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Neural Locomotion Controller Design and Implementation for Humanoid Robot HOAP-1

○Jiang Shan, Fumio Nagashima *Fujitsu Laboratories LTD.*

Abstract — This article explores a biologically inspired approach to control the humanoid robot with many DOFs using Central Pattern Generator (CPG). The CPG is constructed by combination of groups of neural circuits that are modeled by recurrent neural networks. The numerical perturbation method is used to guide the combination procedure for desired motion CPG in a step by step manner. Validity of this approach is examined using HOAP-1, an open architecture humanoid platform. The operation and development environment for neural control is also described in detail.

Key Words: Central Pattern Generator, Humanoid robot, HOAP-1, Locomotion, Recurrent Neural Networks

1. Introduction

Current locomotion control policies are mainly based on trajectory plans that prescribe the desired state of the movement system as a function of time. In terms of the control policies, the locomotion performance can be improved by carefully tuning the controller to map a perceived state to an appropriate action [1]. However, it is largely accepted that these methods do not scale well to high dimensional control problems, such as humanoid robot control. In addition, they are not particularly robust to unforeseen disturbances in the dynamical environment and computationally very expensive. Another important problem is that it is hard to re-use these representations for related movement tasks. To truly understand the nature of robot locomotion control and construct the autonomous robot, other robotics researchers have derived their inspiration from biologically inspired control method. Kimura was able to design highly adaptable quadruped robot using neural oscillators [2]. However, since the stability issues are quite different for bipedal vs. quadruped locomotion, biologically inspired humanoid robot control remains a challenge task, and this is the main target of this research.

As one part of the research, this paper mainly focus on the design and implementation issues for humanoid robot locomotion control using neural controller, also the platform architecture is illustrated. The general motion control theory, basics neural circuit notation and language will be discussed by other paper [3][4].

2. Neural control mechanism

From the viewpoint of neurobiology, human's locomotion is hierarchically controlled at several levels of the central nervous system, namely the spinal cord, the brainstem and the cerebral cortex. The latest research show that rhythmic locomotion patterns, such as walking and running, are produced by neural networks that are called central pattern generators (CPGs) at the spinal cord level. In this research, we focused primarily on activity at the spinal cord level since the spinal cord is believed to provide the basic control units needed to organize locomotion [5].

In most of the related literatures, CPGs for robot locomotion control are modeled as a group of coupled nonlinear differential equations, and flexible movement is generated from the entrainment of neural and mechanical dynamics in an dynamical environment [6], and controller parameters are mostly tuned by trial and error. This method only works for simplified system with few DOFs, and it is extreme difficult to build the controller by hand for a humanoid robot with many DOFs. Several researchers use stochastic algorithms, such as genetic algorithms (GA), to find the structure and parameters of the neural controller, but this approach still faces the problems of high dimensionality and computational inefficiency.

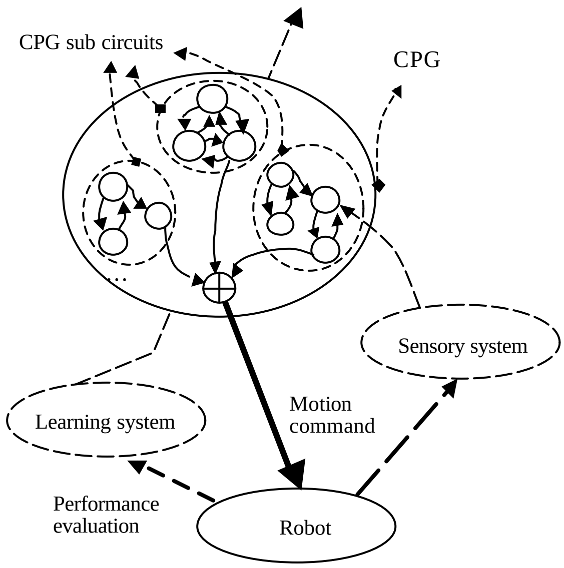

Fig. 1 Neural control mechanism using CPG

In this research, we use CPG for humanoid robot locomotion control, however the total CPG circuit is comprised of different groups of sub circuit, which are called CPG sub circuit (CPGSC) hereafter, for specified motion types. The CPGSC can be viewed as a basis set of motor programs that are sufficient, through combination operators, for generating the entire movement repertoire. The control of locomotion appears to be based upon the integration, switch, sensory-based modulation, and learning of CPGSC. Different CPGSCs are recruited to formulate the desired motion CPG, and learning system takes charge of the CPGSC combination manner and parameter adjustment. Fig. 1 shows the general structure of the robot neural control system.

To use the concept of CPGSC for humanoid robot motion control, the first question is what are appropriate representations for CPG or CPGSC. In our research, all of the CPGSCs are considered as dynamical system and recurrent neural network (RNN) is used to describe the behaviors of them. The basic RNN is described by first order differential equations. Details of the RNN notation and construction method can be found in [4]. The CPG design and implementation issues will be discussed in section 4. In section 3, the neural control development and operation environment is described.

3. Neural control development environment

3.1 Humanoid robot HOAP-1

Fujitsu Laboratories developed HOAP-1, which is an open and flexible humanoid robot research platform [7]. The design principle of HOAP-1 is to use an open hardware and software interface in order to provide users with an open architecture for humanoid robot research. Currently, the robot operation environment is constructed on two standard PCs that running RT-Linux and windows 2000 respectively. Compared with other special-purpose hardware and software systems, this general platform provides researchers with several advantages:

- High modularity and portability.
- Simple developing environment.
- Common interface and APIs, and reusable source codes and components.
- Easy hardware device selection and integration.
- Easy management.

HOAP-1 robot has 20 DOFs in total, 6 in each leg and 4 in each arm. Every joint is driven by lightweight DC servomotor mounted with optical encoders. By incorporating the newly developed motor control board, every motor can be controlled with position and velocity mode. The sensory system of HOAP-1 includes foot force sensor (4 on each foot sole), gyroscope (3 axis output) and accelerometer (3 axis output). Onboard local sensor boards are used for sensory information collection. HOAP-1 robot can be controlled in wire mode and wireless mode according to the control task. When using the wire mode, the control algorithm is applied within the external host control computer, and a USB line acts as the real-time communication channel between command CPU and local onboard microprocessor. This mode provides a flexible platform for testing and implementation of complex algorithms. In wireless control mode, the real-time control algorithm is running on the onboard CPU, and an external computer provides high level commands through wireless LAN.

3.2 Operation environment

For the purpose of neural control, different operation environment programs run in different spaces depend on their functionality. The remote Windows applications deal with the user interface and neural circuit construction. Based on lexer and parser generator tools, such as flex and byacc, the neural circuit can be constructed using the newly developed neural language. Also 3D humanoid simulator is running on Windows machine.

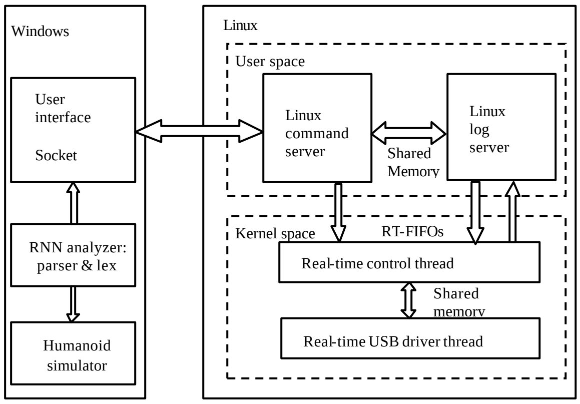

Fig. 2 Operation environment software

Since RT-Linux employs a dual kernel technique that allows time-sensitive processes to cooperate with preemptable general-purpose applications within complex computing environments, the real-time control algorithms is implemented in real-time threads running at RT-Linux kernel space. Linux user space applications are in charge of network interface, user command parsing, message distribution, and data server management. The real-time threads communicate with user space applications by using real-time FIFOs (RT-FIFOs), kernel mode shared memory is constructed for communication between real-time threads. Fig. 2 shows the diagram of system software.

The control algorithms were implemented in real-time control thread. After the construction of kernel RNN circuit, the control thread was scheduled for periodical execution, and real-time integrator was used to evolve the controller with time. Now the control cycle period is 1 millisecond. The RNN input form robot and output to robot was realized by real-time USB driver thread, which take charges of the management of system's USB device.

4. Neural controller design

4.1 Walking

Finding locomotion patterns for HOAP-1 can be considered as an approximation procedure by using CPG that is modeled by RNN. For walking, the motion is be formulated by using three CPGSCs, they are roll, lift and forward/backward. Instead of constructing the total RNN as a whole, the design procedure is carried out in a step by step manner to approximate the desired motion pattern. The approximation procedure is inspired by the concept of numerical perturbation theory. That is, first built the basic low order approximation patterns, then add higher order approximation function series gradually, if necessary. If the total output of CPGSC is P, it is described as:

$$P = e_0 p_0 + e_1 p_1 + e_2 p_2 + \cdots + e_n p_n$$

Where, $e_0, \ldots, e_n$ are approximation constants. p_0 is first order principle approximation and p_1, $p_2, \ldots$, p_n are high order approximation function items.

For the first order motion, roll CPGSC are firstly built for further development. The roll CPGSC control the robot motion in lateral plane, and they are the basic CPGSC since it is always necessary to move the robot's center of gravity (COG) to the right place to make further motion (e.g., leg lifting) possible. The first pattern generated by RNN is a sine curve that determined the basic rolling frequency and amplitude. Details of basic RNN design can be found in [4]. It should be noted that the roll CPGSC (also other CPGSCs) are involved with several related joints (e.g., ankle and hip roll joints), the motor command distributed to corresponding joint is obtained easily using simple kinematic relationship. This property reduces the parameter space remarkably. Also the way to build the roll CPGSC (and other CPGSCs) is not unique since different RNN circuit can generate the same output.

Based on the basic roll CPGSC, different CPGSCs now can be built to move the robot in the sagittal plane. It is natural to consider adding lift CPGSC to make one leg free to move. The lift CPGSC work for lift one leg while the other leg is supporting the total weight. Since roll CPGSC governs the motion of COG, the lift CPGSC must be switched on or off based on the output of roll CPGSC at

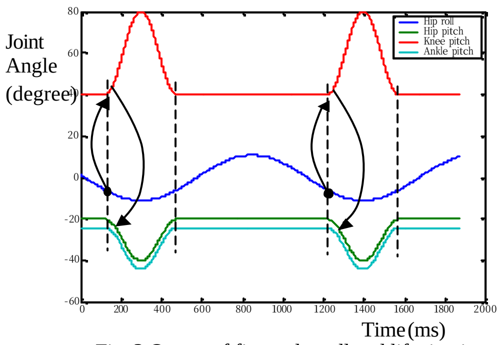

Fig. 3 Output of first order roll and lift circuits

appreciate time instances. The online switches for CPGSCs are very important since they provide the timing information for complex motion control. Part of the RNN output is shown in Fig. 3, the hip roll pattern is used for switch reference, and the dot points are switch thresholds. Various functions can be used for switch, such as step function. Use roll and lift CPG, the robot now can make the stepping motion.

Similarly, the CPGSC for going forward and backward are added in the same manner. They only function on pitch joint of hip and ankle. The first order approximation for going forward and backward is just linear function generated by RNN. Fig. 4 shows the pitch motions of hip joint, linear summation is used to combine the two CPGSCs' output to format the motion command sent to robot.

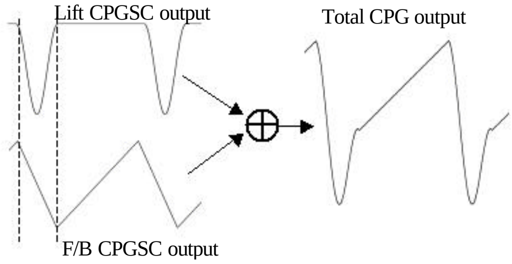

Fig. 4 Linear combination of hip pitch CPGSCs

By means of combination of first order approximation RNN, the walking CPG controller was constructed and then tested on HOAP-1. Since using the CPGs can reduce the parameter searching space, the successful walking pattern was obtained by just several trails. Another important aspect of the CPG control is that the controller output is based on the linear summation of groups of linear equations, this provides a straightforward method for CPG design. This CPG pattern can make HOAP-1 robot walk at frequency of 6 rad/s, and the step length is about 8 cm.

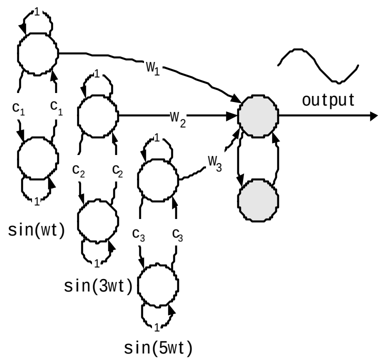

Fig. 5 Diagram for high order roll CPGSC circuit

After the first step, higher order approximations were considered to improve HOAP-1's walking performance. The order of roll and pitch CPGs were added, and Fig. 5 shows the RNN circuit and their combination for high order roll CPGSC. The CPGSC's output, named P_r, can be formulated as

$$P_r = w_1 \sin(wt) + w_2 \sin(3wt) + w_3 \sin(5wt)$$

Where w_1, w_2, w_3 are approximation constants and they have the relationship that $w_1 > w_2 > w_3$. Here the last two items are the high order approximation for roll CPGSC.

In the design of high order approximation, it is always desirable to add independent order to avoid different orders' coupling. For example, for the pitch approximation, sets of orthogonal function (e.g. polynomials generated by RNN) was adopted to generate the desired pattern. One obvious advantage is that the tuning for one special order approximation can be carried out without considering lower approximation order. The selected joints trajectories are illustrated in Fig. 6.

Compared with low order CPG, high order CPG, with number of RNN increasing, shows more stable and flexible

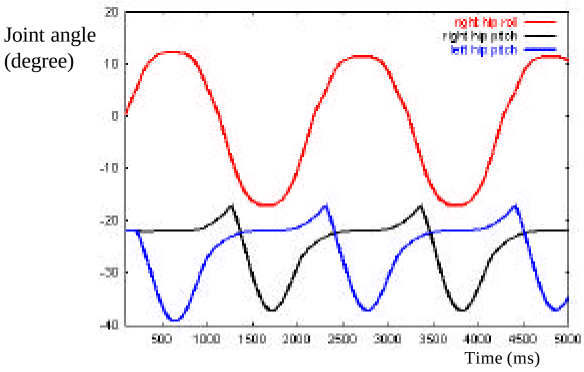

Fig. 6 Output of high order CPG circuits

motion on HOAP-1. A large step length (about 20 cm per step, which is difficult for low order CPG) pattern was realized. The robot also could walk successfully using different large steps (ranging from 0 cm to 24 cm, approximately) and corresponding walking frequency. The waking characteristics, such as relative timing, frequency, duty cycle, and step length can be adjusted in a large range of parameter space.

4.2 Up and down stairs

From the above discussion, CPGs are known to be capable of producing a cyclic set of neural trajectories without peripheral sensory input. However, they are also capable of generating many different patterns under the modulation of sensory input. For example, the RNN is also capable of generate the pattern for up and down stairs using sensory feedback. Sensory input can play a crucial role in initiating or modifying motor patterns. In this paper, cycle-by-cycle correction is investigated, since the pattern generated by RNN might be required to match rapidly changing environmental conditions.

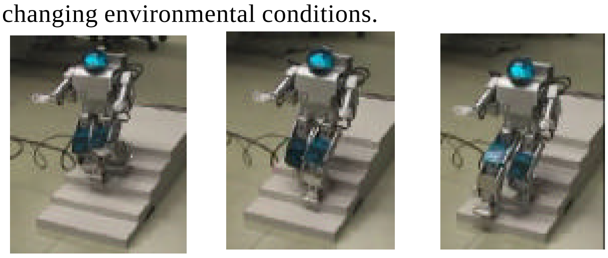

Fig. 7 Snapshots of HOAP-1's stair motion using CPG

To make the HOAP-1 robot walk up and down stairs, a stair CPGSC firstly was integrated to the previous pitch CPG to and upward or downward motion. In addition, gyroscope sensor was selected to modulate the CPG's output. In current stage, ankle strategy is used for sensory integration, that is, the output of sensor based control was applied to both ankle joints of HOAP-1 robot. The experiment demonstrated HOAP-1 robot could walk up and down stairs by adding additional stairs motion and fine tuning the CPG parameters. The locomotion frequency for up and down stairs are 2.2 rad/s. Fig. 7 shows the snapshots of HOAP-1's down stair motion.

5. Conclusions

A strategy for biologically inspired humanoid robot locomotion control was proposed and tested in this research. In this research, high dimensional humanoid robot walking pattern was generated by groups of RNN, named CPG, which were governed by sets of linear differential equation. The RNN provide us a very flexible and powerful tool to approximate the complex nonlinear phenomenon in humanoid locomotion. What's more, the motion for humanoid locomotion is characterized by groups of motion CPGs, which is also biologically plausible. It is found that the RNN was appropriate representations for modeling the CPG since it is flexible to model the desired dynamical behaviors. The output of CPG is inserted into control loops by coding for motion trajectory of corresponding joints groups based on linear summation of specified CPGSCs. For particular task, the CPGSC was constructed using the basic concept of perturbation, which provided a reasonable framework for efficient RNN development. Also, due to the parameter space reduction, the CPG tuning can be carried out in a straightforward manner. It is also found that the sensory feedback can be integrated into the CPG by online modification of the desired CPGSC. Based on this design strategy, stable and flexible locomotion control was realized for HOAP-1 robot.

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