A Dung Beetle-like Leg and its Adaptive Neural Control

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Abstract: Dung beetles show fascinating locomotion abilities. They can use their legs to not only walk but also manipulate objects. Furthermore, they can perform their leg movements at a proper frequency with respect to their biomechanical properties and quickly adapt the movements to deal with external perturbations. Understanding the principles of their biomechanics and neural computation and transferring them to artificial systems remain a grand challenge. According to this, we present here a first prototype of a real dung beetle-like leg developed by analyzing real dung beetle legs through μ CT scans. We also apply adaptive neural control, based on a central pattern generator (CPG) circuit with synaptic plasticity, to autonomously generate a proper stepping frequency of the leg. The controller can also adapt the leg movement to deal with external perturbations within a few steps.

Keywords: Central pattern generator, Bio-inspired robotics, Neural control, Embodied AI, Adaptive locomotion

1. INTRODUCTION

During the last few decades, research in the domain of bio-inspired robotics has tried to imitate natural features of walking animals with artificial legged locomotion systems. Examples include the HECTOR robot based on the studies of a stick insect, the AMOS robot inspired by a cockroach [3], the robot BILL-ANT inspired by an ant [1], just to name a few. However, these robots have been so far designed for locomotion purposes. Thus, if manipulation tasks are required, additional manipulators and/or grippers need to be installed on the robot instead of using existing leg structure [2], [4], [1]. In contrast, insects with moderate computing can use their legs for both locomotion as well as object manipulation and transportation [5]. For example, dung beetles use their legs to walk on different terrains. While walking, they can also drag or push a dung ball using some legs [6], [5]. They even can use their legs as grippers for stable climbing up and down the ball.

Inspired by this, we have investigated biomechanical structures of real dung beetle legs and kinematics through μ CT [7]. As a first step, this paper presents 1) a prototype of a hind leg of the beetle based on the biological investigation and 2) its adaptive neural control. We use a 3D printer to create the first prototype and employ an adaptive neural central pattern generator (CPG) circuit with synaptic plasticity [8] as its control to generate the leg stepping motion and adapt the motion to deal with external perturbations. In the following sections, we present the dung-beetle like leg. Afterwards, we show the adaptive neural CPG-based control circuit and provide our preliminarily results on stepping motion and adaptation.

2. DUNG BEETLE-LIKE LEG

In this study, we first focused on a hind leg of the dung beetle which plays an important role for both locomotion and object manipulation and transportation. We analyzed the leg by using a desktop μ CT scanner (Skyscan 1172) which captures x-ray images over a 360° rotation of the beetle. Based on these x-ray images, we reconstructed a volumetric 3D dataset that consists of a stack of virtual cross-section images through the entire specimen. Then during post-processing of the μ CT data, we interactively segmented the parts of the beetle's legs from the dataset by assigning different labels to individual pixels within the stack of cross-sectional images. The segmented structures can then be visualized independently from the remainder μ CT dataset (Fig. 1) and be exported as polygonal surfaces for 3D printing.



Fig. 1 3D structure of a dung beetle (posterio-lateral view). Zoom panel shows the segmented hind leg of the beetle.

The leg consists of six main segments from the proximal part to the distal part. They are called coxa, trochanter, femur, tibia, tarsus, and pretarsus. There are three main active joints that connect body (thorax) and

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coxa (TC-joint or subcoxal joint), coxa and trochanter (CT-joint), and femur and tibia (FT-joint) and perform large movements. Trochanter and femur segments are connected by the joint which shows very small movements and, therefore, can be considered as a fused component. Tarsus is formed by a series of five parts where pretarsus is attached to the last one.

As a first step, for developing a real dung beetlelike leg, we here focus only on the three active joints of the dung beetle hind leg. Three segments (coxa, femur, and tibia) between the joints are simplified and designed by following the proportion of the hind leg (i.e., coxa:femur:tibia is 1:1.2:1, see Fig. 2, Left). The lengths of the coxa, femur, and tibia parts are 7 cm, 8.4 cm, and 7 cm, respectively. They are printed using 3D-printing (Fig. 2, Right).



Fig. 2 Left: Schematic diagram of the dung beetle-like hind leg. Right: Real dung beetle-like hind leg and its support. In this current setup, the tarsus and pretarsus of the leg are omitted. However, they together with the passive joints with springs are currently developed and will be integrated into the leg.

For simplification, the CT- and FT-joint rotate around the z-axis while the TC-joint rotates around the x-axis. These rotations follow the joint rotations of the real dung beetle leg. The TC-joint is driven by the Hitec HS645MG servo motor with a maximum torque of magnitude 10.0 kg-cm while the CT- and FT-joints are driven by the Hitec HS85MG micro servo motor with a maximum torque of magnitude 3.5 kg-cm. The main purpose for using different servo motors is to balance between torque and the length of the segments and keep it in a minimal size. A study of the dynamic forces applied to each joint of the leg suggested to only use a full size servo motor for the TC-joint which supports the whole body structure, while the last two segments require a smaller torque. In addition, all the servo motors are modified to obtain potentiometer sensor signals for detecting the actual joint angle positions. The base of the TC-joint is attached to a linear slide allowing the leg freely move in a vertical direction during a stance phase. A flexible cable is used to hold the leg during a swing phase for ground clearance. This mimics the action of the legs not represented in the current setup. All servo motors are driven by output signals of an adaptive neural controller (described below) through the Multi-Servo IO-Board (MBoard). The potentiometer signals are also digitized using this board. The MBoard is interfaced with a personal computer (PC) via an RS232 serial connection at 57.6 kbits per second.

3. ADAPTIVE NEURAL CONTROL

Neurophysiological studies suggest that central pattern generators (CPGs) [9] are a key ingredient underlying locomotion. They are neural circuits capable of producing basic periodic outputs without any rhythmic inputs or sensory feedback. Nevertheless, sensory feedback to CPGs is very important for ensuring coordination, adjusting the frequency of CPG signals with respect to body and leg properties, and also adapting leg movements to deal with external perturbations.

There is a wide variety of different CPG models available ranging from detailed biophysical models to pure mathematical oscillator models [13], [11], [10]. Compared to these models, an adaptive neural oscillator with synaptic plasticity developed by [8] shows an impressive performance. It is able to quickly adapt to and memorize an external frequency and works within a wide frequency range. It has been successfully applied to different physical systems [8], [12]. According to this, we employ it as adaptive neural control to drive the leg (Fig. 3).



Fig. 3 The dung beetle-like leg system. It consists of the artificial biologically-inspired leg and the adaptive neural controller. The leg provides the TC-joint angle signal θ_{TC} as a sensory feedback to the controller. Sensory noise is filtered at a sensory signal processing unit. The outputs $o_{0,1}$ of the controller is translated into proper motor commands ($M_{TC,CT,FT}$) at an output signal processing unit.

The controller consists of three discrete-time neurons with a hyperbolic tangent (tanh) transfer function. The two neurons $H_{0,1}$ are fully connected with four synapses $(W_{00}, W_{01}, W_{10}, W_{11})$. This forms an oscillator while the third neuron H_2 with additional synapses (W_{2P}, W_{02}, W_{20}) receives sensory feedback and passes it to the oscillator. Here we use the TC-joint angle sensor signal as the feedback. The controller can react and adapt its internal frequency to the feedback by using an adaptation process. The process consists of two mechanisms: Shortterm synaptic plasticity and long-term synaptic plasticity. The short-term synaptic plasticity based on a Hebbiantype learning rule controls the three synapses (W_{2P} , W_{02} , W_{20} , not shown here but see [8]) for reacting to sensory feedback or external perturbation. The long-term synaptic plasticity rule is for frequency adaptation given by:

$$\varphi(t+1) = \varphi(t) + \eta \cdot w_{02}(t)o_2(t) \cdot w_{01}(t)o_1(t), \quad (1)$$

where φ is proportional to the internal frequency of the controller. The modulation of φ basically influences the four synapses $(W_{00}, W_{01}, W_{10}, W_{11}, \text{ see [8] for de-}$ tails). η is a learning rate, o_1 and o_2 are the outputs of the neurons H_1 and H_2 , respectively, and w_{02} and w_{01} are synaptic weights (Fig. 3). As soon as the controller has adapted to the external frequency of the sensory feedback, the average correlation of $o_2(t)$ (sensory feedback) and $o_1(t)$ (controller output) is equal to zero. After adaptation, the sensory feedback can be removed from the controller while it maintains to oscillate at the adapted frequency. According to the hardware setup, a certain phase shift $\Delta \phi$ between the sensory feedback and the controller outputs occurs. This leads to instability of the adaptation process. Thus we introduce a mechanism to compensate the delay (i.e., output signal processing). It is given by:

$$s_0(t) = z\cos(\Delta\phi_{set})o_0(t) + z\sin(\Delta\phi_{set})o_1(t).$$
(2)

The constant factor z is for adjusting the amplitude of the signal $s_0(t)$. $\Delta \phi_{set} \in [0, 2\pi]$ acts as a phase shift compensator which can be also used to obtain any desired phase relation. By driving the joints of the leg with the motor commands $(M_{TC,CT,FT})$ proportional to $s_0(t)$ and feeding back the current actual joint angle of the motor as a feedback signal, the adaptation process stably converges at a stepping frequency at which the angle sensor signal θ_{TC} is delayed by a phase shift $\Delta \phi_{set}$ compared to the motor command M_{TC} .

4. EXPERIMENTS AND RESULTS

In this section, as a first step of this development, we present here some preliminarily experiments and results of the developed dung-beetle like leg system (Fig. 3) on stepping motion and adaptation. Typically, activating only the TC- and CT-joints is sufficient for stepping or walking. Thus, in all experiments shown here, we control only the TC- and CT-joints while keep the FT-joint fixed at a certain position. The first experiment shows the adaptation process of the neural controller. Here we set the phase shift $\Delta\phi_{set}$ between the TC-angle feedback and the motor command of the TC-joint to 0.2π and started the controller at different frequencies. It can be seen that after a few seconds the adaptation process of the controller stably converges to a certain frequency which allows the leg to perform a proper stepping motion. Note that different initial frequencies are defined by initializing different values of the synaptic weights $(W_{00}, W_{01}, W_{10}, W_{11}, \text{see})$ [8] for details) of the oscillator of the controller.



Fig. 4 Time series of the frequency changes during stepping of the dung beetle-like leg for different initial frequencies ω_0 . In all cases, the predefined phase shift $\Delta \phi_{set}$ is set to 0.2π .

The second experiment shows the stepping behavior of the leg on a treadmill and the adaptation of the leg to different situations. At the beginning, we suspended the leg to let it step in the air and then placed it on the treadmill at a speed of 0.23 m/s. Afterwards, we increased the speed of the treadmill to 0.29 m/s and finally again suspended the leg in the air. Figure 5 shows the frequency adaptation with respect to the different situations. It can be seen that the controller can quickly react and adapt its output frequency to generate proper stepping behavior.



Fig. 5 Online frequency adaptation of the controller for three different situations: Stepping in the air, stepping on the treadmill with a speed of 0.23 m/s, and stepping on the treadmill with a speed of 0.29 m/s. We encourage readers to watch the video clip of this real robot stepping experiment at http://www.manoonpong.com/SW2015/DVideo.mp4.

The last experiment shows the adaptation of the controller when an external perturbation is applied to the leg. At the beginning, we let the leg step on the treadmill at a speed of 0.29 m/s and then we applied an external perturbation to the leg by holding it. Afterwards, we released the leg (i.e., removing the perturbation from it). Figure 5 shows the frequency adaptation with respect to the different situations. It can be seen that the controller can quickly decrease its output frequency when the leg movement was constrained by the external perturbation; thereby protecting the leg from getting damage.



Fig. 6 Online frequency adaptation of the controller to deal with an external perturbation. We encourage readers to watch the video clip of this experiment at http://www.manoonpong.com/SW2015/DVideo.mp4.

5. CONCLUSIONS

This paper presents the development of a whole dung beetle-like leg system, from biological investigation to biomechanical construction and control. We analyzed the morphology of a real dung beetle by using μ CT imaging to obtain a 3D computer model. As a first step, here we focus only on the hind leg of the beetle for the conceptual design of a robot leg. The structures of the robot leg having the same proposition to the beetle leg were printed using a 3D printer. The robot leg was equipped with three active joints for moving the leg and potentiometer sensors for detecting the actual joint angle positions. Adaptive neural CPG-based control with short- and long- term synaptic plasticity was employed for stepping movement generation and adaptation of the leg. Experiments show that a combination of the proper biological-like structure with the corresponding self-adaptive neural control results in proper motion behaviors and fast adaptability of the leg to changing locomotory situation.

In the next step, we will extend the controller by using three adaptive CPG circuits, each of which controls each joint. This will lead to highly adaptivity and flexibility to deal with complex situations. Furthermore, we will implement cable-driven compliant tarsus and pretarsus (currently being developed) on the leg. We anticipate that the tarsus and pretarsus will enhance stepping behavior and also allow for object manipulation and transportation, two dung beetle-like leg systems will be employed.

6. ACKNOWLEDGEMENTS

This research was supported partly by Bernstein Center for Computational Neuroscience II Goettingen (BCCN grant 01GQ1005A, project D1), Center for BioRobotics (CBR) at University of Southern Denmark (SDU), and the Scandinavian Guest Professorship program of Kiel University (CAU).

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