Model: Salamander CPG model based on abstract oscillators

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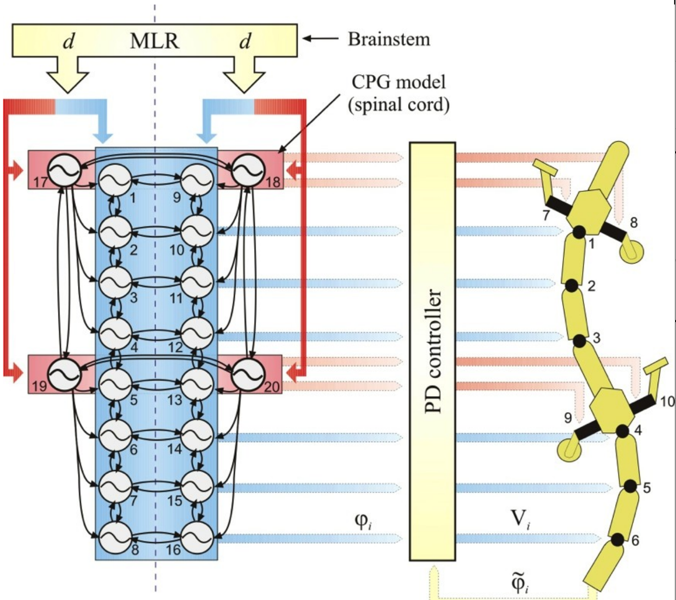
Brief Description *	The central pattern generator (CPG) for locomotion in the salamander spinal cord is modeled as a system of coupled abstract oscillators. The model reproduces the coordinated rhythmic activity of the CPG recorded during swimming and walking in the animal, as well as transitions between these gaits.
Narrative *	[Note that the model itself is only the left part of the figure. The middle and right part show the context in which the model is used].This is a model of the central pattern generator (CPG) that generates muscle activities for locomotion in the salamander, as published by Ijspeert et al. (2007). In the animal, this neural network located in the spinal cord receives inputs from the brainstem, for example the mesencephalic locomotor region (MLR), and produces several outputs, as different parts of the network produce periodic bursts of activity at different times. In the model, a part of the network that produces a sequence of bursts is represented by an abstract oscillator that produces a smooth oscillation (one oscillation cycle corresponds to one burst and one silent period). The model includes 20 of these oscillators: 8 oscillators represent the neural networks that generate the rhythm to control muscles on the left side of the animal (numbered 1-8 in the figure), and 8 represent the networks that control muscles on the right side (numbered 9-16). The neural networks controlling the four limbs are each represented by a single oscillator (numbered 17-20).The state of each oscillator is fully characterized by its phase and amplitude variables. Couplings between oscillators, represented with black arrows on the figure, allow the sending oscillator to influence the phase of the receiver. By influencing the phases of the oscillators, the couplings establish a particular "pattern" of activity in the network.During swimming, the limb oscillators are inactive (they saturate due to the high level of drive). The horizontal couplings in the axial network (blue) establish an anti-phase relationship between the oscillations in the left and right parts of the network. The vertical couplings establish a uniform phase lag (delay expressed as a fraction of an oscillation cycle) between oscillators from the head to the tail, i.e. the phase lag between oscillators 1 and 2 is the same as that between oscillators 2 and 3, etc. This results in a traveling wave of activity from the head to the tail: first oscillator 1 reaches its maximum value, then oscillator 2, etc.During walking, the limb oscillators are active (the level of drive is below their saturation threshold), and the strong couplings they send to the axis force synchronous oscillations in the trunk and the tail. For example, oscillator 17 forces oscillators 1-4 to oscillate together. This leads to a standing wave of activity in the axis: all trunk (respectively tail) oscillators reach their maximum value

	together.The CPG network thus provides a simple mechanism for the transition between the walking and swimming patterns of oscillation (standing wave and traveling wave respectively), through the saturation of the limb oscillators, which can be controlled by adjusting the global level of drive. This mechanism mirrors the observations in the animal where transitions between swimming and walking can be elicited by varying the intensity of an electrical stimulation of the MLR (Cabelguen et al. 2003).
Tags	computational, cpg, gait transition, ocillators, robotic system, salamander

Architecture

Diagrams	
	Salamander CPG model and robot schematic. Left: Circuit diagram of the CPG model used in Ijspeert et al. (2007). A drive signal d representing the excitation coming from the mesencephalic locomotor region (MLR) of the brainstem modulates the amplitude and frequency of the 20 CPG oscillators. Four oscillators constitute the limb CPG (red) and are globally coupled to the axial CPG (blue). Reciprocal axial connections (between the left and right sides) and inter-limb connections impose anti-phase oscillations between sender and receiver. Ipsilateral intra-axis connections maintain a uniform phase-lag, and limb to axis connections enforce axial oscillations in phase with the limb oscillators. Middle: the states of the CPG oscillators are used to calculated the desired joint angles. A proportional-derivative (PD) controller modulates the voltage in the robot motors to achieve the desired joint angles. Right: The salamander-like robot.

Inputs		
Name	**Data Type**	**Description**
Drive signal d	Tonic input	An excitation level (representing descending signals from the brainstem to the spinal cord) that determines the intrinsic frequency and amplitude in the oscillators that compose the CPG. For the same level of drive, the intrinsic frequency of limb oscillators is lower than that of axial oscillators. When the level of drive is too high, oscillators saturate (the amplitude drops to zero). The threshold for saturation is lower for limb oscillators, i.e. they saturate more easily. Although the limb and axial oscillators have different intrinsic (uncoupled) frequencies for a given level of drive, the strong couplings from limb to axial oscillators imposes the limb frequency on the axial oscillators when the limb oscillators

		are active (non-saturated).
Outputs		
Name	**Data Type**	**Description**
Joint angle phi	Oscillation	Each pair of oscillators in the axial network (for example oscillators 8 and 16) produces two oscillations that are in anti-phase. The two oscillations are subtracted to determine the desired joint angle for the corresponding joint in the robot (joint 6 in this example).
States		
Name	**Data Type**	**Description**
Amplitude r	State variable	The oscillator amplitude determines the amplitude of oscillations. In the model a differential equation ensures that the amplitude r quickly converges to the intrinsic amplitude R. The intrinsic amplitude R is a moving target as it can be adjusted by changing the drive.
Output x	Oscillation	The output of the oscillator is an oscillation that is calculated from the current amplitude and phase of the oscillator.
Phase theta	State variable	Each oscillator has a phase, which represents where the oscillator is in the oscillation cycle. It can be expressed as a percentage of a full cycle, or in degrees modulo 360, or in radians modulo 2*pi (e.g. a phase of 0.3 or 2*pi+0.3 in radians represents the same part of the oscillation). The phase in an isolated oscillator increases linearly with time. The rate of increase of the phase determines the oscillation frequency (e.g. 360 degrees in one second corresponds to an oscillation frequency of 1 Herz). The rate of increase of the phase is determined by the intrinsic frequency (function of the drive) and by the couplings between oscillators.

Submodules	
Name	**Description**
Axial CPG	Neural networks that generate the rhythm to control muscles on the sides of the animal
Limb CPG	Neural network controlling a limb - a single oscillator

Submodule: Axial CPG

Brief Description *	Neural networks that generate the rhythm to control muscles on the sides of the animal
Tags	

Submodule: Limb CPG

Brief Description *	Neural network controlling a limb - a single oscillator

Tags	