CONTROL SYSTEMS WITH LARGE PARAMETER SPACES

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I. Introduction

In the task of developing a micro aerial vehicle (MAV), designing an efficient flapping wing is a major challenge. The aerodynamic forces, lift and thrust, are largely produced by the unsteady separation vortex at the leading edge. The parameters influencing the wing performance include oscillation frequency, amplitude, stiffness distribution, and leading edge profile. However, the experimental evidence indicates that, at a fixed operating regime, the spatial distribution of the wing stiffness determines whether the resultant force provides net thrust or drag. The spatial stiffness distribution alone needs a large number of tests to determine the optimal design. Instead of laborious step-by-step tests, we use a feedback control loop with a stochastic search scheme. This approach proved to quickly converge to a desired stiffness distribution that created thrust, not drag.

The flexible flapping wing emulating natural flyers is an engineering system but it is not a complex system since it lacks a large number of design parameters. To test a complex system, we then apply the feedback control approach to a biological cell under a large number of cytokine stimulations. The cell is a basic system of life and it is a complex system. We use a 293 T human kidney cell as the target system and a molecule for indicating the drug effects, NFκB, as the output of the feedback loop. After only about 30 trials instead of 1,000,000 test possibilities, we found the optimal cytokine combinations to positively affect the 293T cell outcome.

II. Unsteadily Separated Flexible Flapping Wing

With a wingspan of approximately 15 cm and a flight speed of a few meters per second, MAVs experience the same low Reynolds number (10^4 – 10^5) flight conditions as their biological counterparts. In this flow regime, rigid fixed wings drop dramatically in aerodynamic performance while flexible flapping wings gain efficacy and are the preferred propulsion method for small natural fliers. Researchers have long realized that steady state aerodynamics does not properly capture the physical phenomena or forces present in flapping flight at this scale. Hence, unsteady flow mechanisms must dominate this regime (Fig. 1). Visualizations by smoke wire techniques clearly indicate that the leading edge separation vortex is the dominate feature of the unsteady flow field.

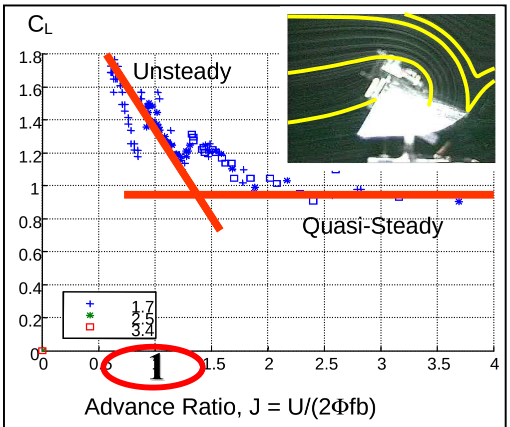

Fig. 1: The MAV and the natural flyer wing operated at the unsteady regime, J<1

Further experimental evidence [1] suggest that the spatial stiffness distribution of the wing is a critical factor in the flexible wing design. To optimize performance, a suitable feedback control system and actuation technology must be developed so that the wing can maintain an optimal stiffness distribution in this dynamic situation; one where the unsteady separated flow field and wing structure are tightly coupled and interact nonlinearly. Natural flyers, birds and bats, use their flexible wings and their control muscles to successfully deal with rapid changes in environment. Drawing from their example, perhaps MAVs can use micro actuators in conjunction with adaptive feedback control to shape the wing stiffness distribution and achieve active flow control. An examination using a computational

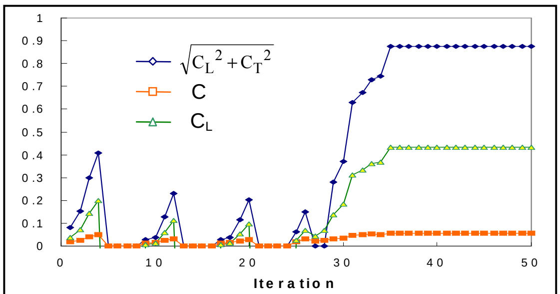

Fig. 2: 35 instead of 250,000 iterations for taking the feedback loop approach

fluid dynamics simulation of the flapping wing integrated with the Gur Game distributed control algorithm illuminates the underlying physical processes and offers a rapid wing optimizing methodology. Fig. 2 shows that the spatial distribution of wing stiffness reaches satisfactory aerodynamic performance in 35 interactions instead of 250,000 step-by-step tests.

III Feedback Control of Complex bio-systems

The cell is a basic unit of life. The design and operation of cells are extremely complex. While understanding of the cellular process is important for life science and medical applications, it is very challenging to discover the underlying mechanisms. These processes are active, dynamic, stochastic, nonlinear, and multi-parametric. Novel tools and approaches for accelerating our study in these aspects are highly desirable [2]. We have developed a generic microfluidic platform for performing different cellular studies[3]. *E. coli*, C2C12 myoblasts, and human embryonic kidney (HEK) 293T cells have been successfully cultured in the micro cell culture system (Fig. 3). The micro cell culture system with integrated actuators allows study of the cellular responses under different external stimulations.

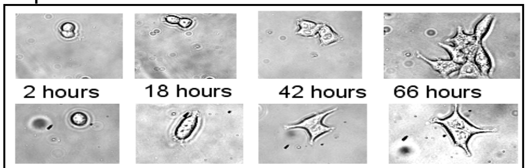

Fig. 3. 293T cell cultured in the microfluidic system.

Many cells regulate their gene expressions by integrating multiple external signals. One of the principle challenges in life sciences is to understand how cells receive, process, and respond to information form the environment[4]. These processes are generally controlled by the cellular signal transduction network. The signal transduction network is actually a cascade of biochemical reactions inside the cell that eventually modify the cellular activity, such as a transcription factor. A transcription factor is a protein that binds to the DNA and regulates the gene expression process. Since most of the cellular phenotypes are the result of gene expression, active control of the transcription factor activity has great importance in cell biology. However, our understanding in the signal transduction pathways is far from complete and a rational design of stimuli for regulating the networks is extremely difficult.

Combining regents, such as drugs or cytokines, has been known to be effective for manipulation of signal transduction pathways and for disease treatment. In a typical biological experiment, the pathways are isolated and studied individually. Important information in the regulation of the cellular process is lost. However, a rational design of stimuli for regulating the signal transduction pathways is extremely difficult due to the complexity of the networks. Extensive optimization of the dosage is required to establish the potential additive and synergistic effects. We developed a novel approach to cooperate multiple stimuli for controlling complex biological networks. The technology is fundamentally different from the traditional approaches of conducting biological research, in which each component is isolated and studied independently. Our feedback cell control strategy, on the other hand, allows us to take a systematic approach permitting the regulation of complex biological networks.

CONCLUSION

This presentation has illustrated how to apply the engineering feedback control concept to dramatically reduce the effort to designing a flexible wing flapping in an unsteady flow regime and in directing a natural complex system to a desired phenotype.

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Reference

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