Multiple Decoupled CPGs with Local Sensory Feedback for Adaptive Locomotion Behaviors of Bio-inspired Walking Robots

Subhi Shaker Barikhan[1,2], Florentin Wörgötter[1], and Poramate Manoonpong[1,3,*]

[1]Bernstein Center for Computational Neuroscience (BCCN), The Third Institute of Physics, University of Göttingen, 37077 Göttingen, Germany
[2]Institute of Computer Science, University of Göttingen, 37077 Göttingen, Germany
[3]Maersk Mc-Kinney Moller Institute, University of Southern Denmark, 5230 Odense M, Denmark
`{s.shaker.barikhan,worgott}@dpi.physik.uni-goettingen.de`
`*poma@mmmi.sdu.dk`

Abstract. Walking animals show versatile locomotion. They can also adapt their movement according to the changes of their morphology and the environmental conditions. These emergent properties are realized by biomechanics, distributed central pattern generators (CPGs), local sensory feedback, and their interactions during body and leg movements through the environment. Based on this concept, we present here an artificial bio-inspired walking system. Its intralimb coordination is formed by multiple decoupled CPGs while its interlimb coordination is attained by the interactions between body dynamics and the environment through local sensory feedback of each leg. Simulation results show that this bio-inspired approach generates self-organizing emergent locomotion allowing the robot to adaptively form regular patterns, to stably walk while pushing an object with its front legs or performing multiple stepping of the front legs, to deal with morphological change, and to synchronize its movement with another robot during a collaborative task.

Keywords: Adaptive behavior, Hexapod locomotion, Brain-body-environment interaction, Autonomous robots, Neural networks.

1 Introduction

Legged animals show various locomotion behaviors (e.g., walk, trot, and gallop for quadruped, and metachronal, tetrapod, and tripod for insects) which are used for particular situations like walking on different terrains and/or morphological change. They also show impressive flexibility and adaptivity of their movements generated by a combination of biomechanics, neural control (e.g., central pattern generators (CPGs)), local sensory feedback, and their interactions during body and leg movements through the environment [5]. While all these key ingredients are important for the complex achievement, they have not been fully applied to artificial legged systems. Several works utilize multiple distributed nonlinear oscillators with predefined phase relationships among them as coupled CPGs for interlimb and intralimb coordinations as well as locomotion generation [3], [4], [10]. However, this control technique fails to adaptivity due to the lack of sensory feedback and the consideration of body-environment interactions.

A few works use sensory feedback to utilize the dynamic interactions to generate adaptive locomotion [13]. One of the sensory feedback techniques is a phase reset scheme which resets the phase of a CPG at the same time the foot of the robot touches the ground. It has been employed for locomotion control of quadruped and hexapod robots [2], [6]. Aoi et al. [2] have used the phase reset scheme to allow the quadruped robot to perform various gait patterns and to exhibit a hysteresis in gait transition similarly to humans and animals. Ambe et al. [1] have extended the phase reset scheme by including a phase inhibition mechanism. This results in the improvement of gait stability. However, the phase reset and inhibition mechanisms require the predefined phase relationships among CPGs (i.e., predefined interlimb coordination); thereby lacking in flexibility and independency. According to this, another sensory feedback approach which does not require predefined interlimb coordination has been introduced [12]. This approach is based on the alteration of CPG's phase with respect to the magnitude of local sensory feedback. This results in flexibility and adaptability to deal with the changes of weight distribution and locomotion speed of a quadruped robot.

Inspired by [12], we present here our hexapod walking system where its intralimb coordination is formed by six decoupled CPGs while its interlimb coordination is not predefined but achieved by the interactions between body dynamics and the environment through local sensory feedback of each leg. This results in self-organizing gaits allowing the robot to adaptively form regular patterns, to stably walk while pushing an object with its front legs or performing multiple stepping of the front legs, to deal with morphological change (handicap), and to synchronize its locomotion with another robot during a collaborative task. We emphasize that the novelty of this work is the resulting complex self-organizing behaviors which, to our knowledge, have not been so far presented.

2 Multiple CPGs with Local Sensory Feedback for Adaptive Locomotion Behaviors

Our neural locomotion control system (Fig. 1a) is composed of six identical decoupled control components. Each one of them consists mainly of four elements: 1) CPG mechanism with neuromodulation and local sensory feedback for generating adaptive locomotion, 2) CPG post processing unit (PCPG) for shaping CPGs' output signals, 3) phase switching network (PSN) and velocity regulating network (VRN) for walking directional control, 4) motor neurons for transmitting motor commands to the specific leg joints of a hexapod robot (Fig. 1b). Note that the PSN can switch the phase of the CPG outputs to lead or lag behind each other by $\pi/2$ in phase with respect to a given input for walking sideways. The VRN functions qualitatively like a multiplication function, having capability to increase or decrease the amplitude of the TC-joint signals and even to reverse them with respect to their control inputs. This results in various walking directions, like forward/backward, turning left/right, turning in different radians, or curve walking in forward and backward directions [11]. All neurons of our neural locomotion control system are modeled as discrete time non-spiking neurons. The activity of each neuron is developed as follows:

$$a_i(t+1) = \sum_{j=1}^{n} W_{ij} o_j(t) + B_i; i = 1, ..., n, \tag{1}$$

where n denotes the number of units, a_i their activity, B_i represents a fixed internal bias term together with a stationary input to neuron i, W_{ij} the synaptic strength of the connection from neuron j to neuron i, and o_i the neuron output. The output of neurons is calculated by using the hyperbolic tangent (tanh) transfer function, i.e., $o_i(t) = \tanh(a_i(t))$, where $o_i(t) \in [-1, 1]$, except CPG post-processing neurons, whose outputs are calculated by deploying a step function with a threshold value of 0.85 and integrator units, thus the CPG outputs are translated into ascending and descending slopes. Moreover, the motor neurons deploy piecewise linear transfer functions to calculate their outputs, where the upper and lower bounds are $+1$ and -1 respectively. For more details on all neural components except the CPG one, we refer to our previous work [11].

3 A CPG Mechanism with Local Sensory Feedback

In our locomotion control system, CPGs serve as rhythmic pattern generators producing asymmetrical periodic signals to control leg joints. Each of them consists of two fully connected neurons and an extrinsic modulatory input S which is projected to the synaptic connections of the neurons. This enables the frequency change of the CPGs by modifying the synaptic weights W (not shown here, but see [11]). To adapt the CPGs' signals for dealing with external perturbations and self-organizing interlimb coordination, we use a local sensory feedback mechanism inspired by [12]. Here, the ground reaction force at each leg is used as feedback to modulate the phase of its target CPG (see Fig. 1d). The neural activities of each CPG are given by:

$$a_1(t+1) = \sum_{j=1}^{2} W_{1j} o_j(t) + B_1 - \gamma_1 F(t) \cos(a_1(t)), \tag{2}$$

$$a_2(t+1) = \sum_{j=1}^{2} W_{2j} o_j(t) + B_2 - \gamma_2 F(t) \sin(a_2(t)), \tag{3}$$

$$o_i(t) = \tanh(a_i(t));\ i \in \{1, 2\}, \tag{4}$$

where γ_1 and γ_2 are positive constants. Here, γ_1 and γ_2 of the front legs are 0.04 and 0.03 respectively, γ_1 and γ_2 of the middle legs are 0.03 , and γ_1 and γ_2

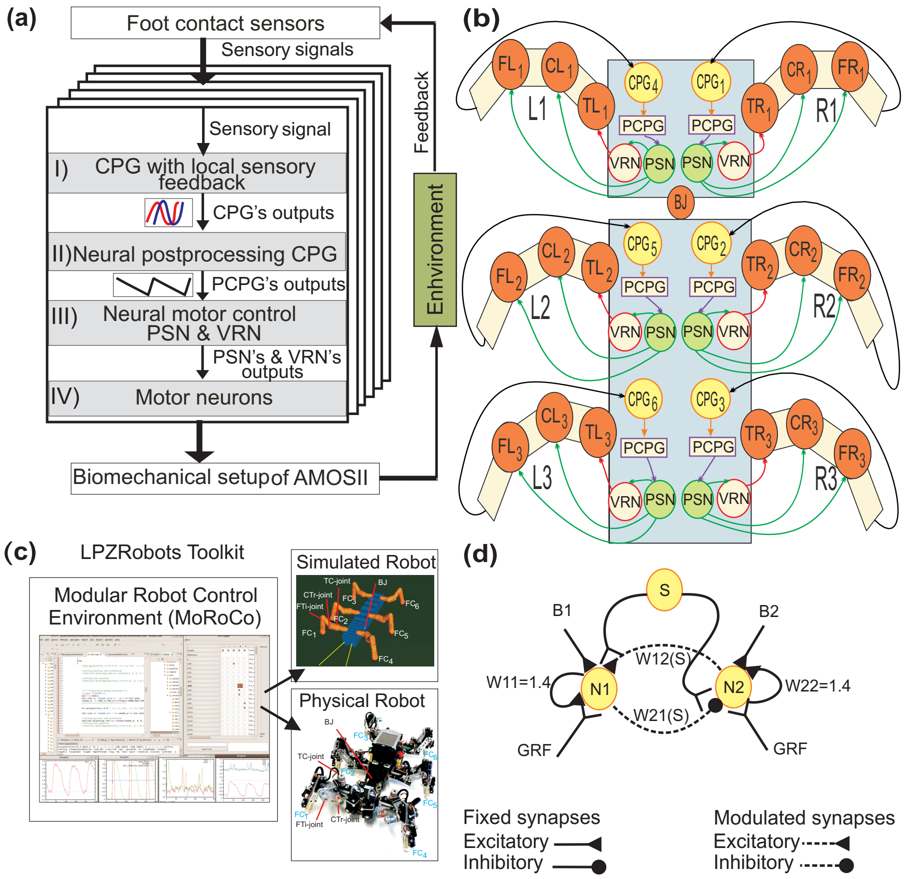

Fig. 1. (a) The diagram of an artificial bio-inspired walking system which consists of the biomechanical setup of the hexapod robot AMOSII (i.e., six 3-jointed legs, a segmented body structure with one active backbone joint (BJ), actuators, and passive compliant components [11]), sensors (i.e., proprioceptive and exteroceptive sensors), and neural mechanisms (I,II,III,VI). As we mentioned previously, our controller comprises six identical decoupled control components controlling six legs of AMOSII. **(b)** Multiple decoupled CPGs system applied to AMOSII for adaptive locomotion. CPG's outputs are modulated by local sensory feedback (black arrows). CPG outputs are projected to PCPGs (orange arrows) which translate them into ascending and descending slopes. These slopes will be fed to the PSN components (purple arrows). The outputs of the PSN are projected to the F(R,L), and C(R,L) motor neurons, as well as to the VRN (green arrows). The VRN's output is projected to the T(R,L) motor neuron (red arrows). **(c)** Modular Robot Control Environment embedded in the LPZRobots toolkit [9]. It is used for developing a controller, testing it on the simulated hexapod robot, and transferring it to the physical one. FC1, FC2, FC3, FC4, FC5, and FC6 are foot contact sensors. Each of them is installed at each leg. Each leg has three joints: the thoraco-coxal (TC-) joint enables forward and backward movements, the coxa-trochanteral (CTr-) joint enables elevation and depression of the leg, and the femur-tibia (FTi-) joint enables extension and flexion of the tibia. The morphology of these multi-jointed legs based on a cockroach leg [14]. **(d)** Wiring diagram of the CPG circuit. GRF represents the afferent feedback to modulate the CPG's outputs.

of the hind legs are 0.035 and 0.03 respectively. $F(t)$ represents the continuous ground reaction force (GRF) detected by the foot contact sensor (FC), $F(t) \approx 0$ if a foot does not touch the ground.
The modulated CPG's output signals respond to the changes of the ground reaction force received from the foot contact sensor (FC). As local force feedback informs about the gait pattern, the robot state, and the terrain, the hexapod robot AMOSII will autonomously adapt its walking pattern. The effect of local sensory feedback on the CPG's outputs is not the same for all CPGs, but rather corresponds to the magnitude of the ground reaction force (GRF) and the activity of neurons. This variation of the influence on the CPGs will automatically yield phase differences among them, which will, in turn, be translated into proper interlimb coordination. As a result, the robot will perform an adaptive walking pattern. In this case, we do not have a fixed interlimb coordination, but rather a flexible one, since the walking pattern is subject to local sensory feedback, neural activities, and the body-environment interaction.

4 Intralimb and Interlimb Coordinations

Locomotion is achieved by proper interlimb and intralimb coordinations. The conventional way to design a gait is by defining the interlimb and intralimb neural connections. While the intralimb neural connections determine the coordination between joint movements within the leg, the predefined phase relationships among oscillators (CPGs) will fulfill interlimb coordination and enforce the planned gait. For example, a tripod gait is generated when the phase difference between each two adjacent CPGs is maintained to π. However, Owaki et al. [12] have proposed another hypothesis that interlimb coordination could rely on the physical interactions during walking rather than on explicit interlimb neural connections. Based on this assumption, the interlimb coordination of our system is realized by the body-environment interaction through local sensory information, whereas the intralimb coordination in each leg is achieved by the prewired neural connections from the PSN and VRN components to the motor neurons of each leg. Fig. 1b shows our decoupled CPGs model.

5 Experimental Results

We tested the performance of our artificial bio-inspired walking system on the simulated hexapod robot AMOSII in different cases. In all cases, we initiated AMOSII with an irregular gait, where the lateral legs move in phase, and the contralateral legs move antiphase. The CPG's frequency for all legs was 0.4 Hz except the CPG's frequency for the front legs (R1 and L1) in a multiple stepping experiment. Note that the amplitude of swing and stance phases is in a range of 45 and 75 degrees.

5.1 Transition from Irregular to Regular Gaits

As we have already mentioned, we initiated AMOSII with an irregular gait; therefore there is no leg elevation during swing phases. As soon as we enabled the local force feedback mechanism, AMOSII started to properly perform swing movement, i.e. no ground contact during the swing phase. A few steps later, AMOSII automatically adopted its walking pattern similar to a metachronal gait, where at least four legs are in the stance phase, and two legs are in the swing phase (see Fig. 2). The average walking speed of AMOSII after enabling the local force feedback mechanism was ≈ 5.01477 [cm/s].

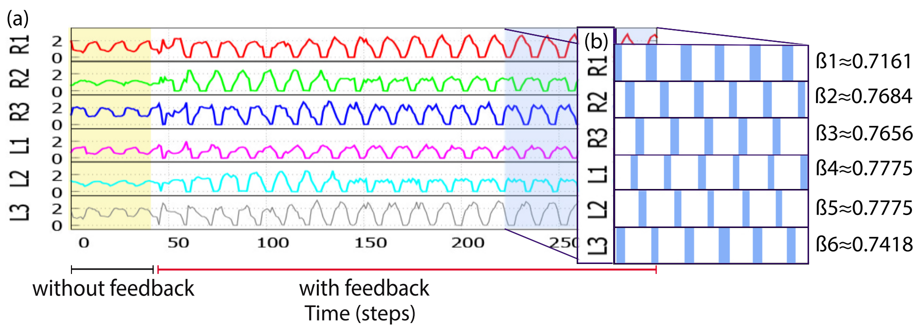

Fig. 2. **(a)** Experimental result of transition from irregular to regular gaits. Shown are the ground reaction forces (GRFs) detected by foot contact sensors. The yellow highlight area demonstrates that the robot could not lift up its legs during swing phase. **(b)** Gait diagram and the duty factors (βi $where$ $i = 1, ..., 6$) matching the blue highlight area in (a). The blue bars refer to no ground contact during swing phase. Note that one time step is ≈ 0.037 s. It should be also noted that the foot contact sensors (FCs) in the simulated AMOSII calculate the ground reaction forces (GRFs) by measuring collision forces (penetration depth). We encourage readers to also see the video of this experiment at http://www.manoonpong.com/SAB2014/S1.mpg.

5.2 Adaptability to Different Functionalities of the Front Legs

Multiple Stepping of the Front Legs. Grabowska et al. [7] have referred to the special functionality of the stick insect front legs. It has been shown that the front legs perform multiple stepping and probing behavior during walking. This behavior is partially responsible for irregular gait occurrences. However, when prothoracic legs are ignored in the analysis of irregular gaits which are caused by the multiple stepping behavior, regular stereotypic gaits of the other legs can be observed. Inspired by this, in this experiment we tested our proposed walking system when the front legs were performing multiple stepping. We changed the default frequency of the two CPGs controlling the two front legs; thus both legs perform more steps than the other legs. The magnitude of the frequency change was arbitrary set as $f_1 = 1.3 * f_2$ and $f_4 = 1.6 * f_2$, and $f_2 = f_3 = f_5 = f_6 =$ 0.4 Hz, where f_i is the frequency of the ith CPG. Fig. 3b exhibits that the mesothoracic and metathoracic legs performed a regular pattern. This walking pattern (two single leg swing phases follow synchronous swing of a diagonal pair of legs) is similar to a pattern of adult stick insects walking on a horizontal surface and their front legs performing multiple stepping [7]. The average walking speed in this situation was $\approx$ 5.29808 [cm/s]. Fig. 3a shows the locomotor behavior described as ground contact forces.

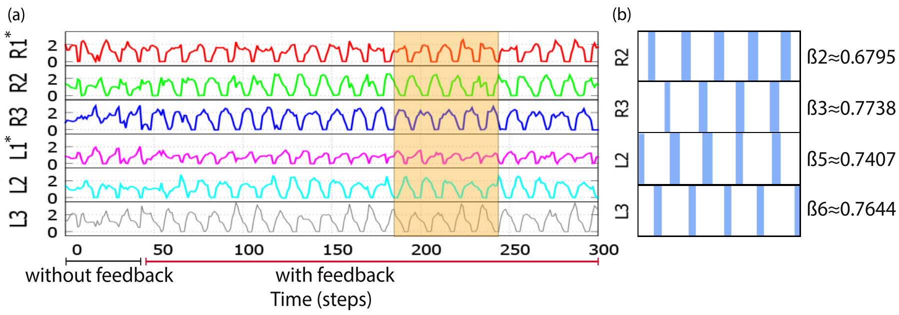

Fig. 3. Experimental result of multiple stepping of the front legs (R1 and L1). **(a)** The ground reaction forces (GRFs) exerted by the ground on the legs during multiple stepping. **(b)**. Gait diagram of AMOSII and the duty factors (βi) matching the state in the highlight district in (a) after ignoring the ground reaction forces exerted on the front legs. The blue areas indicate no ground contact during swing phase. The video clip of this experiment can be seen at http://www.manoonpong.com/SAB2014/S2.mpg.

Pushing an Object. Another instance of the special duty of the front legs is for pushing an object. In this experiment, we modified the joint angles of the front legs to be suitable for the pushing mission. AMOSII revealed two different gaits based on the position of the pushed object related to AMOSII. The first gait was noticed when the mesothoracic legs were moving in phase to lift up the front part of the body. This pattern happened when AMOSII was trying to put the front legs above the pushed object (the average walking speed was $\approx$ 2.4178 [cm/s]). The second gait was tetrapod, which occurred when the front legs were already above of the pushed object (the average walking speed was $\approx$ 3.902 [cm/s]). The previously observed behavior plainly demonstrates the self-organizing locomotor behavior of our control system. However, different factors such as the shape of the object and its position related to AMOSII facilitated the occurrence of this locomotor behavior. Fig. 4 shows this behavior illustrated as the ground contact force signals, gait diagrams, and duty factors.

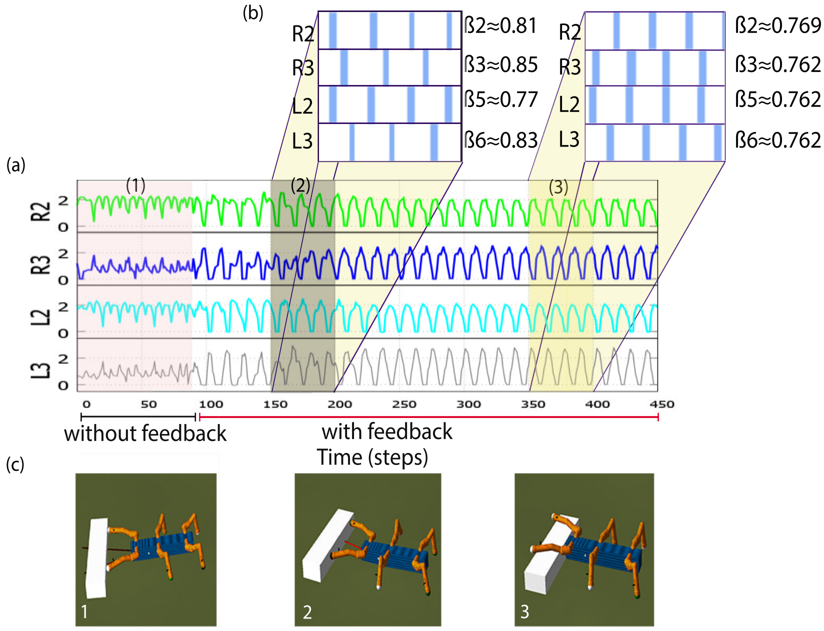

Fig. 4. Experimental result during pushing process. **(a)** The ground reaction forces (GRFs) exerted by the ground on the legs. State (1) presents the ground reaction force signals before introducing the feedback. State (2) presents the ground contact signals after activating the local sensory feedback mechanism. These signals indicate the middle legs were moving in phase. State (3) presents the ground contact signals where the front legs were on the top of the pushed object. **(b)** Gait diagrams and duty factors (βi) matching the states mentioned by (2) and (3) in (a). The blue areas indicate no ground contact during swing phase. **(c)** Snapshots of AMOSII while pushing the object. These snapshots match the states mentioned by (1), (2), and (3) in (a). Note that the weight of the object is 100 g. The video clip of this experiment can be seen at http://www.manoonpong.com/SAB2014/S3.mpg.

5.3 Adaptability to Morphological Change

Insects show a good ability to deal with different circumstances. They can overcome the problems arising from amputation of one or two legs. Graham [8] has investigated the impact of the leg amputation on locomotion. His observations indicate that insects can adapt their gaits after a leg amputation. In this experiment, we focused on the influence of the middle leg amputation on the locomotor behavior of AMOSII and assessed the efficiency of the proposed walking system to deal with a handicap situation. Therefore, we disabled the mesothoracic legs temporarily during the movement by lifting them up. In this way, they did not play any role in the walking process. The experimental result, illustrated by Fig. 5, indicates that AMOSII adopted a new gait (diagonal stepping) and was able to continue walking properly. This behavior provides a clue to the importance of sensory feedback to adapt gaits in response to morphological changes. The average walking speed of AMOSII while the middle legs were disabled was ≈ 4.7455 [cm/s], while the average walking speed before disabling the middle legs and after enabling them were 5.0075 [cm/s] and 5.1498 [cm/s] respectively.

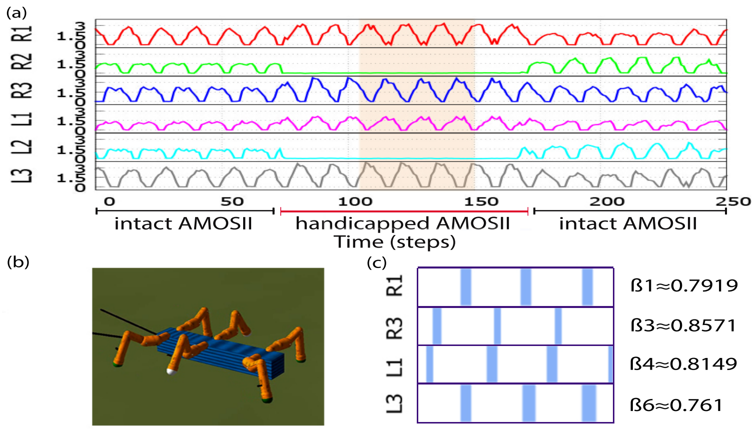

Fig. 5. Experimental result of our controller applied to the temporarily handicapped AMOSII. **(a)** The ground reaction forces during the movement of AMOSII whose middle legs were disabled temporarily. **(b)** Picture of AMOSII with the deactivated middle legs. **(c)** Gait diagram and duty factors (βi) corresponding to the highlight district in (a) after ignoring the middle legs. The blue bars refer to no ground contact during swing phase. We encourage readers to also see the video of this experiment at http://www.manoonpong.com/SAB2014/S4.mpg.

5.4 Coordinated Locomotion for a Collaborative Task

Coordinated locomotion between legged robots through local sensory feedback is an interesting aspect. This mission is difficult for a conventional nonadaptive locomotion control system. The is because the synchronization and coordination between the robots need to be achieved in order to generate combined locomotion. In addition, even if the locomotion is fulfilled, any minor perturbation can yield irregular gaits. According to this, an adaptive locomotion control system is required. Fig. 6 illustrates the ability of our adaptive control system for coordinating the locomotion of the two connected robots holding a sphere weighted 200 g (Fig. 6b). The coordinated locomotion is fulfilled by deploying only the physical interactions during the movement. Note that we implemented the same controller on these two robots and the two legs of each robot are fixed together. The average walking speed of these two robots was approximately 4.495 [cm/s].

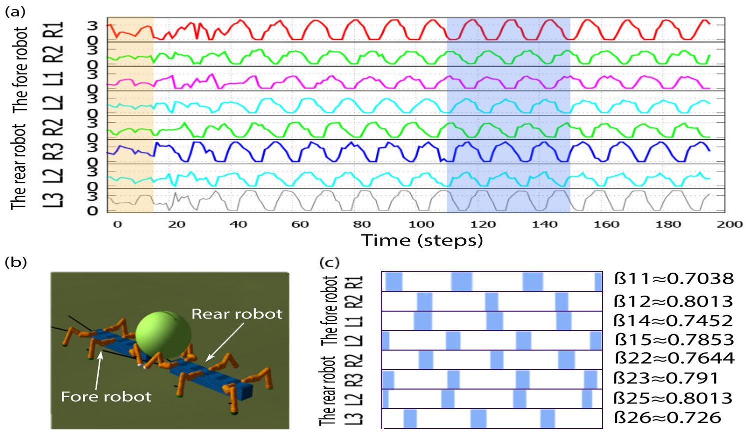

Fig. 6. Experimental result of locomotor coordination between two AMOSII. **(a)** The ground reaction forces detected by the foot contact sensors. The orange highlight sector represents the initial state, at which the local sensory feedback mechanism was not activated. The blue highlight area represents a sample of the GRFs after introducing the feedback mechanism. **(b)** Two connected robots holding a sphere. **(c)** Gait diagram and duty factors ((βij) where $i = 1, 2$ indicates the robot, i.e., $i = 1$ denotes the fore robot, $i = 2$ denotes the rear robot, and $j = 1, ..., 6$ refers to the legs). The gait diagram and duty factors match the blue highlight area in (a). The blue bars indicate no ground contact during swing phase. The video clip of this experiment can be seen at http://www.manoonpong.com/SAB2014/S5.mpg.

6 Conclusion

We presented an artificial bio-inspired walking system which is controlled by multiple decoupled CPGs. Besides, deploying the ground reaction forces (GRFs) as local sensory feedback allows for: 1) the modulation of CPGs' output signals, 2) the modification of the phase differences among CPGs. Due to a combination of biomechanics (body and leg structures), neural control (multiple decoupled CPGs), local sensory feedback, and their dynamical interactions through the environment, AMOSII can autonomously adapt its gait from irregular to regular gaits after a few steps. It is also able to perform suitable gaits corresponding to biological findings in the case of multiple stepping of the front legs, and to deal with morphological change as well. In addition, this approach can also coordinate locomotion between two connected robots for a collaborative task and realize a special functionality of the front legs such as pushing an object. While this approach can generate adaptive locomotion, it cannot achieve specific gaits due to the lack of neural connections among CPGs. In the future, we will further introduce the proper connections for specific gait generation. We will also apply this approach to our real hexapod robot AMOSII and test it in a real environment.

Acknowledgments: This research was supported by Emmy Noether grant MA4464/3-1 and BCCNII grant 01GQ1005A (project D1).

References

1. Ambe, Y., Nachstedt, T., Manoonpong, P., Wörgötter, F., Aoi, S., Matsuno, F.: Stability analysis of a hexapod robot driven by distributed nonlinear oscillators with a phase modulation mechanism, IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.5087-5092 (2013).
2. Aoi, S., Yamashita, T., Tsuchiya, K.: Hysteresis in the gait transition of a quadruped investigated using simple body mechanical and oscillator network models. Physical Review E, 83(6), 061909 (2011).
3. Campos, R., Matos, V., Santos, C.: Hexapod locomotion: A nonlinear dynamical systems approach. In IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society, pp. 1546-1551 (2010).
4. Canavier, C. C., Butera, R. J., Dror, R. O., Baxter, D. A., Clark, J. W., Byrne, J. H.: Phase response characteristics of model neurons determine which patterns are expressed in a ring circuit model of gait generation. Biological cybernetics, 77(6), 367-380 (1997).
5. Dickinson, M. H., Farley, C. T., Full, R. J., Koehl, M. A. R., Kram, R., Lehman, S.: How animals move: an integrative view. Science, 288(5463), 100-106 (2000).
6. Fujiki, S., Aoi, S., Kohda, T., Senda, K., Tsuchiya, K.: Emergence of hysteresis in gait transition of a hexapod robot driven by nonlinear oscillators with phase resetting. 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 1638-1643 (2012).
7. Grabowska, M., Godlewska, E., Schmidt, J., Daun-Gruhn, S.: Quadrupedal gaits in hexapod animals-inter-leg coordination in free-walking adult stick insects. The Journal of Experimental Biology, 215(24), 4255-4266 (2012).
8. Graham, D.: The effect of amputation and leg restraint on the free walking coordination of the stick insectCarausius morosus. Journal of comparative physiology, 116(1), 91-116 (1977).
9. Hesse, F., Martius, G., Manoonpong, P., Biehl, M., Wörgötter, F.: Modular Robot Control Environment Testing Neural Control on Simulated and Real Robots. Frontiers in Computational Neuroscience, Conference Abstract: Bernstein Conference 2012, doi:10.3389/conf.fncom.2012.55.00179 (2012).
10. Ijspeert, A. J., Crespi, A., Ryczko, D., Cabelguen, J. M.: From swimming to walking with a salamander robot driven by a spinal cord model. Science, 315(5817), 1416-1420 (2007).
11. Manoonpong, P., Parlitz, U., Wörgötter, F.: Neural control and adaptive neural forward models for insect-like, energy-efficient, and adaptable locomotion of walking machines. Frontiers in neural circuits, 7, 12-12 (2013).
12. Owaki, D., Kano, T., Nagasawa, K., Tero, A., Ishiguro, A.: Simple robot suggests physical interlimb communication is essential for quadruped walking. Journal of The Royal Society Interface, 10(78) (2013).
13. Shim, Y., Husbands, P.: Chaotic exploration and learning of locomotion behaviors. Neural computation, 24(8), 2185-2222 (2012).
14. Zill, S., Schmitz, J., Büschges, A.: Load Sensing and Control of Posture and Locomotion. Arthropod structure & development, 33: 273-286 (2004).