoto University in 2005 and 2006. Additionally, a workshop was jointly held with the Korea Advanced Institute of Science and Technology (South Korea) in 2006 in the fields of materials dynamics and control system engineering.

6. Epilogue- In the Tradition of Autonomy in Research and Academic Freedom

Among the researchers autonomously and freely conducting fundamental studies, an organic relationship emerges spontaneously, which tends to create a high level of activity towards a common research objective. This relationship is the basis of research activities at a university. Our Center has been carrying out our activities in order to create such a research environment. Our endeavors have been supported by the atmosphere of interdisciplinary and fundamental collaborative research cultivated by Kyoto University's tradition of autonomy in research and academic freedom. In order to further our tradition, we would like to continue our endeavors.

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