

Modular Neural Control for Bio-Inspired Walking and Ball Rolling of a Dung Beetle-Like Robot

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Abstract

Dung beetles can perform impressive multiple motor behaviors using their legs. The behaviors include walking and rolling a large dung ball on different terrains, e.g., level ground and different slopes. To achieve such complex behaviors for legged robots, we propose here a modular neural controller for dung beetle-like locomotion and object transportation behaviors of a dung beetle-like robot. The modular controller consists of several modules based on three generic neural modules. The main modules include 1) a neural oscillator network module (as a central pattern generator (CPG)), 2) a neural CPG postprocessing module (PCPG), 3) a velocity regulating network module (VRN). The CPG generates basic rhythmic patterns. The patterns are first shaped by the PCPG and their amplitudes as well as phases are later modified by the VRN to obtain proper motor patterns for locomotion and object transportation. Combining all these neural modules, we can achieve different motor patterns for four different actions which are forward walking, backward walking, level-ground ball rolling, and sloped-ground ball rolling. All these actions can be activated by four input neurons. The experimental results show that the simulated dung beetle-like robot can robustly perform the actions. The average forward speed is 0.058 cm/s and the robot is able to roll a large ball (about 3 times of its body height and 2 times of its weight) up different slope angles up to 25 degrees.

1. Introduction

The concept of bio-inspiration has been applied for solving many problems in different fields, especially in robotics. Bio-inspired robotics looks at how nature solves complex tasks and uses it as an inspiration for designing robot control and structures. One example of bio-inspired robots is the MIT cheetah robot that can perform impressive locomotion, like running and jumping, with high energy efficiency (Seok et al., 2013). This shows an advantage of bio-inspired robotics that uses four-legged animals as a blueprint for developing a legged, walking, running, and jumping robot.

While locomotion is a basic function of legged robots, recently object manipulation and transportation have been also considered as their important functions for applications, like search and rescue, transportation and exploration, where

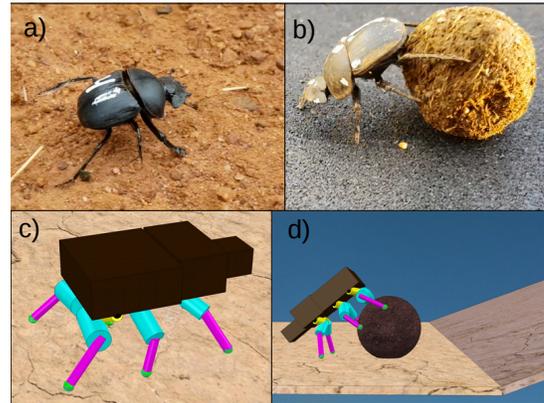


Figure 1: (a) A standing posture of the African dung beetle *Scarabaeus galenus*. (b) A ball rolling posture of the dung beetle. (c) A standing posture of our simulated dung beetle-like robot. (d) A ball rolling posture of the robot. The environment and robot model for simulation is provided by the robot simulation platform called V-REP (Rohmer et al., 2013). The dynamical property of the simulation is based on the Vortex physics engine. The parameter of the simulation is adjusted to be as close to reality as possible with some simulation constraint. The overall bounding box size of the robot (i.e., robot body) is 18.6 mm x 10.3 mm x 4.3 mm. The weight of the robot is around 1.1 kg and the dung ball is around 2.3 kg. We encourage the readers to see (Thor et al., 2017) for more details of the robot model.

mobile robots with versatility are in high demand. A traditional way to provide the object manipulation and transportation abilities for legged robots is achieved by installing additional manipulators and grippers (Roennau et al., 2014; Rehman et al., 2015; Schwarz et al., 2016). For example, SpotMini¹, a small four-legged robot from Boston Dynamics, is equipped with a single manipulator with a gripper for grasping a small object. To deal with a large object,

¹<https://www.youtube.com/watch?v=wXxrmussq4E>

the centaur-like robot Momaro with four legs uses two extra 7 degrees of freedom (DOF) manipulators with dexterous grippers (Schwarz et al., 2016) for the mission. Other legged robots, like six-legged robots LAURON V (Roennau et al., 2014) and Scarabeus (Bartsch and Planthaber, 2009), have a small gripper on one leg. In general, all these robots have been developed with separate locomotion and object manipulation/transportation systems. Having an additional manipulation system on the robots often requires extra control as well as power consumption.

In contrast to the traditional robot developments with locomotion and object manipulation/transportation abilities, small insects, like dung beetles, can efficiently use their legs for locomotion as well as object manipulation and transportation (see Figs. 1(a) and 1(b)). In other words, they can perform walking and ball rolling actions by only using their own legs and do not require an additional manipulation system. Therefore, when using the beetle as a source of inspiration for a legged robot, the robot should be able to use its legs for both locomotion and object manipulation/transportation.

Only a few works have shown legged robots which follow the beetle strategy by using their legs to walk as well as manipulate and transport objects (Koyachi et al., 2004; Takeo et al., 2009; Inoue et al., 2010; Chen et al., 2017). However, all these robots require precise kinematic and complex force feedback control. This ends up to the stop-and-go motions in order to maintain their stability. In other words, they cannot perform continuous movements for transporting an object, especially a large one.

To overcome the problem, we have developed a series of dung beetle-like robots with different bio-inspired control approaches (Sørensen and Manoonpong, 2016; Strøm-Hansen et al., 2017). While our previously developed dung beetle-like robot systems can perform continuous locomotion as well as object manipulation and transportation, they can only stably move on a level floor. To expand the operational range of the beetle robot, we present here for the first time our new modular neural control mechanism that allows the robot to not only walk with a tripod gait but also use its hind and middle legs to roll a large ball (3 times of its body height) (see Figs. 1(c) and 1(d)). With the control approach, the robot manages to stably and continuously roll the ball on a level floor as well as up different slope angles up to 25 degrees. To the best of our knowledge, the dung beetle-like robot with multiple functions (i.e., locomotion with object manipulation and transportation) that can deal with different terrains (i.e., different slope angles) has not been investigated or shown so far. However, the rationale behind this study is not only to demonstrate the complex behaviors but also to show that this neural control approach with a modular structure can be a powerful technique to solve sensorimotor coordination problems of many degrees-of-freedom systems (like legged robots) and to effectively provide complex multi functions to the systems.

2. Modular Neural Control

The modular neural control has been design for both walking and ball rolling. The structural design is based on the modular neural controller for a hexapod robot proposed by Sørensen and Manoonpong (2016). The main components of the control are the input neurons, the hidden neurons, three generic neural networks or modules (neural oscillator network acting as a central pattern generator (CPG), neural CPG postprocessing network (PCPG), and velocity regulating network (VRN), see details below), and the motor neurons. The complete diagram of the modular neural control is shown in Fig. 2. The CPG module generates the rhythmic patterns from its neurons (C_1 and C_2) which drive the motor neurons. The modulatory input (MI) projecting to C_1 and C_2 can change the frequency of the rhythmic patterns. The output signals from the CPG module are preprocessed by the PCPG modules to further shape and smooth the signals. The output signals from the PCPG modules are then passed to the VRN modules that regulate the amplitude of the signals before driving the motor neurons. Input neurons I and hidden neurons H play important roles in regulating the amplitude. The four inputs $I_{1,2,3,4}$ shown in Fig. 2(a) are used to activate different actions of the simulated robot. All inputs are passed through six hidden neurons $H_{1,2,3,4,5,6}$ by excitatory synapses. Hidden neurons receive four inputs from $I_{1,2,3,4}$ and their outputs are used as inputs to the VRN modules that regulate the amplitude of the signals from the PCPG modules. After that, the signals from the VRN modules will be transmitted to the motor neurons of the robot in order to perform locomotion and object transportation.

All neurons of the CPG and VRN modules are modeled as discrete-time non-spiking neurons, with an update frequency of 15 Hz. The activity of each neuron is described by

$$a_i(t+1) = \sum_{j=1}^n w_{ij} o_j(t) + b_i; i = 1, \dots, n,$$

where n is the number of neurons, b_i is a fixed internal bias term of neuron i , and w_{ij} is the synaptic strength of the connection from neuron j to neuron i . The neuron output o_i is given by a hyperbolic tangent (tanh) transfer function. Note, however, that the input neurons ($I_{1,2,3,4}$) are configured as linear buffers ($a_i = o_i$). Each PCPG module is modeled as a combination of a threshold neuron and a mechanism to convert the neural output into a sawtooth wave signal. The hidden neurons $H_{1,2,3,4,5,6}$ are configured with a linear transfer function. All connection strengths and bias terms are indicated by the numbers beside the connection lines (see Fig. 2(a)). These fixed connection strength and bias values are here empirically set to obtain the desired locomotion and object manipulation patterns.

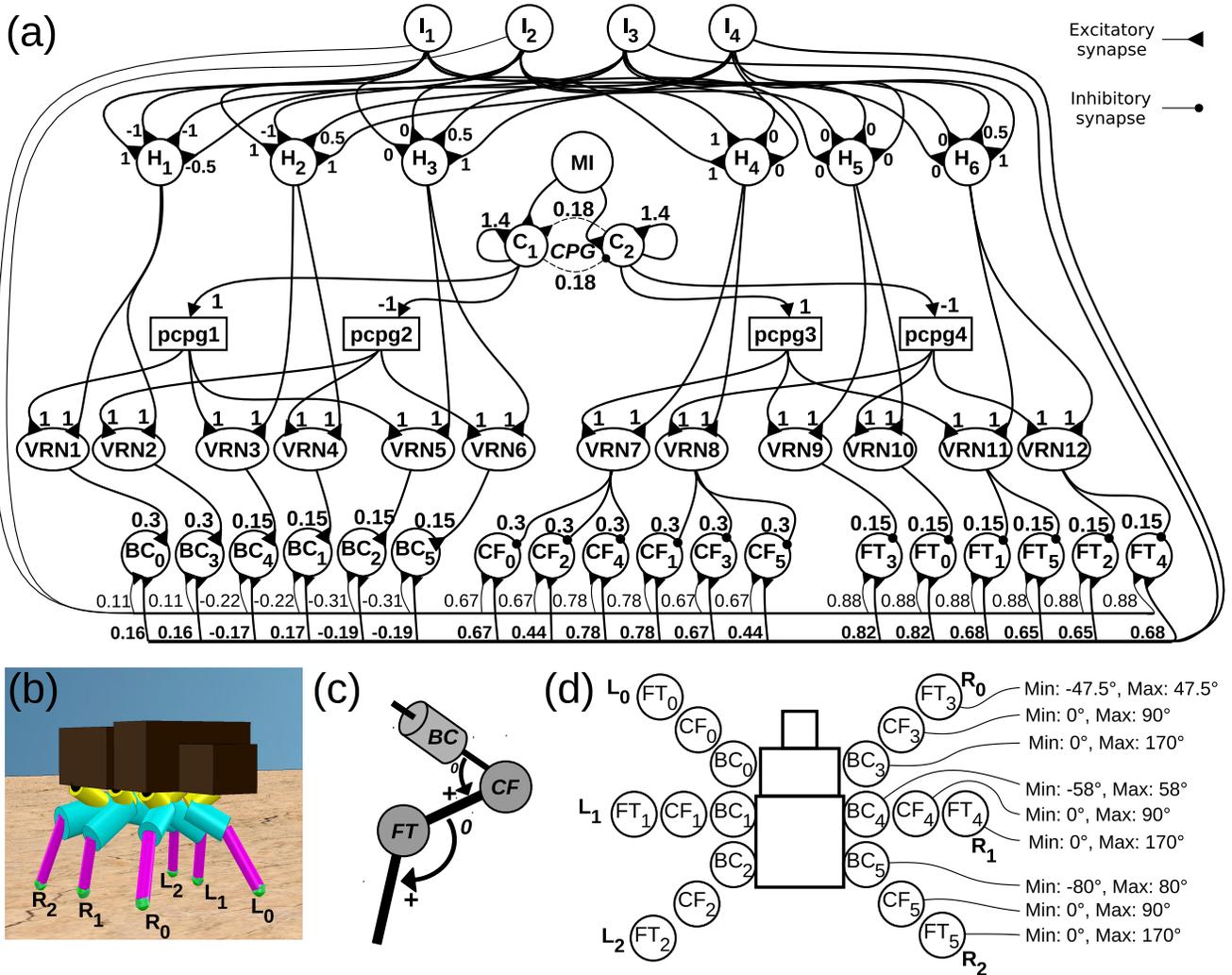


Figure 2: (a) Modular neural control for locomotion and object transportation. (b) The simulated bio-inspired dung beetle robot using the V-REP simulation environment. There are four main physical components of the simulated dung beetle. First is the body (brown color) containing abdomen, thorax, and head. Second part is coxa (yellow). Third part is femur (blue). Fourth part is tibia (purple). (c) The positive angle direction of each joint. The BC joint angle is positive (+) when the joint swings forwards and negative (-) when it swings backwards. The CF joint angle is between 0 to its maximum angle (see (d)). The FT joint angle is between 0 to its maximum angle (see (d)). The configuration of the motor neurons on the simulated robot. Minimum and maximum angles are shown for all joints of the right legs which are identical to those of the left legs. The abbreviation of the joints are BC: Body-Coxa, CF : Coxa-Femur, FT : Femur-Tibia. Subscript numbers of the joints define location of the leg. Subscript numbers (0, 3) refer to the front left and right legs; (1, 4) for the middle left and right legs; (2, 5) for the left and right hind legs.

2.1 Neural Oscillator Network Module (CPG)

Here, the model of a central pattern generator (CPG) is realized by using the discrete-time dynamics of a simple neural oscillator network with two neurons (C_1, C_2) and full connectivity (Fig. 2(a)). It can generate rhythmic patterns. A modulatory input MI is connected to the neurons C_1 and C_2 . By changing the value of MI, it is then possible to change the frequency of the CPG, resulting in different gaits. In this work, the MI value is set to 0.03 to generate a proper frequency for walking and ball rolling. The CPG outputs are visualized in Fig. 3. The detail and analysis of the CPG network are referred to (Manoonpong et al., 2013).

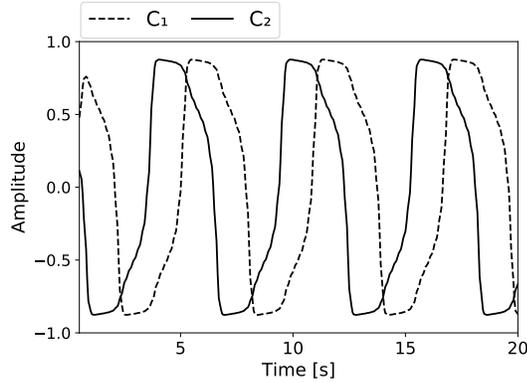


Figure 3: The rhythmic output signals from the neurons (C_1 and C_2) of the CPG with the defined parameters shown in Fig 2(a). Here we use the output signal C_1 for controlling all BC joints and the output signal C_2 for controlling all CF and FT joints.

2.2 Neural CPG Postprocessing Module (PCPG)

The output signals from the neurons $C_{1,2}$ of the CPG are shaped by neural CPG postprocessing such that smooth ascending and descending signals are obtained for motor control (Fig. 4). This kind of asymmetrical periodic signals is appropriate for locomotion as observed in insects which have a different duration of swing (ascending slope) and stand (descending slope) phases, being intrinsically asymmetry (Akay et al., 2004). In this modular neural control, there are four CPG postprocessing modules ($PCPG_{1,2,3,4}$), each receiving an output signal from the CPG. The $PCPG_1$ and $PCPG_2$ modules receive the same output signal of the neuron C_1 with different synaptic weights. Due to the different weights (+1 for $PCPG_1$ and -1 for $PCPG_2$), the output signals from the $PCPG_1$ and $PCPG_2$ modules have 180 degrees phase shift (see Fig. 4).

The same holds for the $PCPG_3$ and $PCPG_4$ modules that receive the same output signal of the neuron C_2 with different synaptic weights. This configuration forms a tripod gait similar to an alternating tripod gait of dung beetles. Addi-

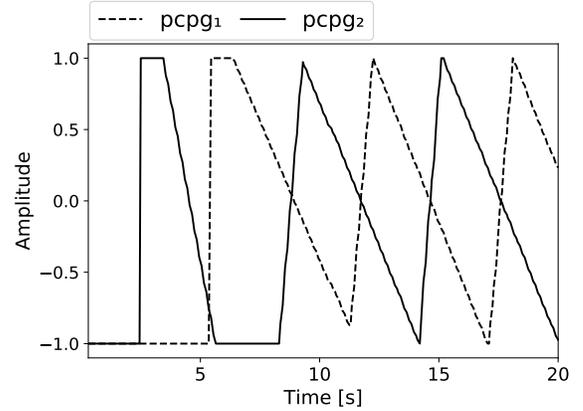


Figure 4: The output signals from the $PCPG_1$ and $PCPG_2$ modules (see Fig 2(a)). The output signals of the $PCPG_3$ and $PCPG_4$ modules having similar patterns to the ones of the $PCPG_1$ and $PCPG_2$ modules are not shown.

tionally, the advantage of this configuration is that the PCPG modules automatically shift the phase of the CPG signals by 180 degrees even if the frequency of the CPG signals is changed.

2.3 Velocity Regulating Network Module (VRN)

To obtain different actions (i.e., forward walking, backward walking, level-ground ball rolling, and sloped-ground ball rolling) and to maintain stability, we need to regulate the CPG signals. According to this, we use 12 velocity regulating network (VRN) modules (VRN_{1-12}) as shown in Fig. 2(a). The VRN taken from (Manoonpong et al., 2007) is a simple feed-forward neural network with two input, four hidden, and one output neurons (see Manoonpong et al., 2007). It was trained by using the backpropagation algorithm to act as a multiplication operator on two inputs applying to the input neurons of the VRN (see Manoonpong et al., 2007 for details).

Here, the VRN modules receive their inputs from H_{1-6} and the outputs of the PCPG modules. We use the VRN modules to reduce the amplitudes of the signals from the PCPG modules based on the values of the hidden neurons H before they are passed to the motor neurons. Examples of the output signals from the VRN_1 module with different input values obtaining from the hidden neuron H_1 are shown in Fig. 5. Each of the 18 motor neurons receives joint biases through the input neurons and a VRN output to obtain proper joint movements for stable walking and ball rolling actions of the simulated robot.

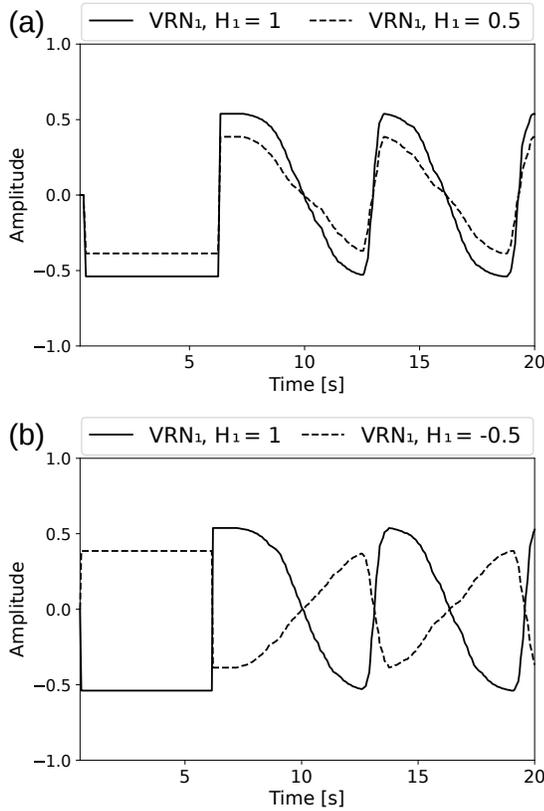


Figure 5: The periodic output signals from the VRN₁ module shown in Fig 2(a). (a) The VRN output signals when $H_1 = 1$ and $H_1 = 0.5$. (b) The VRN output signals when $H_1 = 1$ and $H_1 = -0.5$.

2.4 Input Parameters for Different Behavior Modes

The modular neural controller is able to generate two different behaviors. The first is a walking behavior and the second is a ball rolling behavior. The walking behavior has two modes which are forward walking and backward walking. The ball rolling behavior likewise has two modes which are flat ground ball rolling and sloped ground ball rolling. All four actions of the simulated dung beetle can be obtained by adjusting the input parameters as shown in the table 1.

Table 1: Input parameters for different behavior modes.

Actions	I_1	I_2	I_3	I_4
Locomotion: Forward walking	1	0	0	0
Locomotion: Backward walking	0	1	0	0
Ball rolling: Flat ground	0	0	1	0
Ball rolling: Sloped ground	0	0	0	1

3. Experimental Results

To test the modular neural control on the simulated dung beetle-like robot, two environments have been provided for it to interact with. The first environment is just a ground for the locomotion task. The second environment has both level and sloped ground for the object transportation or ball rolling task. A dung ball has therefore also been provided in this environment, so that the robot can roll it on the level and sloped ground.

Figure 6 shows the simulated robot’s position during walking experiments where each experiment lasts 120 seconds. The average speed of the robot is around 0.058 cm/s and the maximum deviation on the y-axis is 0.5 cm. It can thus be seen that the controller seems to generate a straight walking behavior with low deviation of the lateral direction. Note that in this test, the controller acts as an open-loop controller. It only generates forward walking without sensory feedback.

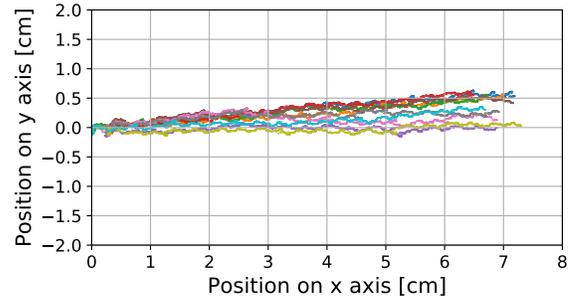


Figure 6: Position of the simulated robot during forward walking. The experiment involves 10 trials with the duration of 120 seconds each.

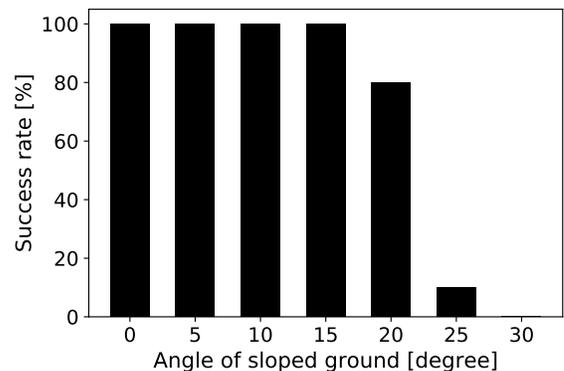


Figure 7: Result of the ball rolling experiment on level and different angle of sloped ground. The success is indicated by not fall from the ball while rolling or can roll continuously without stuck on any position for a long time. Each sloped angle is tested for 10 trials with a duration of 180 seconds.

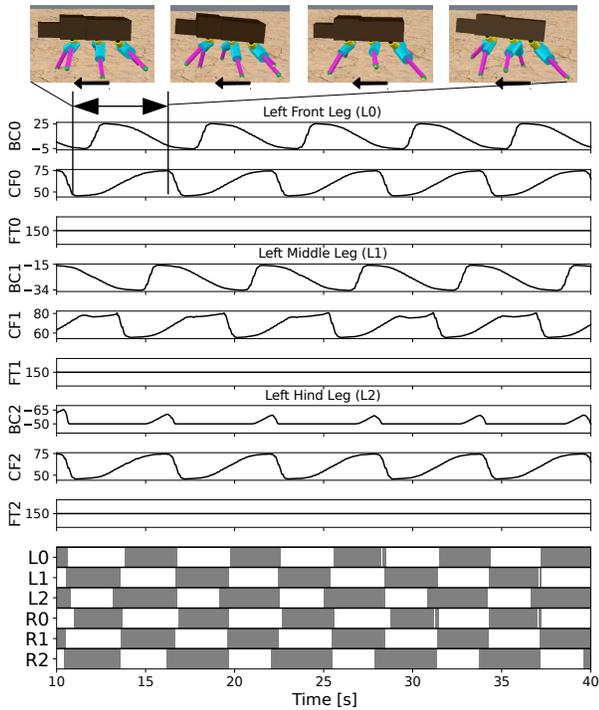


Figure 8: The joint angles (degree) and foot contact sensor signals during forward walking. The gray color bars of the gait diagram show the periods that the feet touch the ground (stance phase). The white color bars of the gait diagram show the periods that the feet do not touch the ground (swing phase).

Figure 7 shows the results from ball rolling experiment on level and sloped ground. The robot can roll a ball on flat ground and up different slopes up to 15 degrees with 100% success rate. Increasing the slope angles reduces the success rate. The robot can achieve up to 25 degrees with 10% success rate. This is due to the joint configuration that is not appropriate for rolling up such a steep slope.

The motor joint signals and gait diagrams for forward walking² and backward walking³ are shown in Fig. 8 and Fig. 9. During walking, the most active joints are the BC-joints and CF-joints. This is with the exception of the BC-joint at the hind leg which is almost non-active during walking. Note also that all of the FT-joints remain non-active during walking. These joint patterns are generated based on the observation of dung beetle locomotion.

Even though the signals from the motor neurons are corrected and smoothed, there still exist some mechanical feedback from the ground. This can clearly be seen in the signals of the middle leg CF-joint and the hind leg BC-joint, which

²see www.manoonpong.com/Alife2018/svideo1.wmv

³see www.manoonpong.com/Alife2018/svideo2.wmv

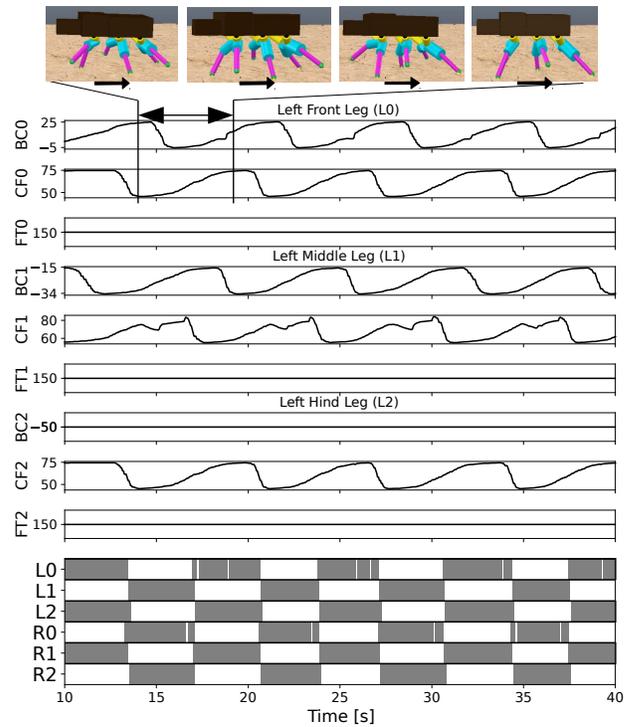


Figure 9: The joint angles (degree) and foot contact sensor signals during backward walking. The gray color bars of the gait diagram show the periods that the feet touch the ground (stance phase). The white color bars of the gait diagram show the periods that the feet do not touch the ground (swing phase).

fluctuate due to the feedback from the ground. The gait diagram show a tripod gait of the robot. For backward walking, the direction of the BC-joint after the leg touches the ground is reversed. Thus, the movement of the robot is changed from forward to backward walking.

The joint signals and the foot contact signals for the robot when rolling a ball⁴ from level to sloped ground are shown in Fig. 10. When the robot is starting to roll the ball up the slope, the body inclination signal is slowly increasing until it gets higher than a threshold. After that the sloped ground rolling action is automatically activated by changing the input values, $I_{1,2,3,4}$, to the network (see Table 1). As a consequence, the joint signals and the walking gait of the robot are changed for ball rolling up the slope.

⁴see www.manoonpong.com/Alife2018/svideo3.wmv

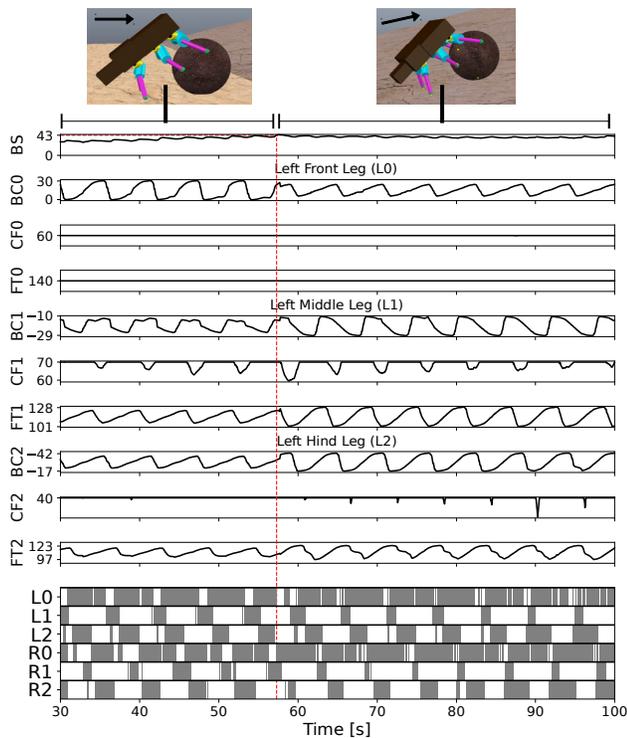


Figure 10: The joint angles (degree), body inclination sensor (BS) feedback (degree), and foot contact sensor signals during ball rolling from level ground to sloped ground (15 degrees). The gray color bars of the gait diagram show the periods that the feet touch the ground (stance phase). The white color bars of the gait diagram show the periods that the feet do not touch the ground (swing phase).

Conclusion

We present the modular neural controller of a dung beetle-like robot. The controller is derived from three generic neural modules (CPG, PCPG, and VRN). The CPG and VRN modules have their functional origin in biological neural systems (see Manoonpong et al., 2014 for details). The controller can generate various motor patterns for locomotion, object manipulation (i.e., pushing a ball), and their combination (resulting in object transportation, i.e., walking backward with rolling a ball). This bio-inspired control approach allows the robot to walk and continuously roll a large ball (i.e., about 3 times the robot's body height and 2 times of its weight) on different terrains (i.e., level ground and different slopes). These behaviors can be activated by changing four inputs to the controller. Switching from level ground ball rolling to sloped ground ball rolling behaviors is done by using body-inclination sensory feedback. Although the resulting ball rolling behavior is inspired by the strategy of dung beetles, the ball used in this study is still lighter than the one that the beetles can roll (i.e., 10 times their own weight).

Furthermore, the beetle can also transport the ball on not only flat but also rough terrains. Thus, in the future work, we will employ neural learning mechanisms with proprioceptive feedback for online adaptation (Xiong et al., 2016) to be able to transport or roll a large ball on steeper slopes and rough terrain. We will also apply this approach to a real dung beetle-like robot and test it in a real environment.

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