IMPLEMENTING AN ARTIFICIAL CENTIPEDE CPG

Integrating Appendicular and Axial Movements of the Scolopendromorph Centipede

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Abstract: In nature, a high number of species seems to have purely inhibitory neuronal networks called *Central Pattern Generators* (CPGs), allowing them to produce biological rhythmic patterns in the absence of any external input. It is believed that one of the mechanisms behind CPGs functioning is the *Post-Inhibitory Rebound* (PIR) effect. Based in the similarity between the PIR functioning and the *Scheduled by Multiple Edge Reversal* (SMER) distributed synchronizer algorithm, a generalized architecture for the construction of artificial CPGs was proposed. In this work, this architecture was generalized by integrating, in a single model, the axial and appendicular movements of a centipede in the fastest gait pattern of locomotion.

1 INTRODUCTION

Central Pattern Generators (CPGs) are neural circuits that can, without any sensory input, produce rhythmic patterned outputs (Marder et alli, 1995). These networks underlie the production, in a large spectrum of species, of a wide variety of rhythmic motor patterns such as walking, swimming or flying. For that reason, the scientific community devotes enormous efforts to full comprehend it and, as fast as new biological explanations are proposed to explain the mechanism underlying the functioning of CPGs, several mathematically strict models are developed with the purpose of encompass their effects to fields like robotics, computing and artificial intelligence.

The most common approach to the development of models for CPGs is based on dynamical system theory (Golubitsky et alli, 1997). Usually, the behaviour of the neurons in CPGs is modelled through the help of non-linear coupled oscillators. As one may know, the strategies to solve those types of systems cover a vast and sophisticated mathematical ground governed by differential equations. The difficulty to analyse those systems increases even more when the biochemical processes involved in the modelling of CPG activity are considered. On the other hand, a discrete and generalized model approach could produce the same results with the advantage of modularity and quick development without any lost of accuracy. In this work, we intend to use one of these models to reproduce the locomotion of a centipede, hoping to demonstrate the power of such models.

A special class of topology-independent graph dynamics called *Scheduling by Multiple Edge Reversal* (SMER), developed initially with the purpose of solve some problems in distributed computing, present itself as an interesting way of predict and reproduce the behavior of many biological oscillatory neuronal networks.

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In the following sections we will try to briefly explain the SMER algorithm and show how, starting from it, we can develop a model for the inner biological behavior of CPGs. After that, we will hold some discussions on centipedes, its axial and appendicular movements, and lastly, an experimental model will be draw as much as the conclusions.

2 SMER AND ARTIFICIAL CPGS

SMER is an algorithm used in Distributed and Parallel Computation as a tool to allow a given number of processes sharing a finite number of resources among them, without the occurrence of *deadlock* or *starvation*. SMER is a generalization of the *Scheduling Edge Reversal* (SER) graph dynamics. In order to understand SER, consider a given number of processes and resources as part of a neighbourhood-constrained system represented by an acyclic graph. Processes are represented by nodes and resources by oriented edges. Each node will be in one of two possible states: *operating* or *idle*; also, each edge will be always point to the process that has the resource turn available to. So, when a node has all the shared edges pointing towards it, i.e., has all the resources turns available, it changes from the idle state to the operating state (in this case, this node is also called *sink* node). Once this operating process has finished operation, it reverses all its oriented edges to its neighbours. Although that is not the purpose of this work, it's possible to prove that if the initial graph is acyclic, then no process will be idle forever and, more importantly, the system will oscillate (see Figure 1). More than that, at any cycle of oscillation, every process will operate the exactly same number of times (Barbosa, 1996).

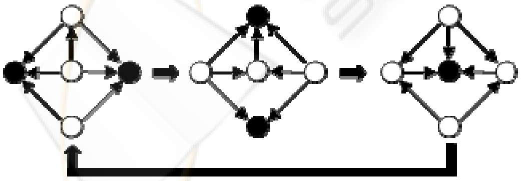

Figure 1: An example of the SER graph dynamics. Black nodes represent operating processes; white nodes represent idle processes.

Note that, even though the above described SER mechanism is enough to solve much of the problems of resource sharing, there is no differentiation among the node's time of task execution. It's fair to imagine that under certain circumstances some processes will need of its shared resources for a longer period of time than the others. To encompass this scenario, the SMER algorithm was created as a generalization of SER. In this new algorithm, all the characteristics of the SER persist with the difference that each node will have associated with it an natural number *r*, called *reversibility*, and between any two nodes is allowed to exist any number of oriented edges. Once a node has pointing towards it, from all of its neighbours, a number at least equal to its reversibility, this node is allowed to operate. When operation has finished, a node will reverse a number of edges equal to his reversibility to all of its neighbours (see Figure 2). Among the characteristics of SMER, one very important is that for any system with arbitrary reversibilities of its nodes, there is always at least one possible periodic SMER solution.

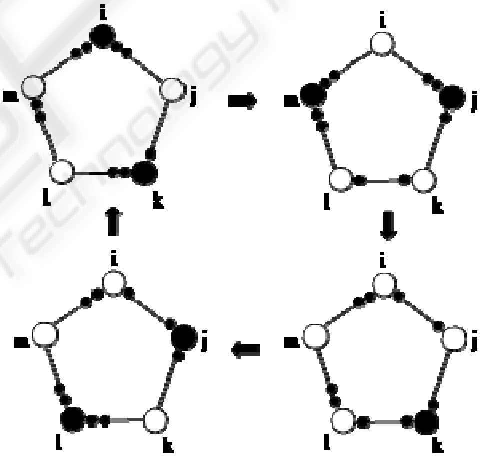

Figure 2: An example of a SMER graph. Note that to avoid the existence of several arrows connecting two nodes, a different representation of resource dependency is adopted. In this example the reversibilities are *i*=*l*=*m*=2, *j*=*k*=1.

Once we have defined what SMER is and how it works, it's important to clarify exactly how it connects with CPGs. As said before, CPGs are the underlying mechanism of a series of rhythmic patterns of locomotion. Although it is not completely clear how it exactly works, some biological mechanisms have been found and are credited as small units in the construction of CGPs. One of those real neuronal mechanisms is called *post-inhibitory rebound* (PIR) and is capable of produce an alternate cycle of activity in a group of inhibitory neurons in the absence of external stimulus (Pirtle and Satterlie, 2007). Although the PIR phenomenon is a complex subject, it is interesting to note that it matches perfectly to the mutual exclusion activity between neighbouring nodes coupled under SMER. It will be the theory behind the construction of modules that, in our model, will act just like a set of interconnected inhibitory neurons exhibiting PIR. These modules will be called *Oscillatory Building Blocks* (OBBs). So, instead of modeling electrophysiological activities of interconnected neurons based on membrane potential functions, we build an artificial CPG network with SMER-based OBBs for the exploration of the collective behaviour networks of purely inhibitory neurons.

3 THE ARTIFICIAL CENTIPEDE

Centipedes form a very special species of arthropods. They are capable of, combining axial and appendicular movements, attaining great speed with energetic efficiency. These unique characteristics of the centipedes stimulate a great number of biologists to study his static anatomy and the kinematics of his locomotion leading to a great amount of interesting information about this animal. For instance, biologists thru the use of high-speed cameras discovered that the number of legs touching the ground at a high-speed movement decreases when compared to the low-speed one , leading to a bigger distance between the supporting legs. In the extreme, a centipede can be supported for only four legs. Also, there is a direct correlation between the axial pattern of undulation and the speed. Nevertheless, whatever the speed is, in each segment contralateral legs will always step alternately (Anderson, Shultz and Jayne, 1995). All this aspects have to be taken into account while modeling the centipede's movement.

As a simple observation of a moving centipede may suggest, the challenge is the integration between two different components: the appendicular and the axial. It's reasonable to infer that a good way of tackle this problem could be made through the analysis of each movement separately, defining its period and trying to construct a SMER-based OBB for a later synchronization between the two. Although it seems a good strategy, it lacks an important aspect of the problem: the two types of movements are connected in a much deeper level. For example, it's impossible to see a real centipede to put two contralateral legs in any position different that the one caused by alternately stepping. Therefore, this approach would not reproduce that subtle aspect of the locomotion of the centipede.

To correctly model the locomotion of a centipede, with the maximum similarity to its complex behavior, one has to construct the OBB with eight nodes, i.e., motor neurons, enclosing one whole segment. In this case, the network responsible for the connection of these OBBs has to be one that follows the full length of the animal, from the anterior to the posterior segment. But before we see in detail the whole model, let's see more of each centipede's movement as a way to understand how this OBB will be made and how the connections among them will be put. Consider in the following a scolopendromorph centipede in the fastest pattern gait of locomotion, i.e., the amplitude of lateral bending has the largest value and the fastest speed of dislocation is attained. Also, it is important to note that this kind of centipede has 21 leg bearing segments linked by flexible membranes serving as the only intersegmental articulation.

3.1 Appendicular Movement

As said before, in any given speed of the centipede, two legs from the same segment are always in opposite positions, i.e., when the left leg of a segment is flexing the other in that segment is extending. Also, it is important to note that the legs that are in the concave side of an undulating wave are always extending. The last statement is the most important one since ties the axial and the appendicular movements.

For the sake of simplicity and without any loss of generality, let's assume the appendicular movement being defined as the action of two antagonic muscles: flexor and extensor. The first one is responsible for lifting a leg from the ground and the later one for doing the opposite. In this simplification, let's also assume that when a leg is touching the ground it is also pushing it backwards, allowing the effective movement of the animal.

3.2 Axial Movement

In the fastest speed a centipede can attaining approximately 1.5 times his length per second ($1.5Ls^{-1}$) with a correspondents $f = 3.45Hz$ and $\lambda = 11$ (Anderson, Shultz and Jayne, 1995). As a result, we infer that each concave section of the undulating wave it is composed for approximately 5 body segments. Also, for the sake of simplicity and without any lose of generality, let's suppose the lateral bending of a centipede as the result of a pair of antagonic muscles: one causing the left and the other causing the right bending.

4 EXPERIMENTAL EXPLORATIONS

Our artificial centipede was designed to reproduce the macroscopic features of its real counterpart. Following the before mentioned characteristics and simplifications, each segment will have six artificial muscles: two pairs of extensors and flexors (one pair per leg), one muscle responsible for the lateral bending to the right and another for the left. As a didactic resource, Figure 3 shows the schematic representation of our artificial centipede's segment taking into the account the artificial muscles mentioned before. The intersegmental articulation is represented by a single pivot. Once more, note that we consider that the extensor muscle is in action, the respective leg is producing traction.

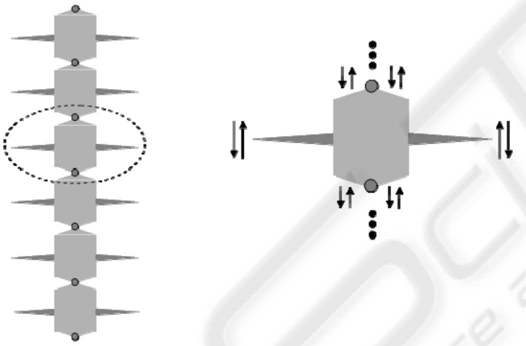

Figure 3: The Artificial Centipede design. In the left it is displayed 6 of the 21 segments of the model. In the right, the degrees of freedom in one segments is showed.

4.1 The Centipede OBB

As we saw before, to integrate the two types of movements, the OBB has to enclose the whole animal's segment. So, in this model we have to generate a SMER-based network capable of reproducing all the intermediate positions that each muscle assumed during the periodic movement. At this point, all the information retrieved during the analyses of real centipedes comes together.

In this OBB there are also two additional nodes, represented in the middle of Figure 4, that are responsible for the connection among the OBBs, represented by the dotted line, and for the activation of the others nodes, the artificial muscles. Note also that the reversibility of those two connection-nodes is 5, meaning that both of them are only activated when each connected edge is fully directed to them. Under another point of view, this also means that the others nodes, the artificial muscles, will be activated for a period of time five times longer them those two, since its reversibility is one.

The above mentioned reversibility, i.e., $r = 5$, was obtained from the analysis of the undulating wave that covers the centipede from the anterior to the posterior segment (see Figure 5.b). It is half of the wavelength.

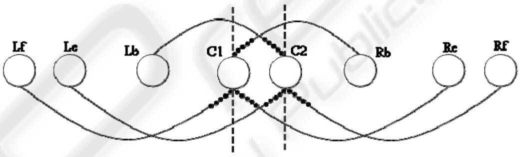

Figure 4: The resulting Oscillatory Building Block (OBB). C1 and C2 are the inter-segment connection nodes; dotted lines display the connection to other OBBs. Lb and Rb are nodes representing the artificial motor neurons/muscles responsible for the left and right bending, respectively. Le and Re are nodes representing the artificial motor neurons/muscles responsible for the extension of the left and right legs, respectively. Finally, Lf and Rf are the nodes representing the artificial muscles responsible for the flexion of left and right legs, respectively.

4.2 The SMER Network

Now that the OBB is built, it is necessary to connect them in a network that will reproduce the body behaviour of the animal. Since the locomotion pattern of the centipede is an undulating wave covering the whole body, the design of the network started with this perception and tried to reproduce this characteristic. Fortunately, this proposition proved correct and the SMER-based network, responsible for the connection of the OBBs is one that produces the activation of each OBB in the same direction as the travelling wave (see Figure 5).

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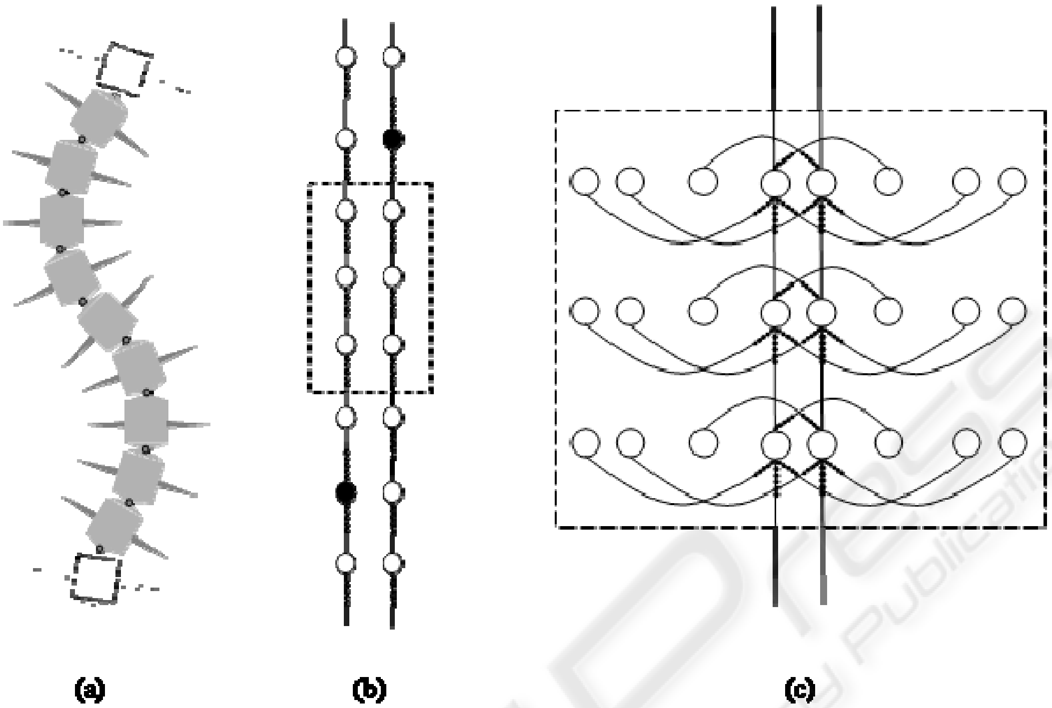

Figure 5: (a) The artificial centipede scheme (only 11 segments shown); (b) The functioning axial SMER-based network (without the OBB details); (c) SMER-based OBBs (3 OBBs shown).

5 CONCLUSIONS

Since the beginning of the study of Central Pattern Generators, one of the most critical problems was to understand and to model the biological macroscopic cyclic behaviour observed in terms of small nonlinear units. As an alternative to the usual continuous numerical methods applied in this field, the use of a discrete and generalized model to mimic the cyclic behaviour of CPGs was proposed in this work. In this aspect, the use of distributed algorithms avoids the usual complexity of the usual approach without losing expressivity or generality.

The present work shows the application of one of these algorithms (SMER) to model the complex locomotion of a centipede at its fastest gait pattern speed. Although others ways of reaching that objective may exist, we believe that our approach showed significant advantages in aspects like time consumed, facility and acceptable correlation with the reality. We believe that the strategy adopted in this work could help biologists and neurophysiologists to not only test the current theories in Central Pattern Generator's functioning, but also develop new points of view in the construction of complete explanations to the phenomenon of the generation of rhythmic patterns in animals.

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