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Theory and Applications of Complex Systems and Robust Control

Tsinghua University Press

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Preface

The *Japan-China joint workshop on control* was initiated in the August of 2004. The first and second joint workshops were held in Beijing and Harbin of China, respectively. The third joint workshop moved to Japan and was held on the 18th of August, 2009 in Fukuoka International Conference Center, as a part of SICE Annual Conference of 2009. The third joint workshop was co-sponsored by the Control Division of Society of Instrument and Control Engineers, Japan (SICE) and the Technical Committee on Control Theory of Chinese Association of Automation, China (CAA).

This joint workshop provides a forum for the scientists and engineers from both Japan and China, who are active in the field of control engineering, to present their most recent research outcomes and to exchange as well as to share their visions, ideas on control engineering. The focus of the third joint workshop is on complex systems and robust control. We are privileged that many world famous scholars from both sides took part in this workshop and delivered four keynote speeches. After a full day active discussion, all participants felt that the presentations in the workshop were both interesting and inspiring. The publication of a book of selected papers from this joint workshop will undoubtedly contribute to the control community of the world. So, the Steering Committee decided to publish this book.

This book is organized as two parts: one on complex systems and another on robust control.

Part I covers the theory and applications of complex systems. Contained in this part are brain science and control theory, target tracking with motion sensors, network failure locating, algebraic solution method for Hamilton-Jacobi equation, stochastic optimal control based on event-based optimization, frequency response computation of controlled spatio-temporal systems, stability analysis of nonlinear systems, nonlinear feedback control for saturated systems, estimation of locally input-to-state stability properties, torque balancing of spark-ignition (SI) engines, experimental validation of air-fuel ratio control algorithms, energy-based control for underactuated mechanical systems, bilateral control for double-screw-drive forceps teleoperation system and identification of respiratory system.

Part II is on the recent development of theory and applications of robust control. It consists of neo-robust control theory, robust hydraulic automatic gauge control in cold strip mill, robust adaptive control of robotic manipulators, delay-dependent robust stability criteria and robust control of active suspension for vehicles.

Owing to the rapid advances in modern technologies, the control systems are getting more and more complicated, in which not only the traditional continuous dynamics but also discrete-event as well as switching of system topology exist. Further, the working environment of control systems is getting much more uncertain. Moreover, the modeling and control of bio-systems, medical support systems are developing steadily. All these new trends require the establishment of new concepts, analysis and design methodologies beyond the existing ones. It is hoped that the publication of this book will make a significant contribution toward this goal.

Finally, we would like to thank Dr. Kai Zheng and Dr. Jiangyan Zhang for their help in the handling of contributed papers.

Jie Huang
Kang-Zhi Liu
Yoshito Ohta
March 25, 2010

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Part I

Theory and Applications of Complex Systems

Towards a Common Principle of Biological Control
—— How Control Weaves the String of Life

Hidenori Kimura[1], Shingo Shimoda[1], Lu Gaohua[1] and Reiko J. Tanaka[2]

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1 Introduction

Control is a fundamental function of the living organism that works in all aspects of life. Control mechanism is ubiquitously built-in at all levels of body structures of living organisms and works all the time to support life. Without control, no life survives. In fact, most of the human diseases are ascribed to some sort of malfunctions of control mechanism of the human body that was carried out by neuronal, endocrine and immune systems. The crucial importance of control is now getting clearer in the rapid progress of the contemporary life sciences and many serious issues of life sciences turned out to be connected to control.

The control research in life science, however, is still being carried out in fragmental ways without any unifying discipline and/or coherent paradigm of the biological control. It is scattered in various fields of life sciences without serious attempt to unify them.

Our aim is to establish a new paradigm of biological control that is common to various biological controls beyond the notion of feedback, feedforward, noise reduction etc. These notions represent the common framework of biological control with control engineering. In other words, we have already exploited some common frameworks of biological and man-made controls. What we need for future progress of biological control research is to find a common framework of control inside biology which reflects the specificity of living organisms. In other words, we need a new framework of biological control research that particularly fits biology and is not shared by control engineering. At this stage, we emphasizing the difference between living and man-made systems, rather than emphasizing the common features.

We came across to the notion of *compound control* as a possible new paradigm of biological control. The most salient characteristic difference between man-made machine and living organisms lies in the capability of living organisms to adapt to the environmental changes. Thus, the notion of compound control emphasizes the adaptability of living organism and tries to explain the mechanisms to attain this capability.

Our effort to integrate biology and control theory is motivated by the transdisciplinary integration of different research areas.

2 Control as a transdisciplinary principle

Control engineering was born at almost the same time as modern technology was born in the era of Industrial Revolution. So, it is one of the oldest disciplines of engineering, which is consistent with saying "no machine works without control". Since then, control engineering has been developed in pace with the progress of modern technology and now it reaches a certain level of maturity on which contemporary technology seriously depends, as we notice.

A salient characteristic feature of control engineering lies in its universality in the sense that it is used commonly in almost all areas of engineering. Engineering disciplines are divided into several categories based on the types of energy resources they use; electrical, mechanical, chemical and so on. Control engineering is out of this categorization. It is used indispensably in these fields and sometimes embedded naturally in these disciplines. We find many other such disciplines, apart from control engineering, namely, systems engineering, network engineering, optimization, design engineering, human/machine interface, reliability engineering, and so on. Now, it is natural to divide engineering disciplines into two categories: The one includes those engineering based essentially on the natural sciences whose objectives are to exploit the potentials of Nature for the use of human being, and the other includes those that do not directly related to the Nature, rather related to the artifacts, society and humans.

The disciplines included in the former category tend to concentrate on refining each component of systems and promote each specific technology, so that further ramifications take place. On the other hand, the disciplines in the latter category tend to integrate different disciplines to challenge the problems. We may call the engineering fields contained in the first category *applied engineering*, while those in the second category *pure engineering*. The names come from the fact that the disciplines in the first category are essentially regarded as applications of natural sciences, while those in the second category are independent from natural science and are closed within the engineering world.

The pure engineering, though its origin also dates back to the birth of modern technology, is relatively new and its scientific foundation was established in 1930-40s. Control engineering, as one of the major disciplines in pure engineering, have played fundamental roles in many fields of applied engineering. Since the advent of the pure engineering as an independent scientific discipline, the interplay between pure and applied engineering has generated fertile and novel results. In other words, the two dimensional structure of cross talks between the disciplines of the two categories characterizes the present research paradigm in engineering for solving problems that challenge the modern society, as is illustrated in Fig. 1.

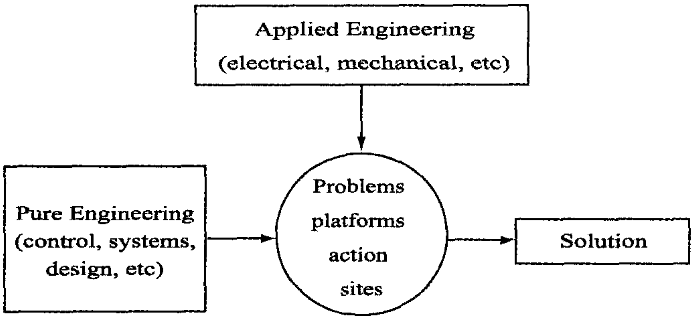

Fig. 1. The Interplay between Pure/Applied Engineering.

3 Histrical remark on the interplay between biology and control theory

Without control, no life survives. In fact, most of the human diseases are ascribed to some sort of malfunctions of control mechanism of the human body that was carried out by neuronal, endocrine and immune systems. The crucial importance of control is now getting clearer in the rapid progress of the contemporary life sciences and many serious issues of life sciences turned out to be connected to control.

At the individual level, motor control has been one of the fundamental issues of brain science with the hope that they give a new insight for understanding the fundamental link between cognition (mind) and action (body). It is also expected to open a new avenue to develop control strategies of the next generation robots. At the tissue or organ level, the metabolic syndrome, a newly identified disease, is identified to be a result of composite effects of metabolic malfunctions, and considered to represent an adverse effect of physiological learning control. Cell differentiation and development are now regarded as the control issues related to genetic regulations. The dominant view for carcinogenesis takes the robustness mechanism of cell regulations seriously. We can list up many other control issues at the cutting edge of life sciences. It is not at all an exaggeration to say that control is a powerful and fundamental key to solve the mystery of life, because control is regarded as *weaving the string of life.*

The ubiquitous existence of control in living organisms suggests a fertile interplay between control engineering (specially, control theory) and biology. Applying Figure 1 to this case leads to Fig. 2.

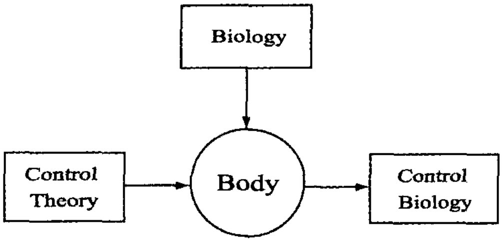

Fig. 2. The Interplay between Biology and Control Theory.

The history of the control research in biology is long and dates back to the late 19th century when French physiologist C. Bernard pointed out that keeping the internal environment (milieu intérieur) constant is of supreme necessity for all living organisms. Later, his idea was elaborated and given physiological basis by W. Cannon who coined the word *homeostasis* to denote the control mechanism for maintaining constancy of the internal environment[1]. After Cannon's work, control became a major area of research in physiology.

Another control aspect was exploited by a British neurologist C. Sherrington who studied various reflexes of neuronal systems extensively and concluded that the animal motions were formed by the combination of elementary reflexes that animals are innately endowed. His thesis laid the basis of neurophysiology and evoked the wide interests in brain motor control. The elementary reflex is strongly connected to feedback control and Sherrington's idea again exhibited the importance of control in biology.

Unfortunately, these control research activities in physiology and neurology have been unrelated and independently pursued, until N. Wiener identified a common principle of control in physiology and neurology. It is *feedback* which has been extensively used in control engineering. This was a great discovery from the view point of knowledge integration that the control used in living organism and that used in man-made machines are essentially the same in their underlying principle. Actually, this discovery triggered his activity towards the establishment of the discipline of *cybernetics*[2].

In early 1960's, Monod, a French biologist, opened up a new field of control in biology, *regulatory biology*, as a discipline to study molecular or cellular level biological control. He anticipated that control also plays a major role in genetic phenomena and metabolism in the cell. He described this area as the microscopic cybernetics in his famous book[3]. Regulatory biology actually paved the avenue towards the advent of systems biology in late 1990's.

The advent of cybernetics accelerated the research activities of control in various areas of life sciences. Many notions in control engineering were found to be useful in studying biological control, specially in brain science. The control theoretic notions like adaptive control, internal model and learning control became suggestive key words in the study of motor control that helped brain scientists to exploit new framework of research.

4 Compound control

In conventional biology, genetic regulation and motion control, for instance, are regarded as completely unrelated subjects except that they use feedback. Researchers in biology normally tend to stick to specificity of each life phenomena rather than to exploit their common features.

We have a different view on biological control. We believe that various control mechanisms built ubiquitously in living organisms have some common characteristic features which are specific in living organisms, embodying strong restrictions under which the life survived during the long history of its evolution. The most essential feature of evolution is of course the body/environment interactions. Since the control mechanisms have evolved through those interactions, they must have some elementary forms and some fundamental rules to combine them to generate complex modes of control. Brain motor control must have some relevance to genetic regulations at the cellular level, though the connection might be subtle and indirect. Tracing out this common track of biological control is a proper way to mimic biological way of control functions in artifacts.

Our aim is to establish a new paradigm of biological control that is common to various biological controls inside biology which reflects the specificity of living organisms. In other words, we need a new framework of biological control research that particularly fit biology and is not shared by man-made control. At this stage, we are emphasizing the difference between living and man-made systems, rather than emphasizing the common features.

The most salient characteristic difference between man-made machine and living organisms lies in the capability of living organisms to adapt the environmental change. The living organisms encounter a huge variety of environmental changes during its life. At each environmental change, the living organism has to find a proper way of reacting to the changes in order to survive, which is not an easy task. Since the number of possible environmental changes is enormous, it is impossible to prepare repertoires of control strategies that fit each environmental change in advance.

On the other hand, the environmental changes do not occur randomly. There must be some intrinsic rules in environmental changes, which the living organism can utilize. The way the living organism devises to cope with the unknown environmental changes in control using the rules of environmental changes is the core of *compound control* which we propose as a common framework of biological control.

Since compound control deals with compound occurrence of environmental changes, it is essentially multivariable control. This is different from multivariable control in control theory which deals with multivariable control inputs. In our notion of compound control, the environmental changes (disturbance in the context of control theory) are regarded as multiple. In control theory, the shift from single-input single-output systems to multivariable systems produced a great impact to the theoretical framework and mathematical tools in control theory. We believe the shift from single environmental factor to multiple environmental factors will create a new paradigm of biological control.

In order to cope with the uncertainty, living organisms have the two different levels of adaptation, *evolution* and *learning*. The former is an adaptation process at the species level, while the latter an adaptation process at the individuals level. The possible environmental changes are relatively simple for elementary species like bacteria and hence, some innate rules can deal with them. As the living organism evolves from the simple to the complex, the variety of possible environmental changes it encounters increases so that the innate rules no longer is capable of dealing with the situation. In that case, individuals must learn the rule to adapt itself to the environmental changes utilizing some innate rules that are inherited through the long history of evolution. In other words, the learning at the individual level is determined its direction and algorithm by the innate rules acquired though evolution at the species level.

5 Computational media

We emphasize here an importance of computational aspect of compound control. Since the essence of biological control lies in responding properly to enormous number of possible environmental changes quickly and economically, it must deal with huge combinations of different inputs. The most effective and economical way of dealing with the huge input combinations from computational point of view is to use homogeneous media of computations. The situation becomes clear if we consider the telephone exchangers which must deal with huge combination of senders and receivers. The homogeneous computational media is the most salient characteristic feature of compound control which we can see as the forms of molecular interactions at the cellular level, blood network at the tissue level and as the neural network at the individual level.

An important idea of compound control is that a great many complex biological regulations result from spatial and temporal combinations of simple homogeneous computational media and/or information processing media in response to the huge variety of compound environmental changes. Homogeneous computational media are embedded in the physical components at each level – cellular, organ, and brain (Table 1). For example, cellular-level control is executed by combinations of molecular interactions, organ level control is executed by combinations of transport and/or diffusion of bodily fluids (e.g. blood), and brain- and nervous-system-level control is executed by combinations of electrical activity transmission. We assert that homogeneity in computational media naturally arises from the need to react quickly to a wide variety of environments using restricted biological resources and to orchestrate the flow of information among heterogeneous physical entities (molecules and genes at the cellular level, transported substances and tissues at the organ level, and nerves and brain areas at the brain level). Use of homogeneous computational media is considered to be the most effective and economical way of embedding regulatory mechanisms under these conditions.

Table 1. Homogeneous computational media at different levels.

Level	Computational media	Example of adaptation
Cellular	Molecular interactions	Cooperative binding of molecules
Organ	Transport of bodily fluids	Increase of blood allocation
Brain	Transmission of electrical activity	Learning by plasticity of neurons

At the cellular level, gene regulation is realized by a combination of direct interactions between transcription factors and the proteins that activate them and those between transcription factors and genes; metabolic regulation is realized by direct interactions among enzymes, ligands, and substrates. For both regulations, the differences in the interacting molecules and genes result in different actions, but their direct interaction serves as the common and homogeneous computational media[4]. At the organ level, both heat and nutrition transportation and endocrine system are regulated by the direct flow of bodily fluids. For example, heat in muscles produced by their movements is dissipated via arterial blood flow which also enhances the O_2 and CO_2 exchange between the blood flow and the infusing tissue; endocrine system is regulated by the relay of hormone secretion through blood at different organs: various hormones secreted from pituitary gland are transported via blood to periphery organs (e.g. the adrenal cortex) and induce the secretion of some other hormones there. For both regulations, the difference in the organs and constituents of the bodily fluids result in different actions but the direct flow of the bodily fluids serves as the common and homogeneous computational media. At the brain level, the difference in regions where the firing neurons belong to, such as respiratory centra and visual cortex, leads to diversity of actions but the electrical activity transmission serves as the common and homogeneous computational media.

The computational media at different levels reflect the restrictions on space and the speed required for computation. Cellular-level control uses direct interactions of molecules with strong stochasticity for calculation in localized space. Organ-level control uses the high-speed circulatory system to direct the flow of bodily fluids to convey information with more certainty to connected organs. Brain- and nervous-system-level control requires quick transmission of information over a long distance, for which the electrical activities in neuron cells is well suited. It can convey more information by using the frequency of electrical activity in addition to its quantity or concentration, which is the main source of information for cellular- and organ-level control. More devel-