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CPGs Inspired Adaptive Locomotion Control for Hexapod Robot

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ABSTRACT: *The problem of controlling locomotion is an area in which neuroscience and robotics can fruitfully interact. Nevertheless due to the large number of degrees of freedom to be controlled, online generation of trajectories in these robots is very complex.This paper deals with the locomotion control of hexapod robots inspired by the biological concept of central pattern generator (CPG) .The proposed architecture is able to generate adaptive workspace trajectories online by tuning the parameters of the CPG network to adapt to various terrains. With the feedback information a hexapod robot can walk through various terrains with adaptive joint control signals. A hexapod platform AMOSII is used to validate the proposed locomotion control system. The experimental results confirm the effectiveness of the proposed control architecture.*

Keywords*-central pattern generation, hexapod robot, locomotion control, workspace trajectory*

I. INTRODUCTION

Biological creatures have muscles which are much stronger for their size than comparable mechanical actuators; body tissue is stronger and lighter in weight than artificial materials would be. Six legs to move with agility over difficult terrain, so the robot must be capable of stable walking in any direction on uneven terrain. A hexapod with at least three degrees of freedom per leg could accomplish this. Hexapods with fewer degrees of freedom cannot move dynamically in any direction and robots with greater degrees of freedom weight more, consume more power, require additional control complexity, and are more expensive [4].

Biology provides a wealth of inspiration: insects are able to transverse harsh terrains, to climb over obstacles or even towalk upside down[1]. Moreover, essential aspects in unmannedmissions as reconfigurability of locomotion strategies, navigationcapabilities and robustness are common features betweeninsects.Therefore, several efforts, both from a behavioral viewpointand from an architectural viewpoint, have been performed todesign an insect-like robot.In this paper, we propose a new approach to the control ofLocomotion totally based on central pattern generator (CPGs).Most of the researches on locomotion control in insectsreveal the presence of a hierarchical organized neural system[2]. The main focus of this work is onthe higher-order level providing adaptive capabilities to therobot control system, while the low level (locomotion control)is solved by the CNN-based CPG[11].

Control of legged robots is difficult, and so a machine-learning solution is needed. One machine-learning method for legged robots, which has great potential, uses artificial neural networks. Neural networks have the advantage of being modeled on the basic mechanisms responsible for biological control mechanisms. They are also well suited for the walking task, as they allow for automated adjustments of the control parameters [7]. Further advantages are found in the natural parallelism that exists in neural networks— allowing distributed computing hardware. Distributing the computing hardware adds to the robustness of the system. However, as was shown in research performed at Case Western Reserve University, there is also a natural robustness in properly evolved neural networks even without using parallel hardware.

There are many difficulties to be overcome in neural networks before they will be truly useful to robotics. No algorithmic method is known to develop the proper topology for a network to control a legged robot [1]. A small network with too few connections might not be able to represent the behavior that is desired. If the network is made to be large and fully connected, the training time and number of training examples needed increases greatly, this is also highly undesirable. This leads us to another problem with neural networks—generating training data. The more complex the network, the more training data needed and the more work that is necessary before one can use the neural network. Currently the best promise comes from copying the topology of neural networks from organisms.

In fact, legged locomotion offers several advantages in terms of:

1) Good control of the trajectory, thus allowing the capsule to pass over critical areas without touching them;

2) Better adaptability to the environment: due to legs, the capsule is adequate to propel in anatomically and biomechanically different areas (stomach, small and large intestine) featured by different average diameter;
3) Simplified adhesion: by localizing the contact points in small areas (tip of each leg),larger contact pressures can be achieved, thus producing a significant local deformation.

II. BACKGROUND RESEARCH

Many walking robot hexapods have a single preprogrammed gait, usually the tripod gait (180°phasedifference between the legs), that they just cyclethrough. Gait is generated in a clockwork fashionand cannot intelligently react to disturbances or loading conditions. Other robots have two or more suchpredetermined fixed gait patterns and can switch between them. One approach to generating a continuum of reactionary stable gait patterns rather thanseveral predetermined patterns is currently being researched by Cruse and colleagues.

The gait of rectangular six-legged robots has motivated a number of theoretical researches and experiments which nowadays reached to some extent a state of maturity. In 1998 Lee et al. showed for rectangular hexapods the longitudinal stability margin, which is defined as the shortest distance from the vertical projection of center of gravity to the boundaries of the support pattern in the horizontal plane, of straight-line motion and crab walking. A series of fault-tolerant gaits for hexapods were analyzed by Yang et al. [Yang & Kim, 1998a, 1998b, 2000 and 2003][11]. Their aim was to maintain the stability in case a fault event prevented a leg from supporting the robot. In 1975, Kugushev and Jaroshevskij proposed a terrain adaptive free gait that was non-periodic. McGhee et al. in and other researchers [Porta& Celaya, 2004; Erden&Leblebicioglŭ] went on studying free gaits of rectangular hexapod robots.

At the same time, the hexagonal hexapod robots were studied with inspiration from the insect family, demonstrate better performances for some aspects than rectangular robots [10]. A. Preumon et al. in 1991 proved that hexagonal hexapods can easily steer in all directions and that they have longer stability margin, but he did not give a detailed theoretical analysis. Takahashi et al. in 2000 found that hexagonal robots rotate and move in all directions at the same time better than rectangular ones by comparing stability margin and stroke in wave gait, but no experimental results were presented. Chu and Pang in 2002 compared the fault tolerant gait and the 4+2 gait for two types of hexapods of the same size. They proved theoretically that hexagonal hexapod robots have superior stability margin, stride and turning ability compared to rectangular robots[4].The project aims to demonstrate elegantmotion on a robot with a large number of DOF under the controlof a simple CPG-distributed neural system. CPG-inspired control methods arealso increasingly used for the control of biped locomotion,often inspired by the seminal work of Taga and Taga*et al.*on neuromechanical simulations. The works of Ijspeert*et al.* confirm the superiority of the environmentaladaptability of CPG-inspired control methods and the feasibility of robotic engineering applications[7][8].The state-of-art works of CPG-inspired methods mostly mimicCPGs in joint space (referred to as CPG-joint-space controlmethod). However, there have been the following limitations.
1)For some crawling robots, such as snakelike robots, sineor quasi-sine joint control signals are enough. For leggedrobots, such as quadruped or humanoid robots, jointcontrol signals are more complex than the current CPGmodels can generate.
2) The stability of a walking robot is usually realized byadjusting CPG parameters to generate coordinated jointcontrol signals. Many CPG units are required to controlthe multi-DOF, and thus, too many parameters need to bemodulated.
The main contributions ofthis paper are as follows.
1) A workspace trajectory generator is designed to map theoutput signals of the CPG network to 3-D workspacetrajectories online for a legged robot.
2) A compensatory variable for the center of gravity (COG)is introduced in the mapping process to improve locomotionstability.
3) Through the mutual entrainment of the CPG networkwith the feedback body-attitude state signals of the robot,the environment adaptive workspace trajectories can begenerated online[9].
4) A motion engine is designed to realize the mapping fromworkspace to joint space. Thus, the adaptive joint controlsignals can drive all leg joints to realize the desiredmotion.
5) The proposed control architecture is validated using aquadruped robot. A comparison byexperiments showsthe superiority of the proposed method against traditionalCPG-joint-space control methods.

III. CPGs IN ROBOTICS

In this section, we will now review how CPG models have been used to control the locomotion of robots. As illustrated by Fig.1, CPG models are increasingly used in the robotics community. The types of CPG models implemented in robots include connectionist models vector maps, and systems of coupled oscillators. In some rare cases spiking neural network models have been used[3]. Virtually all implementations involve sets of coupled differential equations that are numerically integrated (on a microcontroller or a processor). Probably the only exceptions are CPGs that are directly realized in hardware, i.e. on a chip or with analog electronics[6]. Also to some extent related to CPG research are quasi-periodic motions generated by chaotic maps. Models of CPGs have been used to control a variety of different types of robots and different modes of locomotion.

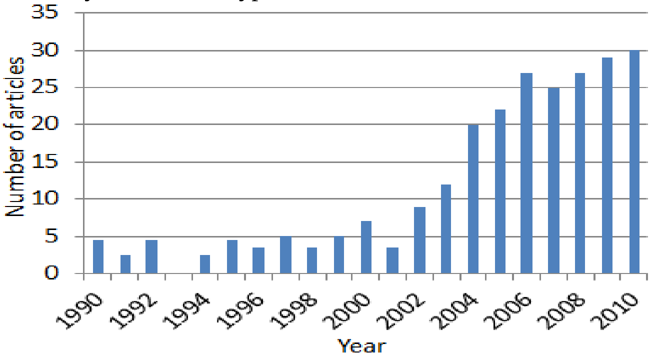

Fig. 1:Number of articles per year whose abstract contains the terms "robot" and"central pattern getenrator(CPG)" in IEEE explorer database, from 1990 to 2010

For instance CPG models have been used with hexapod and octopod robots inspired by insect locomotion for a summary of aspects of locomotor control in insects that are useful for controlling hexapod robots.

There are several interesting properties that make CPG models useful for the control of locomotion in robots as an alternative to methods based on finite-state machines, sine-generators, prerecorded reference trajectories

We identified at least five interesting properties:

(i) The purpose of CPG models is to exhibit limit cycle behavior, i.e. to produce stable rhythmic patterns.

(ii) CPGs are well suited for distributed implementation, which might be interesting for modular robots, i.e. see snake robot

(iii) CPG models typically have a few control parameters (e.g. drive signals) that allow modulation of the locomotion, for instance the speed and direction or even the type of gait.

(iv) CPGs are ideally suited to integrate sensory feedback signals (which can be added as coupling terms in the differential equations).

(v) CPG models usually offer a good substrate for learning and optimization algorithms.

IV. CPF MODEL FOR HEXAPOD

In this section we introduce a CPG model for online generation of trajectories of hexapod robots. It is based in the work of Golubitsky*et al* .We give the general class of systems of ODEs that model CPG hexapod-robot and resume the symmetry techniques that allow classification of periodic solutions produced by this CPG model and identified with common hexapod locomotor rhythms. Figure shows the CPG model hexapod-robot(Fig.2) for generating locomotion for hexapods robots. It consists of twelve coupled oscillators. The oscillators (or cells) are denoted by circles and the arrows represent the couplings between cells. Each cell is a CPG unit and is divided onto two motor primitives, discrete and rhythmic, modeled by simple nonlinear dynamical systems[8].

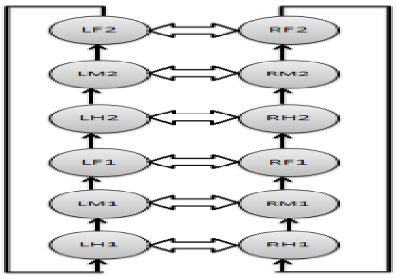

Fig.2:CPG locomotor model for hexapods, hexapod-robot. LF (left fore leg), LM (left middle leg), LH (left hind leg), RF (right fore leg), RM (right middle leg), RH (right hind leg).

CPGs consist of neural circuits that produce rhythmic sequence signals for the control of the movement of legs. The gait pattern can usually be modulated by some parameters, which offer the possibility of modifying the gait (e.g., increasing the frequency and/or amplitude) or even to induce gait transitions[6]. In CPG design, there are certain common assumptions: the nonlinear oscillators are often assumed to be identical; the stepping movements of each limb are controlled by a single oscillator while inter-limb coordination is provided by the connections between the oscillator (see, for example, Fig.3). Moreover, the sensory inputs from lower-level and the higher-level central nervous system can modulate the activity of CPGs[9].

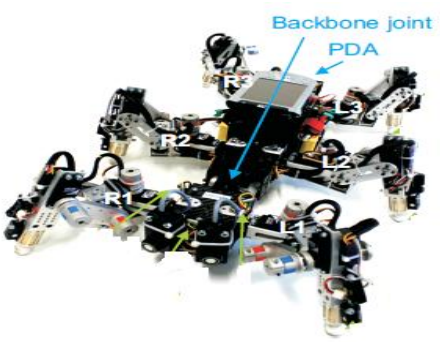

Fig.3:AMOSII, each degree of freedom is controlled by an oscillator and the inter limb coordination is provided by the connections between oscillators.

The CPG-based approach for locomotion control systems has several advantages, such as stable rhythmic patterns, the rapid return of such systems to their normal rhythmic behavior after transient perturbations of the state variables, and the provision of robustness against perturbations. As a result of the natural synchronization and coordination of CPGs, the amount of computation is reduced. The synaptic plasticity of the interconnections and feedback signals, used to integrate sensory information, allow CPGs to produce flexible locomotion in unknown environments.

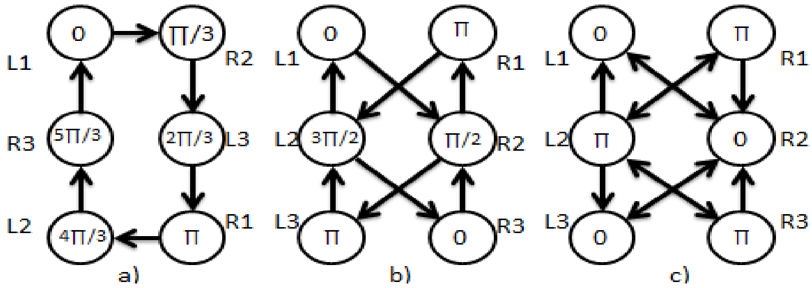

Fig.4: Configuration of typical gait patterns in hexapod locomotion and the relative phases between limbs.The gaits are: (a) slow walk (b)Medium walk (c)fast walk.

V. HARDWARE IMPLEMENTATION

Consider a hexapod robot shown in Fig.5, which has amain body and six legs. Each leg consists of links of thigh andtibia being connected to each other through a knee joint thatcontrols forward movements. Each leg is connected to the mainbody through a rotary joint that controls the forward movementsand a shoulder joint that controls the side movements.A motion engine is to generate a set of joint control signalsto realize the desired walking patterns.

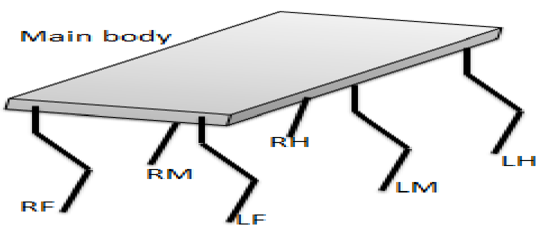

Fig.5: Schematic model of hexapod robot

In nature, when a legged animal walks on irregular terrains,the walking pattern must be adjusted with reflexesin real time to realize stable adaptive locomotion[5]. For alegged robot, to adapt to environments, joint control signalsmust be adjusted online according to surface conditions[2]. Theworkspace trajectory plays a critical role in robot locomotion.In this paper, CPG-based control architecture is proposedfor the locomotion control of legged robots[3], as shown inFig. 6.

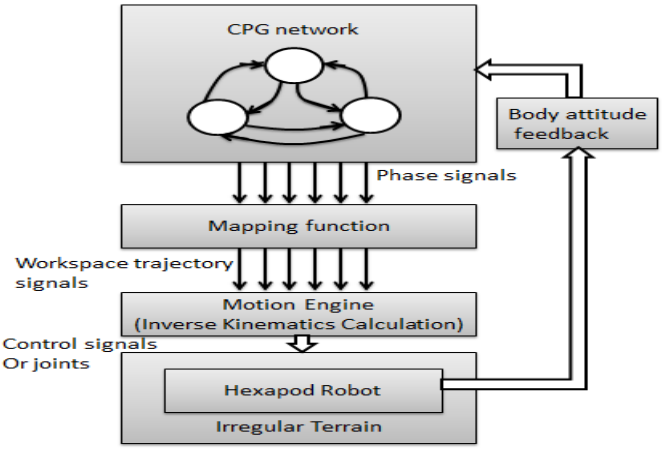

Fig.6: Architecture of the locomotion control system

The control architecture consists of a workspace trajectorygenerator and a motion engine, which allows a robot to self-modulate workspace trajectories in real time according toground conditions. The trajectory generator is built on a CPGnetwork with neuron oscillators. In this figure, three coupledoscillators are used to denote the CPG network[4]. The CPGnetwork can generate a series of phase signals with specificphase relationships. Through function mapping, workspace trajectories of the four legs can be generated online. Due tothe dynamic properties of a CPG network, speed adjustmentand gait transitions of the locomotion can be easily realized.

VI. EXPERIMETNAL RESULTS

In this section, experiments are designed to validate theproposed control method. In order to verify the superiorityof the proposed control method, comparative experimentsbetween traditional CPG-joint-space control method andCPG-workspace control method are designed.*AMOSII* is utilized as the robotplatform to validate the proposed control method. Thisrobot has the similar structure with the constructed hexapodrobot. The behavior analysispresented was usedto design the VDP networks for the hexapod robot'scontrol. Figure 13 shows the pattern generated for thethree hexapod gaits.

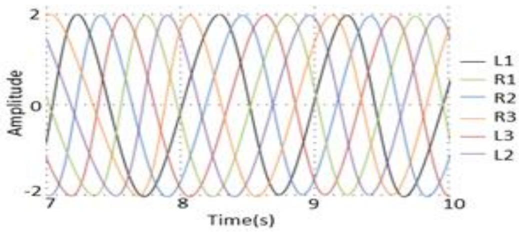

Fig.7: Slow walk movement of hexapod

The hexapodlocomotion needs rhythmic patterns with a specific phaseand order among the limbs. With the slow case, all thesignals have phase differences among them, as follows:*L*1-*R*2-*L*3-*R*1-*L*2 -*R*3. With the medium walk gait,the phase among some signals is equal to 90 degrees, inthe following order: *R*2 -*R*1-*L*2-*L*1. The signals *R*1 and L1 are in phase with *L*3 and *R*3 respectively.With the fast gait, the limb signals are divided into twogroups. The limbs in the same group are movingsynchronously and the phase between the groups isaround180 degrees. Furthermore, adaptive trajectories can be generated in real time through the mutual entrainment of the CPG network with the feedback signals from the body sensors on the robot. With the generated workspace trajectories, the adaptive joint control signals can be calculated using the motion engine.

VII. CONCLUSION

The proposed locomotion control architecture has effectivelyused a workspace trajectory generator and a motion engine forlegged robots to overcome the limitations of the conventionalCPG-inspired control methods. Using the proposed control system, the adaptive walking of ahexapod robot on irregular terrain with a slope and a seriesof stairs has been realized. It must be noticed that the gaittransitions and walking pattern changes have been realized onlyby modifying a few parameters of the CPG network. This paperhas validated the potential of the CPG concept in the study ofthe dynamic walking of legged robots.This methodshould establish a new direction for adaptive locomotion controlof legged robots. By referring to the neural system oflegged animals, the adaptive dynamic walking on nature terrainusing more reflexes has been studied in this paper as the nextchallenge.

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