Stabilization of Periodic Motions
– from Juggling to Bipedal Walking–

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Abstract

This paper presents some examples of stabilization of periodic motions. First, the juggling motion controlled by a duplicated simple controller and neural oscillators is discussed. Next, the bipedal stepping motion of the human like lower body and trunk model is discussed. In this model, the stepping motion was accomplished with neural oscillator and simple posture controllers. At the last part, biped walking of a simple compass like model is mentioned with relation to juggling.

1. Introduction

Many researches have been conducted on the Stabilization of periodic motions.

The most typical of such motion is of Walking. Dynamic periodic stepping motion of stilts type biped model mainly controlled in the frontal plane was taken up and experienced[1]. Stabilizing biped system using limit cycle stability of non-linear van der Pol's equation appeared almost same time[2]. On the other hand, passive(neither actuated nor controlled) walker machine was demonstrated and it accomplished bipedal walking only by using human body physical dynamics [3]. Hopping type walking(running?) machine from mono-pod to quardruped are produced and demonstrated with high gymnastic potentiality[4]. Biologically inspired neural oscillator control is proposed and human like biped walking simulation was shown [5].

The other typical example of dynamic(can't stop) periodic motion is Juggling. There has been precedent research(ping-pong robot) which was not classified strictly as periodic control but as rapid motion control[6]. For juggling, 'mirror algorithm' was proposed and spatial two balls by one hand juggling was accomplished[7]. On the contrary, open loop stable juggling strategies were proposed and demonstrated[8].

The characteristics of these systems can be described as follows:

- The transition of the states is mainly Ballistic.
- The structure of the system is time-varying.
- The control input can only affect the states transition of the system for a restricted duration.

Conventional control methods are in many cases neither effective nor natural for these type of systems, but sometimes the characteristics of these systems (from conventional point of view) can be fitted with some special heuristic control law and can accomplish tasks. However, heuristic control laws for such systems are difficult to derive.

2. Juggling

We constructed a robot juggling(padding) system for the research of dynamical periodic stability [9]. That was mostly inspired by Schaal's open loop juggling machine[8] and the Taga's biped walker[5]. The control of motion was purely performed by neural oscillators.

A brief description of the neural oscillator is given in Section 2.1. The design method for our controller is presented in Section 2.2. An example using this method is presented in Section 2.3. The result of this system is presented in Section 2.4.

2.1. Neural oscillator

One neural oscillator is represented two sets of mutual inhibited adaptive(fatigue) neural elements.

$$\begin{aligned}
\tau_1 \dot{x_1} &= -x_1 - \beta f(v_1) - \gamma f(x_2) + u_0 + u_{f1} \\
\tau_2 \dot{v_1} &= -v_1 + f(x_1) \\
\tau_1 \dot{x_2} &= -x_2 - \beta f(v_2) - \gamma f(x_1) + u_0 + u_{f2} \\
\tau_2 \dot{v_2} &= -v_2 + f(x_2) \\
f(x) &= \max(x, \theta)
\end{aligned}$$

where x_i are the state values, τ_i are the time constants, u_0 represents constant input, and u_{fi} are feedback inputs, γ is connection weight and β represents the adaptive strength. $f(x)$ is the threshold function.

The important characteristics of neural oscillators is their ability to entrain to an incoming frequency. The self-excited oscillation of the neural oscillator is synchronized to certain frequency range of oscillation input u_{fi}[5].

2.2. Designing of the controller

The derivation of the juggling controller can be divided into three basic steps:

1. Measuring the restitution coefficient of the paddle and calculating the stable nominal frequency and amplitude of the paddle.
2. Providing a simple feedback input (for the latter neural oscillator), that works only at the hitting instance.
3. Tuning neural oscillator to generate the nominal frequency and amplitude oscillation pattern.

Each step has the role as follows:

1. Finding the suitable trajectory of the state transition that will allow a stabilize the system by itself.
2. Keeping the states of the system to the neighbor of the stable trajectory, while the states can be controlled. Therefor, it works as a local (short term) controller.
3. Preserving the phase difference structure of the states of the system. It works as a global (long term) controller.

2.3. Example of the controller

The following is an example of neural controller system in one ball and one paddle padding case:

1. decide the object ball height and the hitting phase adequately(about $\pi/4$[rad] phase before the paddle top position) and derive the nominal sinusoidal wave trajectory of the paddle.
2. add local feedback for regulate the hitting speed and adjust the parameters of it adequately.
3. tune neural oscillator parameters to fit the nominal sinusoidal wave.

The equations of the local controller is as follows:

$$\begin{aligned} v_{bd} &= -\sqrt{2gh_d} \\ v_{ad} &= (1-e)/(1+e)\cdot|v_{bd}| \\ k_s &= k\cdot d/(d^4+\epsilon) \\ u_{f1} &= k_s(k_{ah}(v_{ad}-v_a)+k_{bh}(v_b-v_{bd})) \\ u_{f2} &= -u_{f1} \end{aligned}$$

where v_b,v_a,v_{bd} and v_{ad} represent the velocity and desired velocity of the ball and the arm, respectively. h_d is the desired top height of hit ball. e is the restitution coefficient of the arm paddle. d represents the distance between the ball and arm. k and ϵ are constants. k_s means feedback intention scaling coefficient. k_{ah} and k_{bh} are the feedback gain constants. g is the gravitational acceleration. u_{fi} is the feedback input to the neural oscillator.

2.4. Result

We show the one of the results.

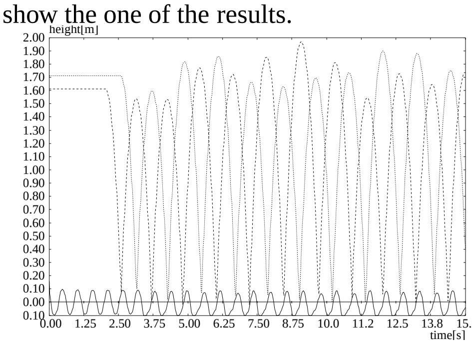

Figure 1: Juggling(padding) with perturbation

On this simulation, we gave perturbations as the fluctuation of the restitution coefficient of the paddle. The open loop wave generator cope with up to $\pm$0.18% range uniform random perturbation. On the contrary, the combination of local and global controller could stabilize up to $\pm$6.15% range. That means the controller expanded the stable basin about 34 times. This result does not mean to impair the value of open loop control method. It prepared the seed to growth. This result is an evidence that the combination of the open loop controller and the neural oscillator has good power.

M. Williamson also analyzed neural oscillator for juggling using the describing function method[10].

3. Stepping

We constructed three dimensional bipedal stepping simulation to prove that adequate interaction and coupling of physical system with neural dynamics produces various behaviors and yield robustness of motions[11].

The three dimensional simulation was an extension of the sagittal two dimensional biped simulation [12].

3.1. Model and controller

The robot model for the simulation is showed in Figure 2. It has a human like biped lower body, but the upper body is simplified to one link. The length and mass of each link correspond to that of humans[13]. The sole

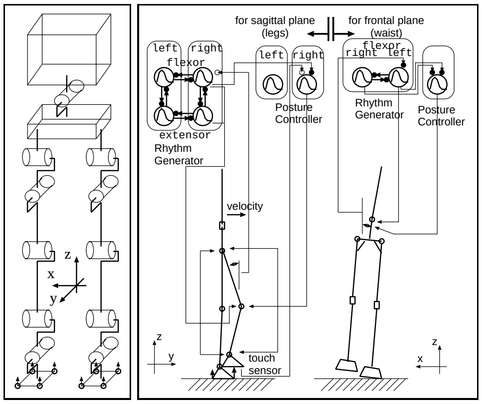

Figure 2: Distribution of degrees of freedom and structure of the system

is a set of 4 contact points.

The neural controller is mainly divided into two parts. One is the stand posture controller and the other is rhythmic motion generator and controller that is constructed by the neural oscillators. These two controllers work in parallel.

The posture controller is a simple PD(Proportional and Derivative) type regulator, and it works on the immediate upper link of each joint standing straight. The posture controller has some inhibit connection from the neural oscillators, that is to ease the fixation of the posture controller for leg bending, allowing rhythmic stepping motion controlled by the neural oscillator.

The rhythmic motion generator and controller is structured by three neural oscillators as shown in Figure 3 [11]. One oscillator corresponds to the waist swing in the frontal plane, and the other two are assigned to each leg for reciprocal bending. These neural oscillators are connected together to keep adequate phase differences of the stepping motion.

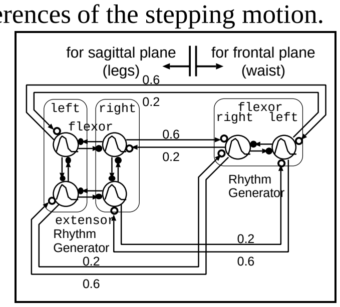

Figure 3: Connection between the leg and the waist oscillators

3.2. Result

The system states move on a stable periodic trajectory. For investigating the stable basin, we added various magnitudes of impact, like perturbation force at various times. Figure 4 shows the stable basin of the trunk in the frontal plane. For comparison, we also show the open loop unstable case for the same perturbations.

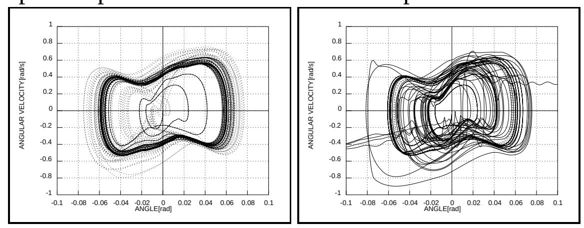

Figure 4: Phase plot of the stability domain(left) and without control(right).

Figure 5 (two rows of left to right sequence in a series)shows the stick figures of the biped facing in the right direction in the view point of the right front upper position. We added perturbation force on the trunk to the forward direction on the upper row third and fourth pictures. That perturbation caused consequent stronger stamp of the left foot and one step forward motion of right foot which was not programmed to do so. This shows the inherent physical stabilization dynamics of the human body.

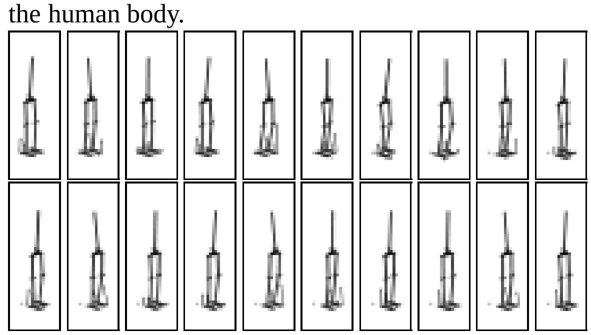

Figure 5: Snapshots of perturbed step motion.

The robot continued the stepping motion with slight motion pattern change, in another perturbation cases(on a slope, waving board and rough terrain).

Neural oscillator base locomotion control is also done by Hase[14] and Kimura[15]. Hase constructed a human whole body model including upper limb and muscle actuators and used genetic algorithms for parameter tuning. Kimura research is based on neural oscillator control of a real physical quadruped robot.

4. Walking

In our current work, we have based our research on the work of passive bipedal walking of [16].

The characteristics of walking and juggling have something in common as mentioned above. Those points pose the question: could open loop control like Schaal's juggler[8] be possible on the bipedal locomotion?

Our biped model is almost the same as the compass-like point foot biped robot[17] except leg length change.

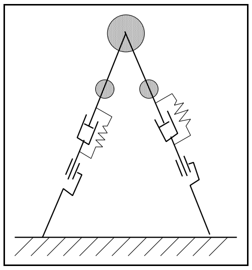

Figure 6: Model of a Compass-like Biped Robot

By setting the leg expansion and contraction sinusoidal frequency 3 times higher than the free motion frequency of the leg swing, this model can walk on a level plane, but the trajectory which we now have is unstable. To get the adequate parameter set and the motion pattern for stable walking is our future work.

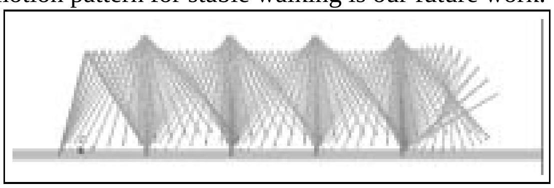

Figure 7: Stick Picture of Open-Loop Walking to the Right

5. Summary

We summarize the results of these case studies as follows.

- It is efficient to use self stabilize mechanism (if it was)of the system as a base.
- The entrainment characteristics of the neural oscillator expands the provided stable basin.
- Interaction between physical and neural system through entrainment generates various motions.

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