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Biologically Inspired Spinal locomotion Controller for Humanoid Robot

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Abstract: A biologically inspired design strategy for humanoid robot locomotion control and its simulation implementation is presented in this paper. Firstly, the dynamics model of humanoid robot, biologically plausible spinal motor neural circuits, and virtual muscular module are constructed. Then, the control strategy for adaptive bipedal locomotion is investigated, also the development of the general-purpose robot simulation environment is discussed. This research shows that the locomotion control flexibility and autonomy are achieved based on integration of biological foundations, computational neuroscience and robotics, and this work also provides primary consideration for future engineering solution for both real robot and neurological disorder.

Keywords: humanoid robot, biologically inspired, locomotion, simulation

1 Introduction

The researches on robotics locomotion can be generally partitioned into several groups. The first involves behavior reflex chains to trigger motion loop. And high level modeling approaches, such as ZMP control, Reduced Model Based control and virtual Model control, dominate the literatures on bipedal locomotion. Also dynamic theory method is used to deal with the complex dynamics of humanoid robots. However, these methods are suffered with the problem of high dimensional, nonlinear, time-varying and delay.

Recently, more attention was attracted to the field of biological inspired locomotion control strategy. The rhythmic locomotion pattern is brought forword by an intermediate level neural network which generates a flexible rhythm pattern based on both sensory feedback and high level brain interaction. Under the govern of this control mechanism, the control space shifts from joint space to the muscle space, and robust walking pattern is yielded from the entrainment between the neural dynamics and robot mechanics [1]. In this paper, we present a humanoid locomotion control strategy, and dynamics simulation and controller design was performed on a general-purpose robot simulator. Implementing this kind controller on real robot is the long-term target of this research.

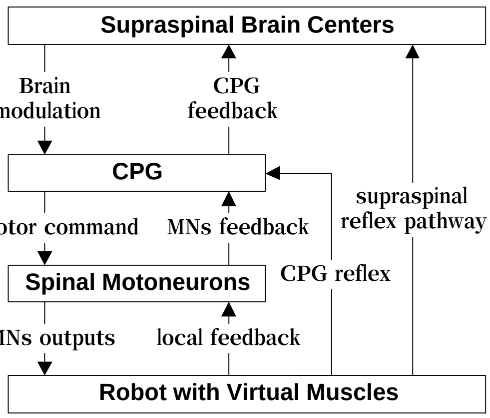

Figure 1 Locomotion controller and robot

Figure 1 describes the general hierarchical structure of the humanoid locomotion controller, and the robot with virtual muscles. The top level of the controller, consists of the brain stem, cerebellum, basal ganglia and cerebrum, is responsible for behaviors that are progressively less automatic and more conscious. The spinal controller generates the rhythmic neural activities for cycle locomotion behavior. Central Pattern Generators (CPGs) and segmental circuitry (etc. Motoneurons, MNs) are the most important elemental components. Virtual muscles are stimulated by MNs control commands and then drive the robot joint. While in this paper, the main content is spinal controller design and dynamics simulation, only balance primitive is concerned with high level brain.

2 System model descriptions

In this section, the computational model of human neuro-musculo-skeletal is described with more engineering consideration.

2.1 Robot body dynamics

In this research, the robot body is constructed by tree structured segmented rigid body system that exhibits complex dynamics properties because of passive joint stiffness and the inertial properties of the limb. The full 3D body dynamics with accurate contact model, which is often over simplified in the literature of computational neuroscience, plays a critical role in robotics researches, especially for real robot implementation. In the low extreme of our robot model, each leg consists of 6 DOF, 3 in hip, 1 DOF in knee and 2 DOF in ankle joint. Movements of limb are driven by virtual muscles that attached on each joint.

2.2 Neural system model

In our model, two nonlinear rhythmic oscillators [2] are used to excite the virtual extensor and flexor around each joint. The joint oscillators are coupled with each other to generate overall phase-locked rhythmic pattern. The oscillator are represented by differential equations as:

$$
\begin{aligned}
T_r \dot{x}_i &= -x_i - \sum_{j=1}^{n} a_{ij} y_j - b f_i + s_i + feedback_i \\
T_a \dot{f}_i &= -f_i + y_i \qquad\qquad (1)\\
y_i &= g(x_i), (g(x) \equiv \max\{0, x\})
\end{aligned}
$$

Where x_i and f_i is the neural activity and adaptation rate of ith oscillator, and $feedback_i$ is the combination of feedback form proprioceptors, tactile receptor and vestibular. We believe, for higher vertebrates, such as human beings, the sensory feedback is essential for the self-organization of motor control, since the distributed and synergistic nature of feedback is what makes locomotors behaviors so robust. This is different form the traditional concept of CPG. The neural mechanisms used to generate the oscillatory patterns may include cellular properties of oscillators as well as interconnections weights pattern.

Motoneurons receive motor commands from CPGs and local feedback. The modeling of MNs is emphasized in this research because they are capable of performing complex integration of signals from multiple sources, and it adaptively filter the periodic signal from the CPGs to generate the stimulation pattern which will activate the virtual muscle. The virtual muscle is mathematically modeled according to the anatomical structure of human skeletal muscle, which has muscle spindle and Golgi tendon organs integrated. The dynamics of MNs is governed by following equation:

$$T_m \dot{u}_m = -u_m + h_m + a_m \cdot G_m + \sum_{j=0} b_{mj} \cdot S_j + d_m \cdot CPG_m + feedback_m \qquad (2)$$

The neural activities are united by custom sigmoid function and then innervate the corresponding virtual muscle of the robot. See [3] for equation details.

3 Dynamics simulator

Dynamics simulation plays a critical role both in robot design and validation of control algorithms. In this research, a general-purpose robot simulator is developed to facilitate the rapid flexible control code testing and high accuracy realistic mechanical simulation for robot.

To simulate the dynamics of tree structure humanoid robot, Freeman' DTS algorithms $O(mN)$, which is based on Featherstone' $O(N)$ algorithms, is adopted. The collision check is implemented using GLUT utility, and penalty-based contact resolution is used to model the contact and slipping friction force generation. The numerical integration method can be chosen from RK4, and Euler algorithms.

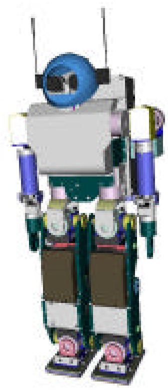

Figure 2 Humanoid robot model

Another important issue is the interfacing between different components, such as dynamics engine, controller, actuator, sensor, GUI and data log. Currently, the interface between each module is defined by carefully designed abstract base class, user only need to provide the core dynamics (for other dynamic controller), control policy (for static controller, e.g. impedance controller) and module configuration that they are interested in. Figure 2 shows the humanoid robot model.

4 Controller optimal design

In essence, both the CPG and MNs can be considered as dynamics recurrent networks. To avoid tedious training sample collection and formulation, we use MultiObjective Genetic Algorithms (MOGA) [4] to solve the multiobjective control problems for humanoid locomotion. The MOGA algorithms is embedded into the simulator and it is easy to choose different GA configuration and fitness functions for different problems at hand. Now walking duration, walking speed and energy cost are used to evaluate the performance of the biologically inspired controller.

5 Discussions

Generally, biological and neurobiological inspired the technological development, and engineering helps us interpret and implement artificial life and adaptive behavior [5]. We believe the integration of these two fields will lead the ultimate robot-humanoid robot, and the motion intelligence of humanoid robot lies in the synthesis of computational neuroscience, AI, neural networks, nonlinear optimal theory and robotics.

The current research on humanoid locomotion controller mainly focuses on the automatic motion pattern generation, which is controlled by low-level spinal level controller. We consider the spinal controller builds the stepping motor primitives which is computational efficient, robust and reusable. The problems left are how can we tune, switch, and combine the controller for different target and integrate the controller to the overall control loop of the humanoid robot. What's more, further analytical research will help to answer why and how the controller works. Another important research topic for biologically inspired motor control is the artificial actuator and sensor.

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