

Toward cultures of rhythm in legged robots

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Abstract

It is widely thought that sensorimotor synchronization, underpinning cultural domains such as music and dance, played a critical role in the evolution of human sociality. Here, we present virtual legged robots controlled by central pattern generators (CPGs) that evolve to synchronize motion to rhythmic sensory input in real time. Multi-stage, multi-objective evolutionary algorithms were used to maximize flexibility of the CPGs with respect to control parameters, and then to optimize a neural input layer for wide-ranging susceptibility to rhythmic inputs. The evolved CPGs self-organize to accommodate the input sequence over a range of frequencies and patterns while keeping the agents upright. We show how this behaviour can be scaled up to multiple interacting agents, including with differing morphologies, to produce novel behaviours. We then outline how spike timing dependent plasticity can be used for the acquisition of new motor patterns. Finally, taking inspiration from biocultural evolution and cognitive neuroscience, we suggest ways in which real-time social adaptation can play a key role in the evolution of complex social behaviours in robots.

Music and dance have been enormously important for human social learning and culture. A key part of musical ability is the ability of body movements to match a dominant frequency of a periodic stimulus. This is known as rhythmic entrainment, and is the subject of intense research in the cognitive and behavioural sciences (Levitin et al., 2018). Due to the fact that animals that can entrain to a beat are often skilled at vocal mimicry (Schachner et al., 2009), it has been widely theorized that musical and linguistic faculties are built on the same neural substrate (Petkov and Jarvis, 2012), and that music may have even been a proto-linguistic means of co-ordination (Cross and Woodruff, 2009). Other hypothesized evolutionary functions for entrainment in particular include signalling group size and intention (Mehr et al., 2021), temporal prediction (Patel and Iversen, 2014), and motor skill learning (Tomlinson, 2015), while related turn-taking behaviours are intimately connected to joint attention (Knoblich and Sebanz, 2008) and separating agents from simple objects (Premack, 1990).

Artificial systems, meanwhile, have been approaching levels of intelligence and autonomy that enable unsuper-

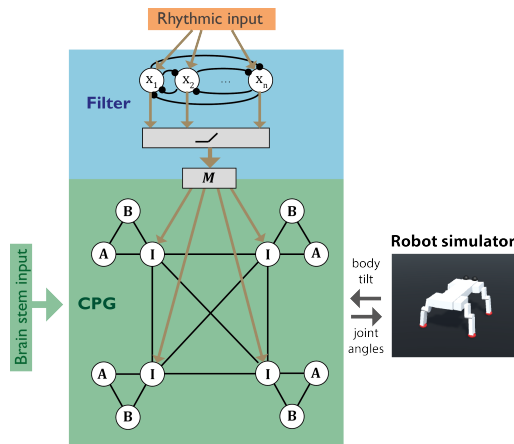


Figure 1: Controller schematic for the quadruped morphology. Circles denote modified Matsuoka neurons. Arrows denote one-way connections (excitatory or inhibitory), lines ending in circles denote inhibitory connections, and regular lines denote mutual connections (excitatory or inhibitory). The CPG (green) and filter (blue) modules are connected via n rectifying linear units, followed by an n by 4 weight matrix M . A/B: motor neurons; I: interneurons. For this study, a fully connected recurrent network of $n = 6$ neurons is used for the filter module. Time-derivatives of the A and B outputs are used to drive two joints on each leg.

vised learning and evolution (Rahwan et al., 2019; Hart and Le Goff, 2022). Most experiments in socially interacting virtual or robotic agents have focused on wheeled robots in a swarm context. In this case, behaviour is expressed as movement trajectories rather than bodily dynamics, limiting the complexity of rhythmic motion. Legged robots, on the other hand, have been created that can adapt frequencies of movement to intrinsic body mechanics (Buchli et al., 2006), to physical environments (Thandiackal et al., 2021), and to other agents (Jouaiti et al., 2018). These are typically based on modifying controller parameters according to phase-error feedbacks. With this approach, however, incremental feedback limits the response time, while the need to calculate an

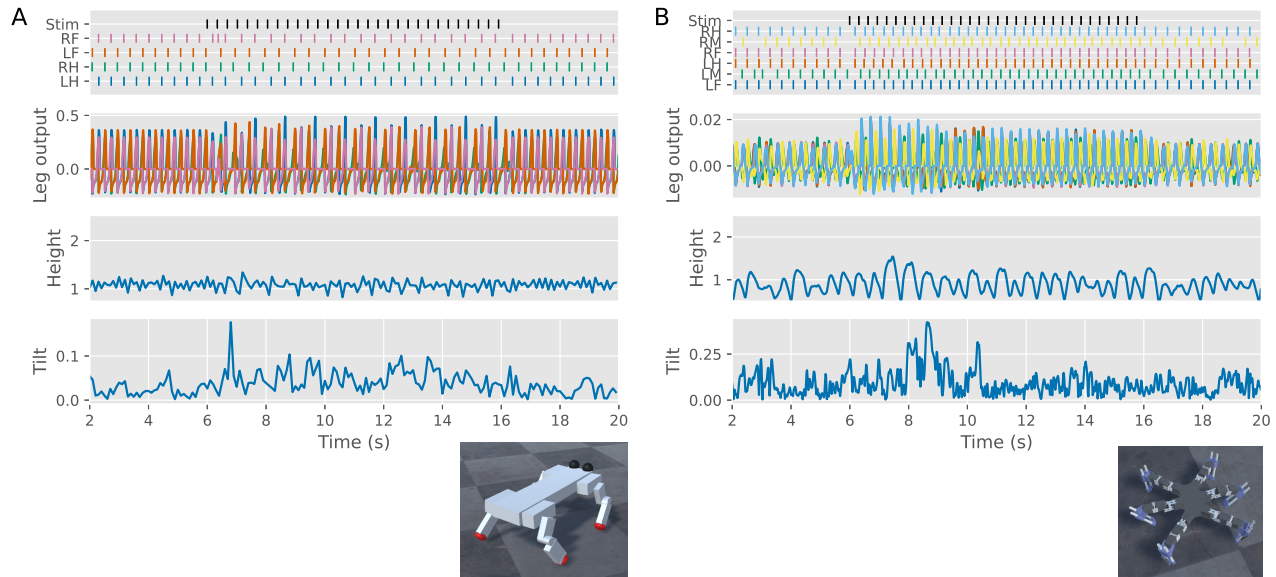


Figure 2: Entrainment to an isochronous stimulus at 80% of the natural period for (A) a quadruped and (B) a hexapod. The stimulus is started at the 6 second mark, and ends at the 16 second mark. Black ticks show the impulse times for the stimulus, and the peaks of the leg output below, corresponding to the extent of the forward and upward swings for the quadruped and hexapod, respectively. Hexapod design from Allard et al. (2022).

error signal limits the complexity of inputs.

Using evolved virtual quadrupeds and hexapods, we tested the possibility that self-organization of central pattern generators (CPGs) is sufficient for real-time entrainment to rhythms. Our approach, using spiking neurons, follows the general strategy of exploiting nonlinear embodied dynamics to generate complex behaviours (Husbands et al., 2021). When scaling this up to a multi agent system, such as a population of evolving modular robots as proposed by Hale et al. (2019), audio signals (or alternately, virtually transmitted event sequences) provide a morphology-agnostic means of coordination for collective behaviour.

As our CPG neuron we used a Matsuoka oscillator (Matsuoka, 1985) modified to have its oscillation rate dependent on both fluctuating and tonic (brain-stem) input, as is the case for biological neurons. Hence, the network’s oscillation frequency was not determined solely by parameters and interconnection weights. Each limb contained an identical module of two motor neurons (A/B) and one interneuron for interlimb connections (see Figure 1). The motor neurons also received feedback input from the body tilt. Using NSGA-III, we evolved populations of CPGs for four objectives simultaneously: backwards walking, forwards walking, forwards acceleration and overall stability. These were evaluated in the same trial by sweeping brain-stem input and body tilt parameters in three phases, resulting in a variety of gait periods and patterns. A “filter” layer was then evolved for entrainment ability on a subset of these CPGs.

The CPGs with more flexibility in oscillation period exhibited greater flexibility in speed and better entrainment ability. Example time series of entrained motion to even rhythms for two robots of very different size and morphology are shown in Figure 2. To a certain extent, agents could also entrain to more complex rhythms, including those not organized hierarchically, with the entrainment ability well predicted by the entropy of the autocorrelation function of the input. Notably, some robots’ gaits created polyrhythms with the input. This “imperfect copying” can be seen as a behavioural mutation that promotes diversity (Winfield and Erbas, 2011). To coordinate multiple robots, each can use the others’ footsteps as an input until synchronization is reached. It is expected that small groups of diverse agents can reach a compromise in their gait patterns. The conditions in which such spontaneous coordination is possible is a topic of current research.

This approach can also facilitate the evolution of social learning in robots. Hebbian-like synaptic plasticity, for example, can be used to reinforce movement patterns that are more frequently performed in the presence of other agents. This would enable sustained propagation of behaviour through social learning, which we can therefore call cultural transmission (Boyd and Richerson, 1985). As is the nature of collective behaviour, scaling up to groups of agents with adaptive interactions can lead to qualitatively new emergent behaviours at the group level and hence new possibilities for autonomous robot ecosystems.

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