Hexapodal robot locomotion over uneven terrain

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Abstract

This paper presents a novel gait generation approach which combines a reactionary and a central pattern generator (CPG) system. The former couples isolated leg controllers by simple gait generation rules that ensure static stability and produce a continuum of gait patterns across the full speed range. The CPG system is based on six coupled oscillators and complements the reactionary system to form an adaptive robust gait generator dominated by reactionary feedback at low speeds and the CPG at high speeds. The gait generation system has been demonstrated controlling a purpose built hexapod robot (MAX) which can traverse uneven terrain.

1. Introduction

Several research groups are contributing to the development of walking machines. The advantages of walking over wheeled locomotion are very attractive to the military who envisage sending powered vehicles where only soldiers on foot can now reach. Space associations have an interest in walking as a means of locomotion in space or on planets. The nuclear industry have an interest in using legged robots to perform tasks in hazardous environments. The development of walking machines has aided understanding of the mechanics of biological locomotion. The problem of co-ordinating legs and balance is also a challenging problem to the world of A.I. and also it can give an insight into the way an animal's nervous system works.

Many small legged robots for example Hector [1], Ghengis [2] , Atilla and Hannibal [2] , the Case Western Hexapod [2] , the TUM hexapod walking machine [2] and Lauron II [2] have been built. Joint motion and leg coordination is central to these walking robots and a number of different control approaches have been investigated. A key problem is that of correct gait generation when locomoting over uneven terrain.

One aim of our research has been to investigate the role of central pattern generation, sensory feedback and inter-leg communication rules in the generation of statically stable gait patterns for various walking speeds for a real hexapodal robot called MAX (Mobile Autonomous heXapod).

2. Background research

Many walking robot hexapods have a single preprogrammed gait, usually the tripod gait (180° phase difference between the legs), that they just cycle through. Gait is generated in a clockwork fashion and cannot intelligently react to disturbances or loading conditions. Other robots have two or more such predetermined fixed gait patterns and can switch between them. One approach to generating a continuum of *reactionary* stable gait patterns rather than several predetermined patterns is currently being researched by Cruse and colleagues [3]. His model is based on biological studies and experiments on stick insects and suggests that each leg has a control system which generates a rhythmical step movement corresponding to a relaxation oscillator, where the change in state between power and return strokes is determined by a leg position reaching certain thresholds. The threshold towards the rear of the insect is termed the *Posterior Extreme Position* (PEP) and the threshold towards the front of the insect the *Anterior Extreme Position* (AEP). While each leg is in contact with the ground, it moves backwards at a constant velocity equal to the forward velocity of the insect. A feedback servo-system controls this velocity. The swing is a fixed motion independent of the velocity of the insect.

Based on his investigations into the walking mechanism of the stick insect, Cruse argues that the former positional influences can be summed up by eight interleg co-ordinating rules, summarised here:

Ipsilateral influences[1]

1. A leg is hindered from starting its return stroke while its posterior leg is performing a return stroke.
2. A leg is temporarily encouraged to stall its return stroke just after a posterior leg has completed its return stroke.
3. A leg is encouraged to swing as its anterior leg moves further backwards in its power stroke.
4. In stick insects, the swing of a leg is targeted so that the tarsus lands immediately behind the anterior tarsus. This influence exists between the hind and middle legs, between the middle and front legs and also between the front legs and the antennae.
5. When the above targeting mechanism fails a treading-on-tarsus reflex causes the posterior leg to lift again and be placed slightly to the rear. This reflex exists between all ipsilateral leg pairs for both forward and backward walking.

Contralateral influences

6. A contralateral neighbouring leg is encouraged to swing when one leg has just started its power stroke.
7. The further back a leg moves in its power stroke, the more its contralateral neighbouring leg is encouraged to swing.

Combined ipsilateral/contralateral influences

8. If a leg is restricted during its power stroke so that its speed falls, the motor output of all neighbouring legs is increased.

Pfeiffer and colleagues [4] have used this model to control the Technical University Munich (TUM) walking machine. The walking machine is loosely based on a stick insect and uses the same assumptions and approximations as Cruse does in his model insect. Only rule 1 above was used but was applied to contralateral pairs as well as ipsilateral pairs of legs. To this rule was added a further mechanism which would not allow a leg to swing unless all directly neighbouring legs were in a power stroke and, if this was not the case, the overall walking speed of the robot was reduced until the condition was fulfilled. This speed was also temporarily reduced if a leg was obstructed during a swing phase. The offending leg is retracted slightly, lifted higher and then the remaining protraction attempted.

Cruse has implemented the above co-ordinating rules 1-4, 6 and 7 into a neural controller which acts to excite or inhibit a PEP detector neuron. The model has been used to drive a simulation of an insect with good results. The model shows the typical change in co-ordination from the tetrapod gait at low speeds to the tripod gait at higher speeds. The co-ordination patterns are stable with co-ordination usually being restored within one cycle of a perturbation. However, there were problems when starting legs from unusual positions where the machine can loose stability.

Beer and colleagues [5] have developed a hexapod that utilises continuous-time recurrent neural networks to control the gait patterns. The neural gait controller can produce a continuous range of wave gaits depending on the excitation level of a command neuron. Each leg has its own controller based on an oscillating pacemaker neuron which fires to indicate the leg should be in swing, otherwise the leg is in stance and moves backwards at a speed determined by the excitation of the command neuron. The pacemakers of one side are phase locked to ensure the back to front metachronal waves[2]. The pacemakers all have mutual inhibitory connections to adjacent leg controllers to ensure static stability. This mechanism is equivalent to a *central pattern generator (CPG).*

Beer has based his locomotion controllers on the Pearson flexor burst-generator model [6]. This has a pattern generator which is in effect a single oscillator whose frequency is determined by a command signal. The output of this oscillator determines if the leg is in swing or stance. The oscillator is modulated by two sensory signals. A hair receptor indicates that a leg has reached its PEP and should commence swinging and cuticle stress receptors indicate that a leg has completed swinging and has come into contact with the surface and that a stance should commence.

Due to the individual strengths of the Cruse (*reactionary*) and Beer (*CPG*) methods, we decided to investigate how we might design a gait generator that effectively combined both approaches. Such a system hopefully providing improved performance beyond that of one method alone. Most importantly, we also wanted to implement our design on a real hexapodal robot.

3. Development of a CPG system

In the typical insect, the lower speeds depend on sensory feedback and it is only at higher speeds that a CPG seems to come into play and the leg movements can be maintained with minimal sensory information. At these high speeds, only one gait pattern exists which is that of the alternating tripod [7]. Thus our first task was to first investigate a CPG oscillator system capable of producing the alternating tripod gait and if disturbed, quickly lock back into this pattern. The CPG system did not have to show multiple gait patterns and symmetry breaking, only lock strongly into the tripod gait. This gait controller should dominate gait patterns in the upper half of the

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[1] Couplings between legs on the same side of the insect are termed *ipsilateral* and those between opposite sides, *contralateral.* The *posterior* leg is the adjacent leg towards the back of the insect but on the same side as the leg in question. The *anterior* leg is the adjacent leg towards the front.

[2] Insect gaits are based on *metachronal waves* which are waves of leg swings that start at a back leg and ripple to the front along the side of the insect.

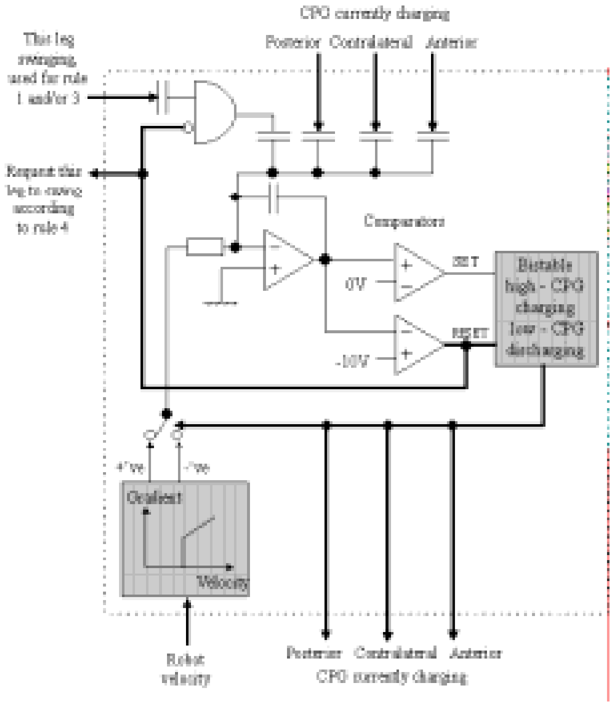

Figure 1: Schematic diagram of one CPG oscillator.

speed range and only be modulated by a reactionary system which should take care of the lower half of the speed range.

Much of the coupled oscillator behaviour in nature is attributed to the pulse coupled locking of oscillators into fixed phase relationship patterns [8]. Experiments were performed with six negatively pulse coupled oscillators to obtain a tripod gait pattern. The arrangement of the six oscillators is shown in the centre of figure 3, and figure 1 shows the details of one of the CPG oscillators. The pulse coupled system was tested with gradients between 0.5 and 1.5, which went beyond the range required for the combined gait system, and from various starting voltage values on all the oscillator capacitors. The system always locked into an acceptable tripod gait within three cycles.

From these experiments, it was decided to use the above CPG system to form a central pattern generator where each time the oscillator passes its maximum threshold and starts to discharge it initiates a swing. By changing the slope of the charge and discharge region, the frequency was altered so the slope would be made a function of the required velocity of the robot insect. When combined with a reactive pattern generator, if the reactionary system initiates a swing before the CPG system does, then a transition from discharge to charge should be made to occur in the respective oscillator before it reaches its maximum threshold. This would serve to align the CPG produced pattern with the legs and reactionary system. Furthermore, it was decided that the two systems should be arranged so that the central pattern generator would only function in the upper half of the speed range where it should dominate.

4. Development of a reactionary system

In order to generate a continuum of gaits from the slowest wave gait, through the ripple gait all the way to the tripod gait at half maximum velocity, it was decided to investigate the AEP and PEP threshold approach.

The output from the designed CPG gait controller to each leg is a velocity signal in the single forward and backward dimension. All legs were assumed to have the same range of motion and this motion was normalised. The single value representing the position of each leg was 0.0 for the furthest forward point and 1.0 for the furthest backward point. A wave-form with a positive gradient was equivalent to a leg in stance. This gradient was made equal to the required velocity of the robot insect. The negative gradient was equivalent to a leg being in swing and had a fixed velocity. The two thresholds at which the gradient changed sign were the lower AEP threshold and the higher PEP threshold. The PEP is the critical threshold because this is the point at which a leg removes its support in order to swing and increases the likelihood of the robot falling over.

The AEP was fixed at zero and the PEP was nominally made equal to 0.92 but could be altered by the position of the other legs. This threshold could not be set at 1.0 because if a leg is swinging and an adjacent leg was already in swing, then the former leg could continue travelling backwards relative to the robot body and thus propel the robot forwards. These values formed a twin positional threshold relaxation oscillator capable of controlling the forward and backward position of a single leg in isolation from all the other oscillators. The negative gradient was related to the velocity of the leg during swing and was set at 1.0 so that the swing took nominally 0.92 secs. The positive gradient was related to the velocity that the robot was travelling, and was between 0.0 and 1.0. Figure 2 shows the resultant leg controller design. Six such isolated leg controllers were then coupled so that stable gait patterns were produced. One method of communication was achieved by allowing the PEP to be altered by the position of the other legs according to a set of rules. Most of the rules were originally based on those identified by Cruse and workers on the TUM walking machine, but some notable differences emerged. These are described as follows:

Cruse **rule 1** was used, but was extended to apply

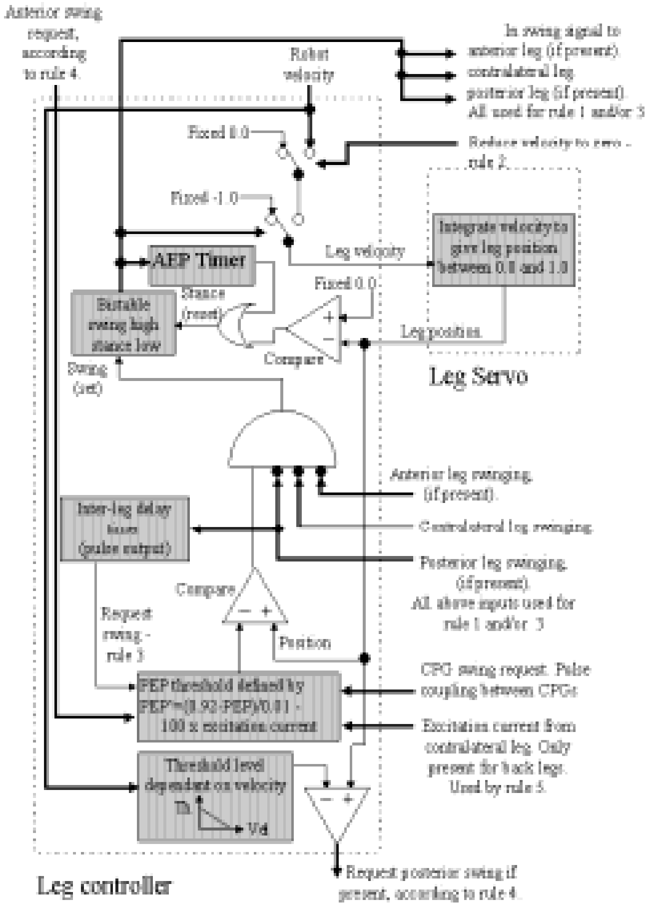

Figure 2: Schematic diagram of one leg controller.

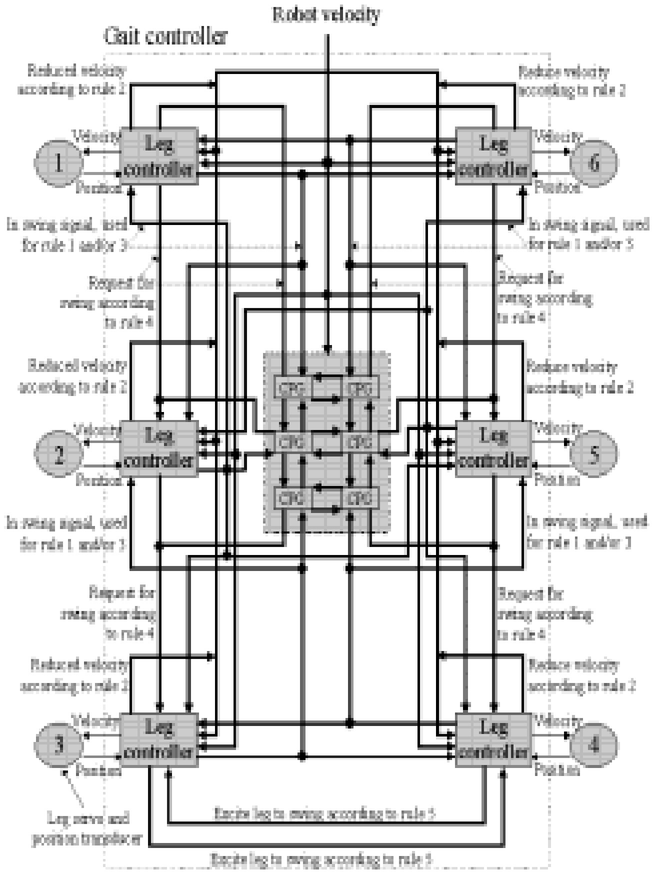

Figure 3: Flow diagram for the combined CPG and reactionary gait systems.

to all adjacent legs rather than just the posterior leg, and extended to prohibit a swing rather than discourage it. Cruse **rule 2** was implemented. Cruse **rule 3** was completely changed from a simple positional excitement, to one based upon a moveable *inter-leg delay* threshold which generates a swing at the correct point in the cycle. Cruse rule 4, 5 and 6 were not implemented. A new **rule 4** was implemented which requests a leg to swing as its anterior leg approaches a point in its cycle that allows enough time for the leg in question to start and complete a swing, and then for the inter-leg delay time to pass just as the anterior leg reaches its normal PEP threshold. This point was limited so that it could not go below a value of 0.23 secs. Cruse rule 7 was implemented only between the hind legs and became our **rule 5**. Cruse rule 8 was not implemented. The result was a system that displayed a continuum of gait patterns up to half speed and then the alternating tripod pattern above this speed. Such results have not yet been demonstrated and published by Cruse.

5. Combining reactionary and CPG generated gaits

This section presents a very robust gait controller that produces insect like gaits and is dominated by sensory information at low speed and operates with little or no sensory information at higher speeds. To achieve this, the CPG alternating tripod gait pattern generator was combined with the sensory threshold driven relaxation pattern generator, see figure 3. The reactionary controller produces the continuum of wave and ripple gaits up to a speed of 0.5, then the tripod gait between speeds of 0.5 and 1.0. The CPG is activated at speeds above 0.5 and was arranged to oscillate slightly faster than the reactionary system would do, for a given velocity, which aids the CPG system in dominating and initiating all the swings, with the penalty that the stance length is slightly shortened from its usual 0.92 value. Every time the CPG wave-form reaches its maximum threshold of 1.0, the PEP threshold of the associated leg is excited to just below 0.0 so that the leg is forced to swing unless prevented from doing so due to an adjacent leg

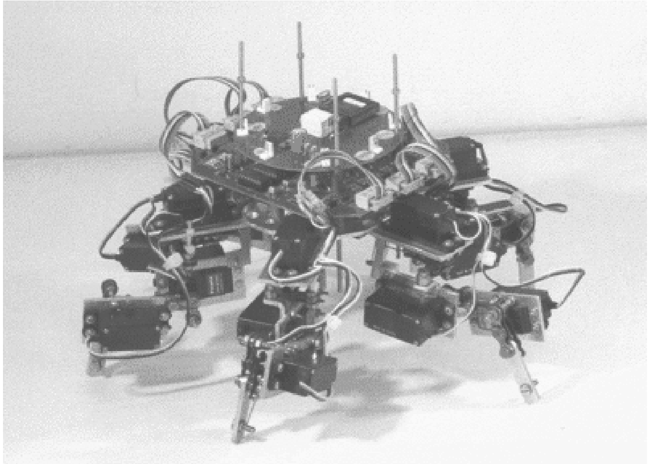

Figure 4: MAX (Mobile Autonomous heXapod).

being in swing. The CPG system will dominate once it is brought into phase with the reactionary system. As the periods of the two systems are very similar, this alignment could take many cycles. So the two systems are also kept in phase due to a coupling value of 0.1 being added to the oscillator value of the associated CPG every time the reactionary system initiates a swing. The hybrid gait controller was implemented on a real hexapodal robot called MAX, see figure 4.

6. Results

The control system produced the required gait patterns. Below speeds of 0.5, the system is essentially reactionary and produces stabilisation into the correct gait pattern within two cycles. Above speeds of 0.5, and from any unfavourable disturbance of both the leg positions and the CPG oscillator voltages, the required tripod gait is usually achieved within just one stepping cycle and the full synchronisation of the CPG oscillators and the reactionary system within two and occasionally three cycles.

If the CPG system fails completely then the reactionary controller will produce the correct gaits across the full speed range from 0.0 to 1.0. Combined with the CPG, the reactionary controller can suffer considerable PEP information loss damage, and also complete loss of all AEP sensory information and still produce the correct stabilised gait.

Most sensory failures of either the CPG or reactionary system do not significantly affect the gait pattern across the whole speed range. The tripod gait region, from 0.5 to the full speed of 1.0, is the most stable part and can withstand complete loss of sensory information and yet still produce the correct stabilised gait pattern. Further still, it can withstand complete loss of reactionary rule 3 which depends on motor information. This amounts to complete failure of the reactionary system and under these circumstances, the gait pattern is being controlled purely by the CPG.

7. Conclusions

This paper has described a central pattern generator (CPG) system based on pulse coupled relaxation oscillators. A reactionary gait generation system, consisting of six separate leg controllers each configured as a positional threshold driven relaxation oscillator capable of controlling a leg in isolation, has also been described. The two systems were then combined to produce a very robust hybrid gait controller. The action is mainly reactive through the lower half of the speed range but then is dominated by the CPG system once the tripod gait pattern is reached at half speed. This is similar to the general gait behaviour of most hexapod insects. From a disturbed state, the controller can quickly re-establish the appropriate gait whilst remaining statically stable.

8. Acknowledgments

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