論文の内容の要旨

論文題目 Phase Synchronization Between Internal and Body Dynamics for Exploration, Memory, and Control of Embodied Behavior

（和訳：身体行動の探索・記憶・制御のための内部および身体ダイナミクス間の位相同期）

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Abstract

The aim of this thesis is to propose an integrated framework based on synchronization in dynamical systems for robotics and embodied AI. Our contribution includes: *(i)* A methodology that exploits the property of nonlinear oscillators to match (synchronize) and amplify the resonant frequencies of any given system (feedback resonance) to explore, quantify and categorize the natural dynamics of a robotic system, independent of its dimensionality and morphology. *(ii)* A methodology that exploits the property of phase synchronization in chaotic systems for information processing purposes. Our novel model based on this property – a multi-layer Coupled Map Lattices (CML) – has the memory function based on the phase-locking of chaotic systems, and can be used for dynamical learning i.e. pattern recognition of scene images, or for the learning and the control of simple robotic motion behaviors. *(iii)* This mechanism permits the dynamical linkage between the internal dynamics of an embodied robot and the external dynamics of the environment. Simple skill transfer (dynamical learning of coordinated body limbs motion) is possible without algorithmic optimization technique. *(iv)* We develop novel measuring tools to quantify dynamical behavior in high dimensional systems: the wavelet bifurcation diagram (spatio-temporal correlations among units and groups of units), two multi-scale causality measure variants (a measure of the causal relationship occuring at different temporal scales between two signals and a measure of the causal relationship occuring *between* the different temporal scales in one signal).

The thesis is organized in eight chapters as follows:

Chapter 1, Introduction, We present our main thesis, the phenomenon of synchronization in dynamical systems can serve as a framework for robotics toward exploration and exploitation of body dynamics, the learning and the recognition of dynamical patterns, the acquisition of external information in an embodied sytem toward development.

Chapter 2, Synchronization, a Central Role for Cognition, we cover briefly the state of the art in cognitive sciences to point out on the central role played by synchronization. We underline the researches done in neurology on the mechanism of phase synchronization between neural assemblies for communication and perception processes, in physiology in the study of corresponding activity between brain processes dynamics with motion behavior which indicates synergy and synchronization, and in developmental psychology, we focus on the importance for infants development to detect, to learn and to reproduce synchronous and coincidental events i.e. contingency and imitation, social interaction.

Chapter 3, Phase synchronization in nonlinear dynamical systems, we present the mechanism of phase synchronization in nonlinear oscillators and its capabilites for control, stabilization, communication, information transfer, detection and learning. We propose a novel architecture of coupled assemblies of chaotic maps to store dynamically external information as phase delay between the units. We give a simple example of its properties for a pattern recognition application to store and discriminate several patterns into the dynamics of the oscillators. The detection process is based on the distance measure between the internal dynamics and the presented stimulus.

Chapter 4, Analysis methods, this chapter treats about the measures that we employed with the novel ones that we propose to quantify and classify spatio-temporal patterns in high dimensional complex systems, and the causal relationships occuring between them. We expose the three novel measuring tools that we developed: the wavelet bifurcation diagram (spatio-temporal correlations among units and groups of units), and two multi-scale causality measure variants.

Chapter 5, Exploration of behavioral patterns, stability and bifurcation, we present the methodology that exploits the property of nonlinear oscillators to match (synchronize) and amplify the resonant frequencies of any given system (mechanism of feedback resonance) to explore, quantify, and categorize the natural dynamics of a robotic system independent of its dimensionality and morphology. We perform experimental analysis on three qualitatively different mechanical system simulations: a compass biped model (one degree of freedom), (2) a dog-like model (two d.o.f.), and (3) a ring-like mass-spring model possessing thirty degrees of freedom. We show that for specific coupling values corresponding to synchronized states, the internal system (nonlinear oscillators) discovers the natural dynamics of the systems i.e. The biped walker performs stable and periodic walking locomotion, the dog-like model explores its stable motions as well as its most impulsive ones like crawling, hopping, walking, and jumping; and the ring-like model shows complex behaviors depending on the level of coordination between the sub-parts that constitutes it, like rolling, fast accelerating, and breaking.

Chapter 6, Implication of synchronization for development and embodiment, in this chapter we expose how the mechanism of synchronization can serve to drive the dynamical learning of sensori-motor patterns and the skills acquisition in an embodied robot. We show that externally imposed dynamics can affect the internal dynamics only when the state of phase synchronization occurs. The rationale is that for only certain coupling values between the internal system and the body, the linkage between the two systems is possible even though they are working at different time scales, it follows the dynamical exchange of information between the external and the internal dynamics. The level of synchronization between the sensor system and the motor system rules their coordination and the amount of information exchanged.

Chapter 7 Control, the dual view of synchronization, this chapter is a synthesis of the previous chapters on coordination dynamics and on information processing. It describes some experiments that we have done to study the causal sensori-motor information flow between the internal dynamics of a chaotic oscillator coupled to the body dynamics in a compass-like biped walker. It shows that synchronization between the two systems permits the linkage, the exploitation of the body dynamics and the dynamical stabilization over time of their coupling. In a final experience, we integrate exploration, learning and control of the sensori-motor information flow for a developmental issue using the biped model and the multi-layer CML map. Through the effect of the sensor signal during walking on the internal dynamics of the chaotic elements, clusters are formed and retained dynamically. Although the patterns were not designed but emerged from the interaction, they are informational i.e. They correspond to adaptive filters of the sensori-motor coordination.

Chapter 8, Conclusion, in the conclusion of thesis, we explain how we have explored the range that goes from the physics (interactions, friction, elasticity, resonance) toward information (gait, patterns, memory effects, etc. . .) using the framework of synchronization in dynamical systems. Three parts can be distinguished on *(i)* body dynamics exploration and coordination, *(ii)* learning and storage of information with the multi-layered maps model, and *(iii)* learning and acquisition of information in an embodied system. We contribute also by providing quantifying tools, three novel analysis methods to measure the multi-scale spatial and temporal phase transition in complex and high dimensional systems that we named the wavelet bifurcation diagram, and two multi-scaled causal relationship between and within the systems. These methods are general methods for the study of complex and dynamical systems that can be applied in biology or physics.