P01

Synergetic Learning Control Paradigm for Forming Adaptive Central Pattern Generators

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1 Introduction

Human motor control/learning is an interdisciplinary field of science. It involves a computational neuroscience question on how the central nervous system contributes to generate coordinated motion, and a computational intelligence aspect of how control paradigms can be implemented to adaptively manage high degrees of freedom of our musculoskeletal system under the given physical environment. It is still an open problem of how motor controllers in the brain solve those kinematic and actuation redundancies under the given physical environment. Such human motor control/learning topic is also important for the neurorehabilitation field. For the aging society, finding our learning mechanisms is essential to design effective neurorehabilitation protocols, where we should induce human learning capability to gain motor function recovery.

The purpose of this work is to study the development of controllers for optimal rhythm generation by self-organized central pattern generators as a new method in computational motor control. Central pattern generators (CPGs) are neural circuits found in vertebrate animals that can produce rhythmic patterns of neural activity without receiving rhythmic inputs. Even if there is strong evidence that CPGs are employed phenomenologically in human motor control and locomotion, the computational mechanisms of how those rhythmic patterns can be generated systematically, are not fully understood. Most of the works regarding CPG application are based on coupled oscillator models [1][2]. As they start with the assumption that oscillatory mechanisms exist, it normally produces somehow rhythmic patterns. Taga [3] performed pioneering work on adaptive CPG-based locomotion against environmental changes, where they also employed coupled oscillator models. In contrast, the objective of this work is to investigate whether rhythmic pattern generation and task execution under the given dynamic environment, can take place without starting with such oscillator model. If it is possible to induce resultant adaptive CPG-like patterns without prior oscillatory pattern assumption, it should be convincing to reveal the authentic control mechanism regarding motor control and learning for redundant system controls.

2 Method

In previous studies, we studied a primitive computational mechanism for realizing optimality along with a Feedback Error Learning-like controller without using specific cost function [4][5]. Acquiring motor synergies under actuation redundancy was firstly enabled with dynamics-model-free and cost-function-free approach, inspired by tacit learning concept [6]. This seamless learning and control is an important aspect in neural control, which is difficult to be replicated and managed with conventional model-based optimization approach, since it is not realistic to apply mathematical optimization every time the environment is changed. This work was for hand reaching task, then toward finding a computational principle for general CPGs self-organization process, in this work the paradigm was extended to produce adaptive rhythmic patterns by motor learning, instead of starting from an assumed coupled oscillator model. Motor command accumulation starts to learn how to compensate the interaction torques under a given environment, and turns into a predictive torque patterns after the motor learning (similarly to previous work on reaching). This method should provide computational adaptability and optimality in CPGs with oscillator-model-free approach, in contrast to previous coupled oscillator studies for CPG.

3 Results

Our body consists of connected limb segments with damping components, it is challenging to find energetically efficient motor control patterns to keep the oscillation of such system. In the conventional approach, the coupled oscillator is used but we normally need to specify its frequency, its amplitude or its phase relationship with trial and error. Making these parameters adaptive to the given dynamics environment is yet an unsolved issue. The connected segment dynamics is known as a highly nonlinear and even chaotic system. A double pendulum is a simplest physical system that exhibits rich dynamic behavior with a strong sensitivity to initial conditions, and is chaotic. It has only 2 joints and its exhibits initial condition dependency and chaotic behavior. The amount of chaotic level is varied with the amount of motion speed. It is more chaotic when the segment moves with certain speed. Then, keeping oscillation in such system requires synergetic articulation of the joints. Especially when the joint has damping effect, the amplitude of oscillation is going to be reduced and the lost energy should be compensated with the active torque of the joint. When the dynamics equation is available, it may be possible to solve it with an analytical approach with mathematical optimization. However, when such dynamics information is not at all available, it is almost impossible to solve with existing approaches. The proposed method as in synergetic motor control paradigm [4], was applied firstly for the double pendulum. The both 2 joints had a certain level of damping. The 2nd joint was only actuated. Thus, the problem was how to manage to produce limit-cycle for both the 2 joints with only 1 controllable joint. As the system has complex interaction torque dynamics between the joints, the active joint should be coordinated intelligently to have synergetic synchronization for the total system.

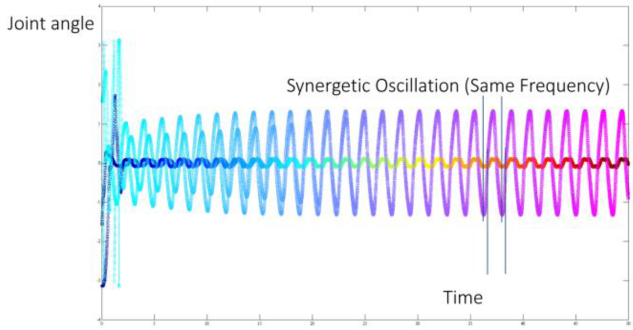

Figure 1: The joint angles of double pendulum controlled with the proposed learning controller. Even with different initial conditions, it was converged into same limit-cycle.

Figure 1 shows the result of double pendulum control. From different initial conditions, the same limit-cycle behaviour was produced with the same frequency over 2 joints. The learning control was added only to the one of the 2 joints. The second link was actively controlled. The first link was totally passive. It is similar situation to the swing seat oscillation. As there is damping, it stops if there is no active joint coordination. Thus, human moves the knee to coordinate the lower limb synergetically to the whole swing seat oscillation, then results in same oscillation with phase delay. Reasonable phase shift with same frequency appeared, and the active motor generated feedforward predictive patterns. This result indicated that limit-cycle oscillation can be created by learning, without so-called coupled oscillator model.

To investigate a more complex situation, and the feasibility of the adaptive capability to the given dynamics, the proposed method was tested with 4 pendulums in series. The first joint is passive and the 3 following joints were active. The system has highly nonlinear behaviour and chaotic relationship if it is only driven passively by gravity, as joints are coupled to each other with interaction torques. The system started with chaotic oscillation. However, it converged to limit-cycle with synchronized frequency oscillation as in Fig.2. It converged to a reasonable phase delay (traveling wave) and with varied amplitudes (from small to large from the base link). Especially, the base link was movable, floating base, then if the joint1 applies the force, the base can be moved as a reaction effect, resulting in loss of energy. Thus, the lower joints are more largely oscillated with higher amplitudes as in the Fig.2. To cancel the interaction force at the joint1, the phase delay was in antiphase between joint1 and joint2,3. The situation allows joint4 to move in-phase with joint1 and to make large oscillation at the end. When we fix the base link, a totally different joint coordination appeared with all joints in in-phase, as it is not necessary to cancel the interaction force at the base link since there is no risk of energy loss when the base is fixed.

Finding this kind of reasonable combination is already challenging when we use the conventional coupled oscillators, as we have frequency parameters, amplitude parameters and phase delays in the oscillator models. The feedback gains in the joints, and the learning rate had same values for all joints, however the system converged to different amplitude by the proposed learning controller.

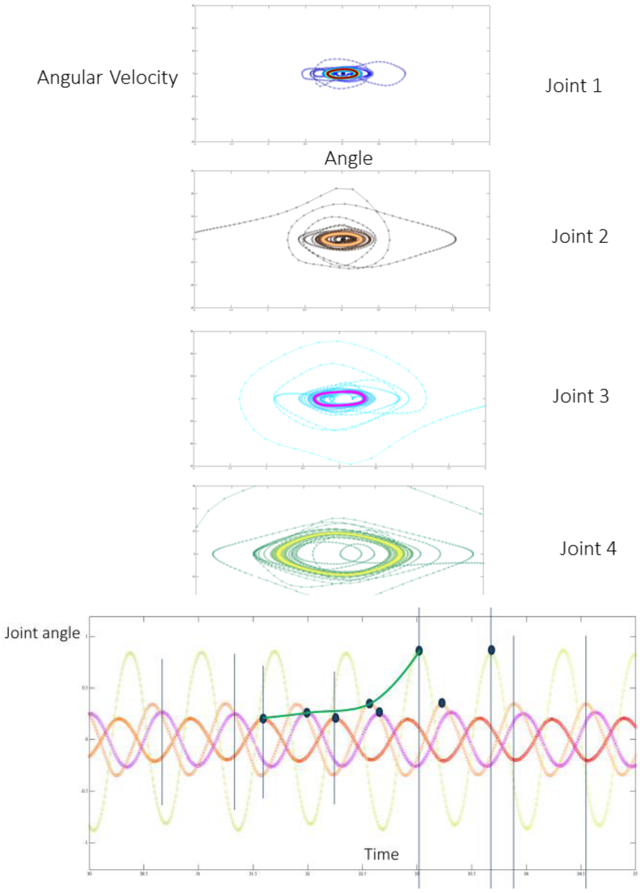

Figure 2: The joint angles of 4 pendulums in series, and the base link was floating base. Coordinated motor patterns were resulted in synchronized frequency over the joints.

4 Conclusion

In practice, a human motor learning and control are executed seamlessly, adapting to environmental dynamics variations and newly-generated goals. Finding adaptive multi-oscillation controllers which are efficient in the given dynamics condition is not a trivial problem. Intelligent, Adaptive, Limit-cycle Oscillation could be created by synergetic learning control paradigm, without employing coupled oscillator models.

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