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Bio-inspired CPG controllers for walking bipedal robots on rough terrains

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1. Abstract

There is a growing interest in biologically-inspired, dynamic control of walking robots, especially for efficiency and robustness. The bio-inspired Central Pattern Generator (CPG) is a simple and robust method to generate periodic movement. CPGs have two main functions: setting the rhythm of the movement and coordinating the activity of different joints. Those two functions can be produced by a single element (1-level CPG) or divided into two sub-systems (2-level CPGs). Both structures have been used in the literature for walking robots. However, their relative merits have not been compared. Here we investigate the relative robustness of these two strategies and which one facilitates learning.

Keywords: CPG, Biped, Robot, Control, Neural network, Genetic Algorithm

2. Introduction

Dynamic walkers, which rely on the natural dynamics of the robot, enjoy high efficiency and speed, by relinquishing the requirement of static or quasi-static stability at each point in the trajectory. Central Pattern Generators (CPGs) are prominent biologically inspired mechanisms to generate periodic movements.

CPGs have two main functions: setting the rhythm of the movement (rhythm generation, RG) and coordinating the pattern of activity of different joints (pattern generation, PG). The activity may refer to muscle activity in biological systems, or to the reference trajectory or torque actuation in robotics.

In 1-level CPGs [1], these two functions are performed by a single system that is generally based on a network of coupled oscillators, which receive continuous feedback signals and whose outputs are used directly as control signals for the motors. In 2-level CPGs [2], these two tasks are performed by two distinct subsystems, one to generate the rhythm, and another to generate the pattern of activity with that rhythm. The Rhythm Generator (RG) in this case is commonly based on a network of coupled oscillators, while the Pattern Generator (PG) could be any type of signal generator or control structure.

A common model for a CPG is based on a network of Matsuoka Oscillators: a simple network of self and mutual inhibiting neurons, each modeled as a second order non-linear system. This model demonstrates a rich variety of behaviors, and analytic conditions for generating periodic cycles have been found.

Our case study for evaluating these control methods is based on the Compass Biped (CB), a mathematical model of a simple 2-link robot, with 3 actuated joints (Hip and two ankles) depicted in Figure 1. The model is piecewise-continuous, and includes discrete transitions of the state at the impact of each foot with the ground. To clear the ground, the swing leg is contracted and extended at predefined conditions. This model's simplicity allows for rapid simulation, while retaining similarity to natural biped dynamics.

Our controllers use one of two limited feedback options; either a continuous signal of the relative angle between the two legs (the joint angle), or a discrete pulse each time a foot touches the ground. The output of the CPG-based controllers are torque commands for the actuated joints, which would be generated in real robots by lower level closed-loop control using series elastic actuation.

3. Methods

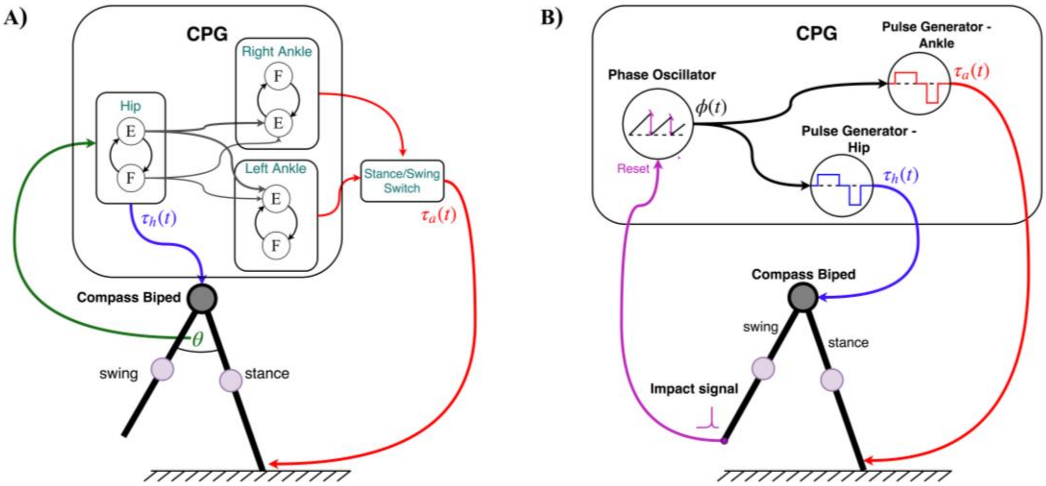

Figure 1.A. 1-level CPG. B. 2-level CPG

We designed 3 control structures; a single 1-level CPG and two 2-level CPG controllers. The controllers were optimized via Multi-Objective Genetic Algorithm [3], aiming for high robustness over rough terrains and speed. Results are summarized over 10 optimizations runs and used for further statistical analysis to assess significance.

Robustness was evaluated as the ratio of the number of successful trials over a stochastically generated terrain divided by the number of attempts (10, in this case). Ten terrains were generated for each optimization process, by using band limited white noise (with a cutoff spatial frequency of $1\left[m^{-1}\right]$).

3.1 1-level CPG

Inspired by the work of Taga et al [4], the 1-level CPG was implemented by a neural network of 3 Matsuoka Oscillators (MO), one for each actuated joint as depicted in Figure 1A. The network is centered around the Hip oscillator, which receives continuous feedback signal from the robot, with a one-way connection to the ankle oscillators. Since our robotic model is symmetrical, the control design is symmetrical as well for the two ankles.

3.2 2-level CPG

The 2-level CPG is based on a hybrid phase oscillator, similar to a Clegg Integrator to generate the rhythm as depicted in figure 1.B. The feedback is a single discrete pulse each time a foot impacts the ground. This keeps the control in synch with the movement of the robot. The pattern generator is a pair of rectangular pulse generators, one for the hip and the other for the stance-leg's ankle. Each pulse generator generates a pair of rectangular pulses per period, characterized by amplitude, offset and duration (in phase).

3.3 Hybrid 2-level CPG

The hybrid CPG is a 2-level CPG, whose rhythm generator is implemented by a single MO that received continuous input from the hip angle. This MO is similar to the hip MO in the 1-level CPG, however, in this case the output of the MO is used to set the rhythm by determining its zero crossing.

4. Results

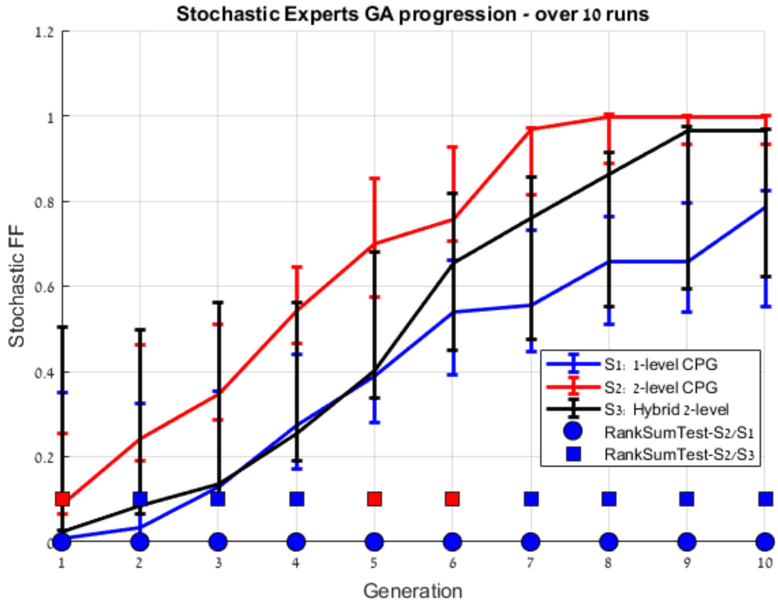

Figure 2. Robustness comparison of the 3 structures

Figure 2 presents initial results of our main comparison. The 2-level CPG shows consistent advantage over the other structures, over the entire learning process. Statistical significance of the difference, calculated using Mann-Whitney u-test, is shown in the two rows of marks at the bottom, comparing the 2-level CPG with the 1-level CPG (lower row) and with the hybrid 2-level CPG (upper row). Statistically significant difference with 95% confidence interval is shown with a blue mark, while failure to reject the null-hypothesis is shown with a red one. We can see that the difference in performance is statistically significant in all generations for the first comparison, and most generations in the second.

5. Conclusions

The main conclusion from this research is that simplicity is more advantageous than expected. The simple 2-level controller has fewer parameters, decreasing the dimension of the search-space considerably, compared with the more complex hybrid controller. The clear improvement over the 1-level controller shows the modular structure of 2-level CPG is beneficial.

Future work includes equalizing the number of parameters in each structure, for a comparison unbiased by the dimension of the search-space, as well as adding on-line learning processes (such as frequency and amplitude adaptation based on the current slope), and evaluating the control structures over a variety of different terrains. We intend to compare the performance over flat terrain (for velocity and efficiency) and varying slopes (to find maximum and minimum slope limits).

6. References

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