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Decentralized control mechanism underlying interlimb coordination of millipedes

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Abstract

Legged animals exhibit adaptive and resilient locomotion through interlimb coordination. The long-term goal of this study is to clarify the relationship between the number of legs and the inherent decentralized control mechanism for interlimb coordination. As a preliminary step, the study focuses on millipedes as they represent the species with the greatest number of legs among various animal species. A decentralized control mechanism involving local force feedback was proposed based on the qualitative findings of behavioural experiments in which responses to the removal of part of the terrain and leg amputation were observed. The proposed mechanism was implemented in a developed millipede-like robot to demonstrate that the robot can adapt to the removal of the part of the terrain and leg amputation in a manner similar to that in behavioural experiments.

1. Introduction

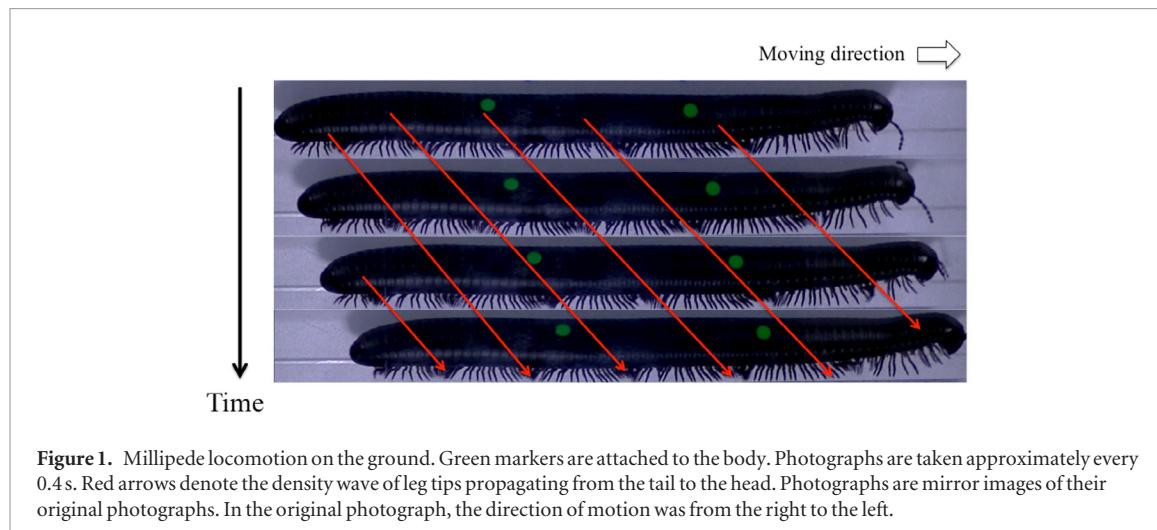
Legged animals exhibit highly adaptive locomotion under various unstructured environments by coordinating their limb movements appropriately. It is likely that the interlimb coordination is achieved mainly by decentralized control. Specifically, each leg is likely controlled by a distributed neural network based on local sensory information detected by the leg itself or its nearby legs. The movement patterns between legs are coordinated in a self-organized manner. In fact, several biological findings suggest the existence of decentralized control mechanisms such as a neural network termed central pattern generator (CPG) [1–4]. Thus, several models are proposed based on decentralized control and implemented in legged robots [4–6].

An extremely challenging problem in legged locomotion is the clarification of the relationship between the number of legs and the inherent decentralized control mechanism. This is a very important problem for two reasons. First, clarifying the mechanism will aid in understanding the evolutionary process of legged animals because it is likely that the neural system would change in response to morphological changes, e.g. number of legs, through a long-term evolutionary process. Second, a systematic understanding of the decentralized control mechanism benefits engineers because it

helps in designing multi-legged robots that can adapt to changes in the environment and their own morphology.

To address these issues, it is necessary to investigate two extreme categories, namely investigating animals with few legs and animals with a large number of legs. This study focused on the latter category, that is, myriapods. This is because fewer studies have examined myriapods when compared with the former category. Specifically, the study focused on the decentralized control mechanism for the interlimb coordination of millipedes. It may be noted that millipedes possess the highest number of legs among various animal species [7] and can move adaptively on various terrains by propagating density waves formed by their leg tips from their tail to their head [8–11] (figure 1).

Myriapods, including millipedes, are studied in various fields such as biology [7–12], robotics [13–23], and mathematical modelling [19–25]. However, only a few studies focused on the decentralized control mechanism for interlimb coordination [19–21, 24, 25]. Inagaki *et al* [19] proposed a decentralized and event-driven control scheme that enabled centipede-like multi-legged robots to walk on an uneven terrain. Matthey *et al* [20] designed a CPG controller that could generate both limit cycle and chaotic behaviours, and showed that the controller could efficiently explore new coordination patterns in different terrains. Onat *et al* [21] used a multi-legged robot to demonstrate that a



stable gait pattern emerged through a decentralized control mechanism in which the ground contact signals of each leg were exploited. Fang *et al* [24] proposed a model which involved switching between several leg states in response to the circumstances encountered. Conversely, Golubitsky *et al* [25] deduced the CPG network architecture of animals with varying numbers of legs (including myriapods) from a mathematical viewpoint. However, these studies included insufficient behavioural findings to support the proposed control schemes, and thus, further clarification is evidently necessary with respect to the decentralized control mechanism underlying interlimb coordination of millipedes.

A previous study proposed a decentralized control mechanism for the interlimb coordination of millipedes based on the qualitative findings of a behavioural experiment in which the locomotion of intact millipedes on a terrain with a gap is examined [26]. In this study, the proposed control mechanism is implemented in a developed millipede-like robot to demonstrate that the robot can qualitatively reproduce the results of the behavioural experiment. An additional experiment is performed to observe the locomotion of leg-amputated millipedes to support the validity of the proposed control mechanism. It is expected that the experimental results will contribute important insights on the interlimb coordination mechanism of legged locomotion.

The remainder of this paper is structured as follows. Section 2 shows the results of behavioural experiments. Section 3 describes the model for interlimb coordination that is developed based on the results of the behavioural experiments. In section 4, it is demonstrated that the proposed control scheme can reproduce the results of the behavioural experiments by implementing the model in a developed millipede-like robot. Finally, sections 5 and 6 present the discussions and conclusions, respectively.

2. Behavioural experiments

The following two experiments are performed using millipedes (*Spirostreptus giganteus*): first, the responses of millipedes are observed when part of the terrain

Table 1. Detailed information on the subjects.

Subject number	Body length (cm)	Weight (g)	Approximate number of legs	Number of legs amputated in the second experiment
1	20.4	51	250	24
2	20.8	60	240	24
3	20.4	53	230	24

is removed during their locomotion to examine the manner in which the ground contact affects leg movement. Second, several successive legs in the middle part of the subjects' bodies are intentionally removed to observe the response to leg amputation. Three subjects are used in the experiments. Detailed information on the subjects is provided in table 1. The first experiment involves performing seven trials for subject 1 and five trials each for subjects 2 and 3. The second experiment involves performing five trials for each subject. All the selected subjects naturally lack a few legs (approximately five or less). Although the first experiment is identical to the experiment performed in a previous study [26], it is performed again in this study to verify its reproducibility and to show more detailed results.

The experimental setup is shown in figure 2. The subjects are forced to move along a narrow aisle formed by plastic plates. Two video cameras are attached such that the side and bottom views are simultaneously obtained. In the first experiment, a part of the terrain with a length of 5 cm is removed during locomotion (figure 2(a)). In the second experiment, several legs are removed in the middle portion of the subject's body (figure 2(b)). Leg-tip positions are visualized through spatiotemporal plots using ImageJ, an image-processing package [27]. More specifically, spatiotemporal plots are obtained as follows: first, a line along the path of the locomotion is drawn on the bottom-view images, and then, the images cropped along the line are sequentially arranged. It should be noted that the colour of the obtained images (figures 4 and 6) is modified to improve visibility.

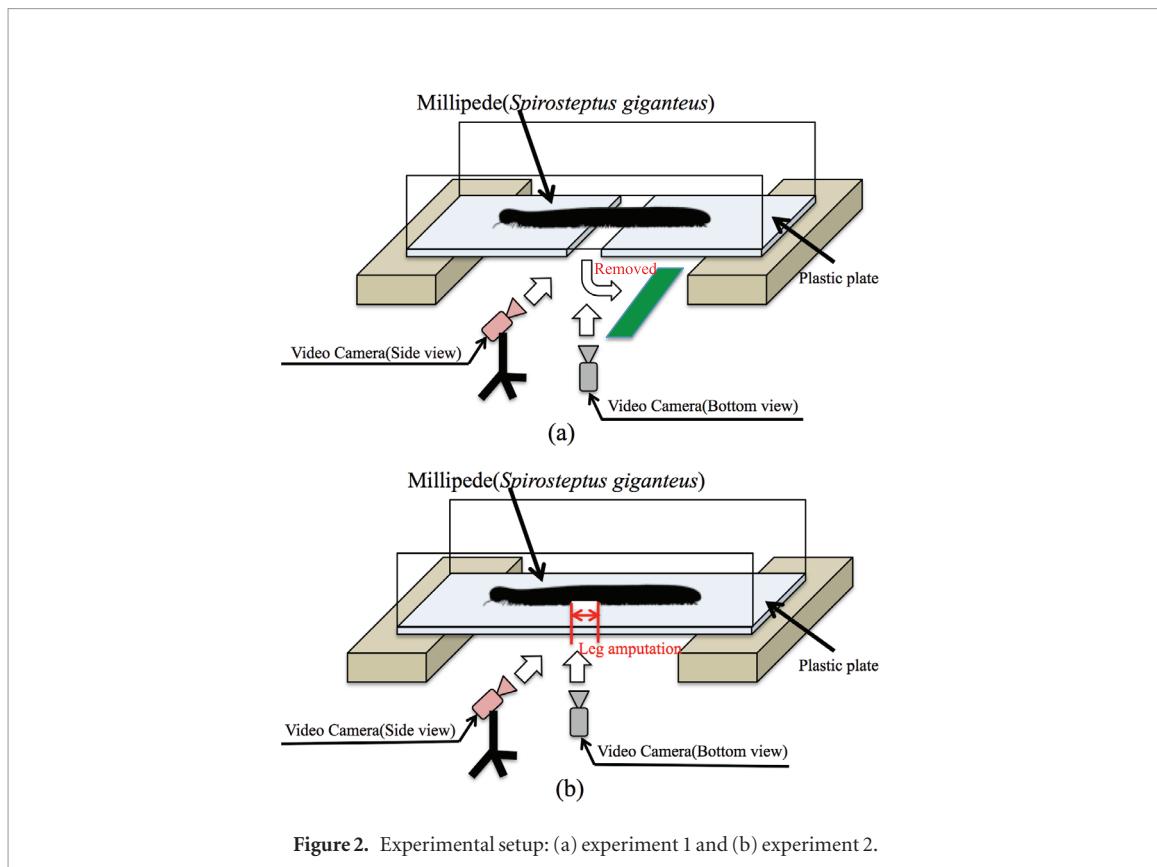


Figure 2. Experimental setup: (a) experiment 1 and (b) experiment 2.

Figure 3, movie 1 (stacks.iop.org/BB/12/036007/mmedia), and figure 4 show the photographs, the movie, and the spatiotemporal plot of the leg tips, respectively, for one of the trials in which part of the terrain is removed. With respect to the ground, the leg tips form density waves that propagate forward. This is in accordance with the results reported in a previous study [8–11]. However, this behaviour changes over the gap. That is, when a leg enters the gap, it continues to move for a short duration (figure 3(A)) and then stops moving (figure 3(B)). It then begins moving again when several of its anterior legs come into contact with the ground (figure 3(C)). This tendency is also clearly observed in the spatiotemporal plot (figure 4). This behaviour is qualitatively consistent for all trials and for all subjects. Thus, it is likely that each leg is driven by the contact between the ground and the leg itself and that between the ground and several anterior legs.

Figure 5, movie 2, and figure 6 show the photographs, the movie, and spatiotemporal plot, respectively, of the locomotion of millipedes that involves the amputation of several legs for one of the trials. The findings indicate that the density waves formed by the leg tips are propagated from the tail to the head. The property of the waves, e.g. wave number, is almost identical to that of intact millipedes. This behaviour is qualitatively consistent for all trials and all subjects. This result suggests that millipedes can adapt to the intentional amputation of several successive legs.

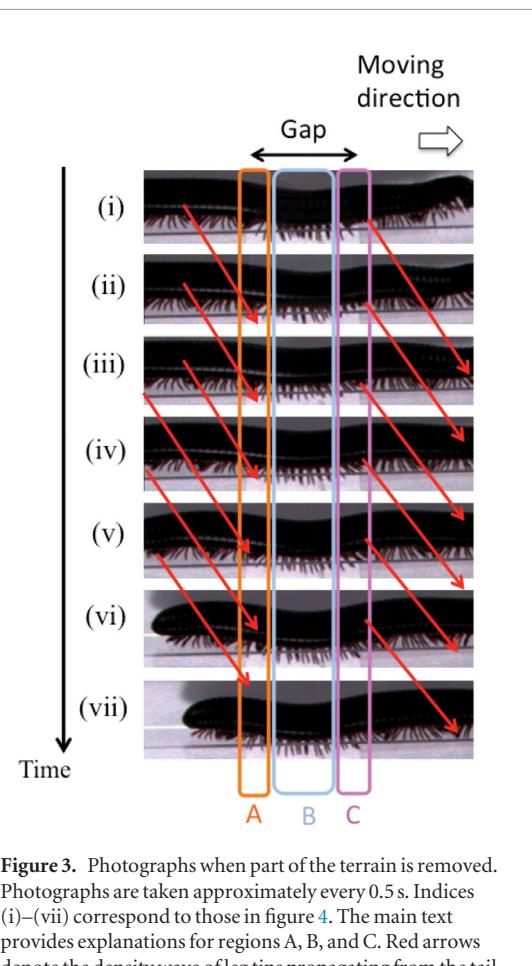
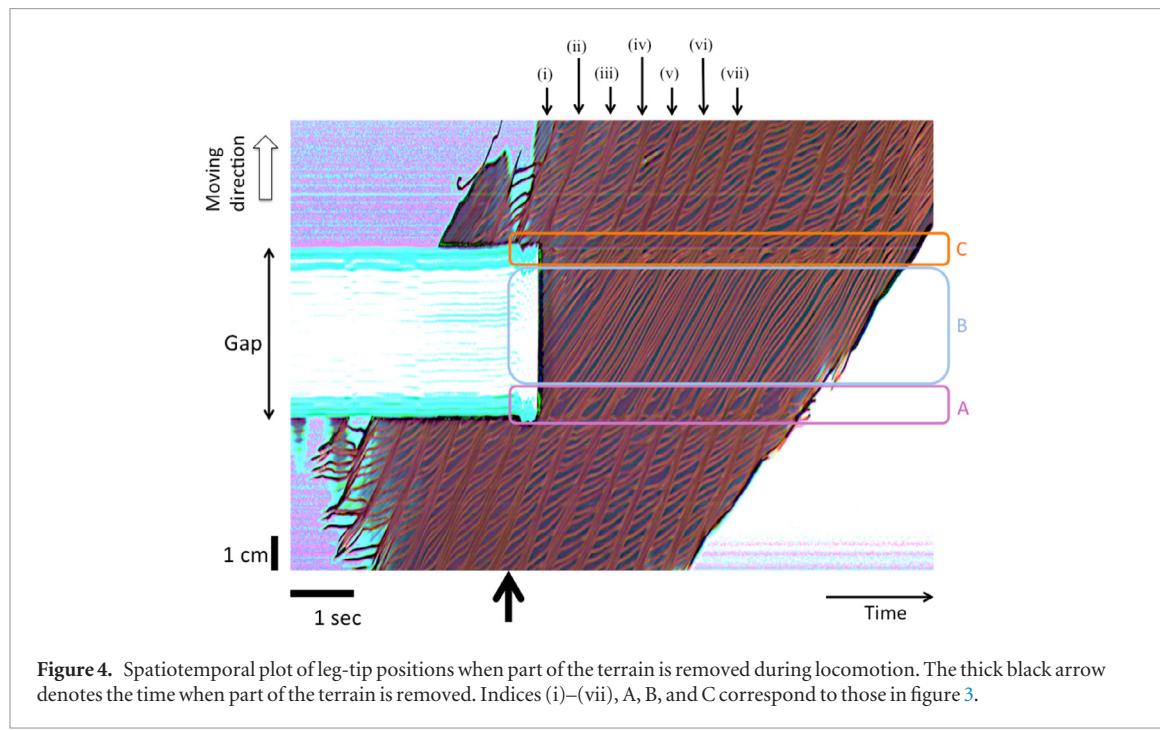


Figure 3. Photographs when part of the terrain is removed. Photographs are taken approximately every 0.5 s. Indices (i)–(vii) correspond to those in figure 4. The main text provides explanations for regions A, B, and C. Red arrows denote the density wave of leg tips propagating from the tail to the head. Photographs are mirror images of their original photographs. In the original photograph, the direction of motion was from the right to the left.



3. Model

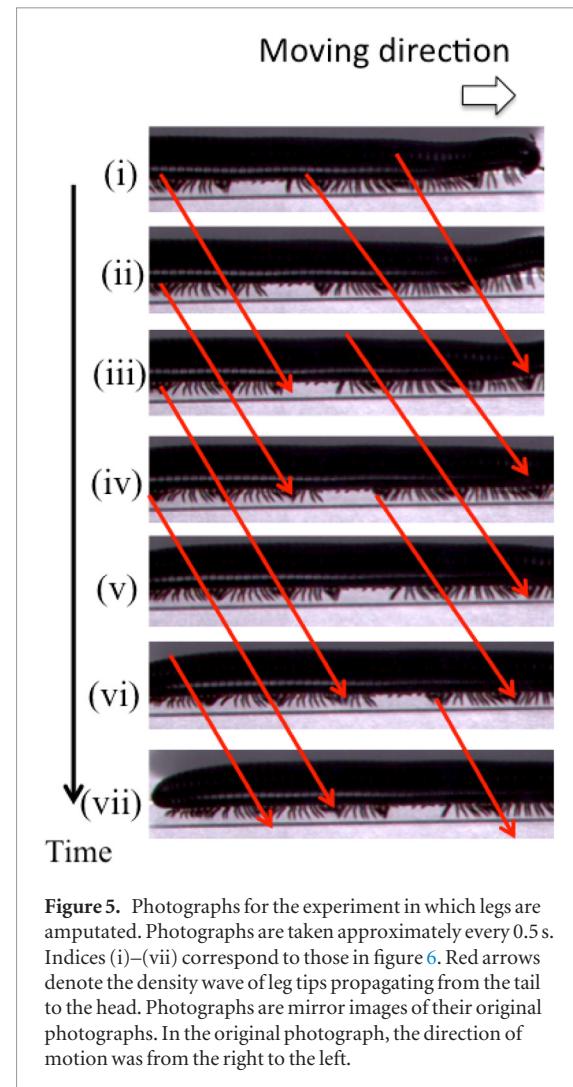
In this section, the decentralized control scheme is presented for the interlimb coordination in millipede locomotion [26], which is proposed based on the qualitative findings of the behavioural experiments. A schematic is shown in figure 7. The body trunk consists of n segments. Although two legs are attached to each side of a segment on real millipedes [7], in this model, it is assumed that only a leg is attached on each side for the purposes of simplicity. Furthermore, it is assumed that each leg can move in both the forward–backward and upward–downward directions. A phase oscillator is implemented in each leg. The motions of the i th leg on the right-hand side and left-hand side are controlled based on the oscillator phases $\phi_{i,r}$ and $\phi_{i,l}$ respectively. The legs tend to be in the swing and stance phases when the oscillator phase is between 0 and π , and between π and 2π , respectively.

The results of the behavioural experiments suggest that the motion of each leg is affected by the ground contact of the leg itself and its several anterior legs. Thus, the time evolution of the oscillator phase is described as follows:

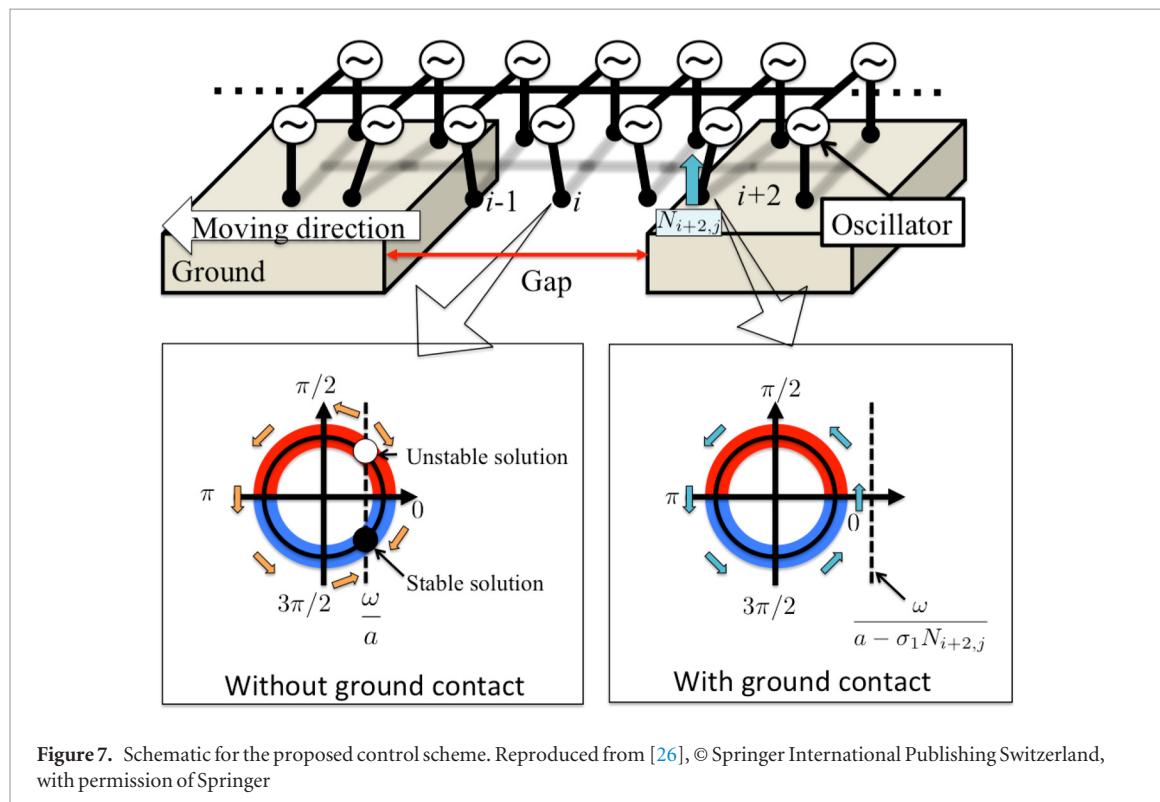
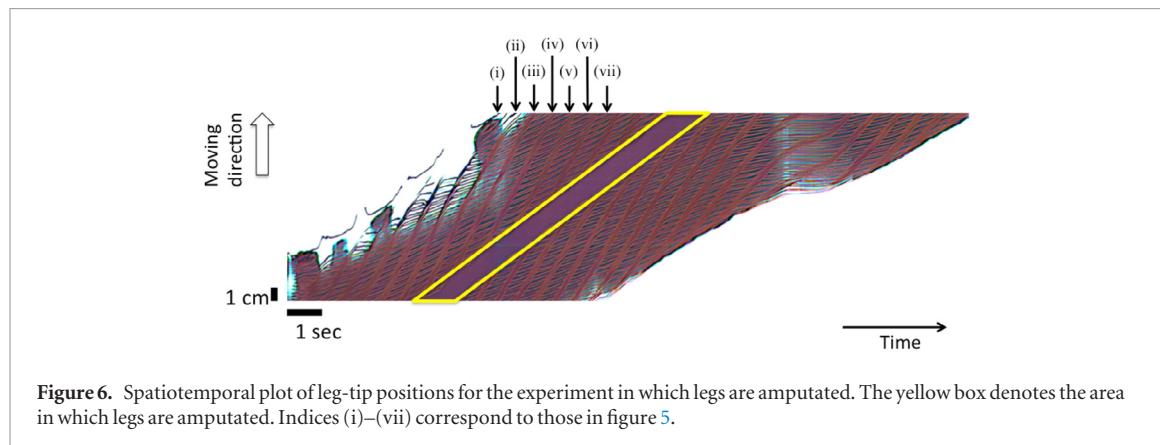
$$\dot{\phi}_{i,j} = f(N_{i,j}, \phi_{i,j}) + g(N_{i-1,j}, \phi_{i,j}), \quad (i = 1, 2, \dots, n, j = r, l) \quad (1)$$

where $N_{i,j}$ denotes the ground reaction force acting on the i th leg on the j th side. Function $f(N_{i,j}, \phi_{i,j})$ denotes the intrinsic oscillator property and the phase modulation due to the ground contact of the i th leg on the j th side, and function $g(N_{i-1,j}, \phi_{i,j})$ denotes the phase modulation due to the ground contact of the $(i - 1)$ th leg on the j th side. The explanation is provided below.

It is considered necessary to feed the ground reaction force of the nearest anterior leg, i.e. the $(i - 1)$ th leg, and also that of several anterior legs back to the oscillator phase. However, the ground reaction forces



acting on the anterior legs (with the exception of the nearest anterior leg) are not used for the control in the study as several adjacent legs of real millipedes are



considered as a single leg in the model. This assumption can be valid given that the several adjacent legs move in a similar manner. Furthermore, the assumption is suitable for robotic experiments as described in the next section because the developed robot only consists of ten segments, and this is considerably smaller than the number of legs present in real millipedes.

Functions $f(N_{i,j}, \phi_{i,j})$ is modelled as described below. From the behavioural experiment on a terrain with a gap (figure 3), it is determined that the leg stops moving over the gap while it exhibits periodic motion when it is in contact with the ground. Hence, $f(N_{i,j}, \phi_{i,j})$ is described as follows:

$$f(N_{i,j}, \phi_{i,j}) = \omega - (a - \sigma_1 N_{i,j}) \cos \phi_{i,j}, \quad (2)$$

where ω denotes the intrinsic angular velocity and a and σ_1 denote positive constants. If $\omega < a$ and the leg is not in contact with the ground ($N_{i,j} = 0$), then $f(N_{i,j}, \phi_{i,j}) = 0$ has two solutions, namely a solution that is stable and

another solution that is unstable (figure 7). Thus, the leg tends to stay at the position corresponding to the stable solution. When the leg comes in contact with the ground and $N_{i,j}$ increases, then the stable and unstable solutions disappear, and thus, the leg moves periodically.

Function $g(N_{i-1,j}, \phi_{i,j})$ is modelled based on the finding that the leg begins lifting itself up when the several anterior legs come in contact with the ground (figure 3(C)). Thus, $g(N_{i-1,j}, \phi_{i,j})$ is described as follows:

$$g(N_{i-1,j}, \phi_{i,j}) = \sigma_2 N_{i-1,j} \cos \phi_{i,j}, \quad (3)$$

where σ_2 denotes a positive constant. It should be noted that N_{i-1} is set to zero for the most anterior leg. When the $(i-1)$ th leg comes into contact with the ground, the i th oscillator phase converges to $\pi/2$, and the i th leg is lifted up. Additionally, it is expected that the density waves of the leg tips are generated in a decentralized manner because it is observed that the i th leg waits for ground contact until the anterior legs are lifted off the ground.

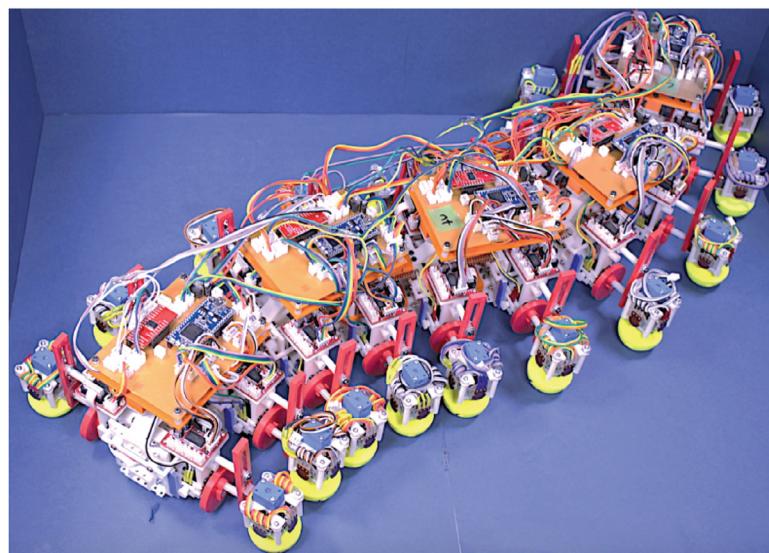


Figure 8. The myriapod-like robot developed in a previous study [26]. Reproduced from [26], © Springer International Publishing Switzerland, with permission of Springer

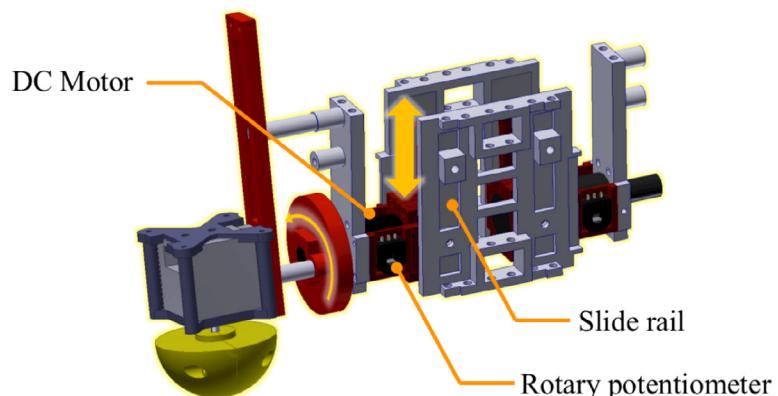


Figure 9. Detailed structure of a segment.

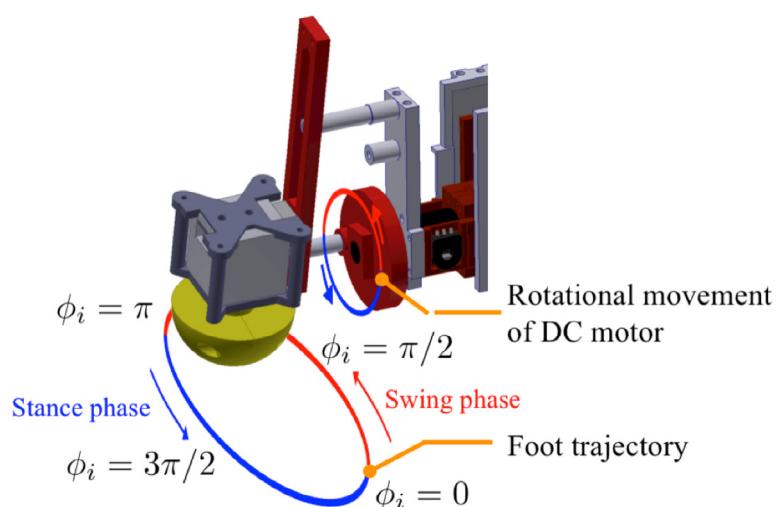


Figure 10. Relationship between the oscillator phase and leg trajectory.

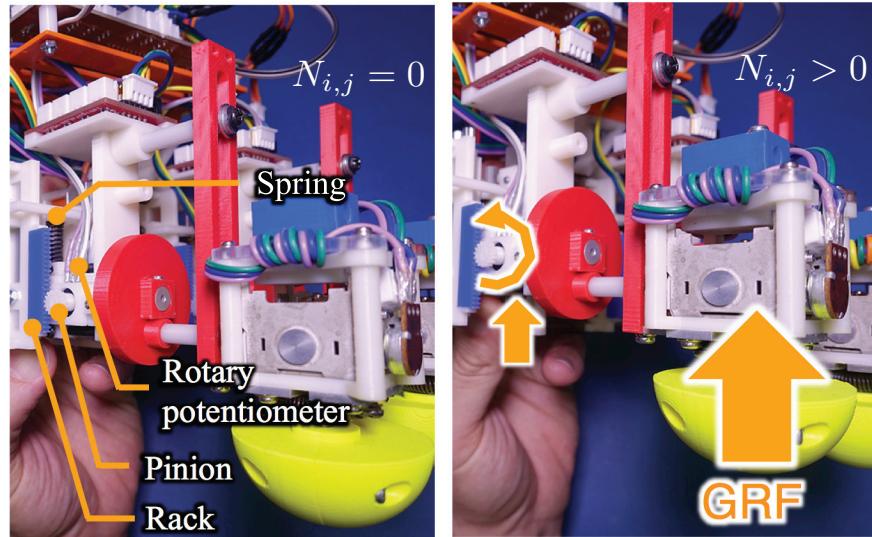


Figure 11. Mechanism for the detection of the ground reaction force.

4. Robot experiment

4.1. Hardware

In the study, a millipede-like robot developed in a previous study [26] was used to test the validity of the proposed control scheme. The hardware design is briefly reviewed in this section. The overview of the robot is shown in figure 8. The robot consists of 10 segments, and the total length, width, height, and weight correspond to 0.75 m, 0.25 m, 0.15 m, and 3.4 kg, respectively. Yaw joints are implemented between the segments such that the robot can bend flexibly although the joints are fixed by penetrating all segments with a rigid bar in this experiment, given that the body of a real millipede is stiff.

Each segment consists of the body trunk and two legs. A DC motor (Maxon Japan Corporation, RE-max17GB 4.5W SL 2WE) is implemented in each leg. The mechanism shown in figure 9 converts the rotational motion of the DC motor into a foot trajectory during the swing and stance phases. The DC motors are controlled by microcomputers (mbed NXP LPC1768) implemented in each segment. The leg trajectory is determined based on the oscillator phase: that is, each DC motor is manipulated on the legs using proportional-integral-derivative (PID) control such that its rotational angle corresponds to the oscillator phase. Thus, the leg tends to be in the swing phase when $0 \leq \phi_{i,j} < \pi$ and in the stance phase when $\pi \leq \phi_{i,j} < 2\pi$ (figure 10).

The mechanism for detecting the ground reaction force is shown in figure 11. Two slide rails are attached on both sides of a DC motor, and the unit is moved up when the ground reaction force is detected. The displacement of the unit is detected by a rotary potentiometer via the rack and pinion mechanism as shown in figure 11. It should be noted that in the following experiments, $N_{i,j}$ in equations (1)–(3) is defined as the value of the rotary potentiometer and not as the ground reaction force itself.

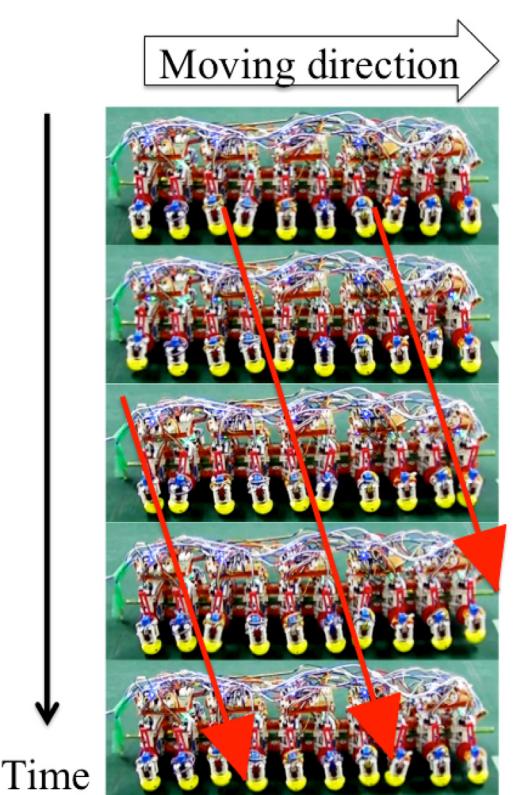
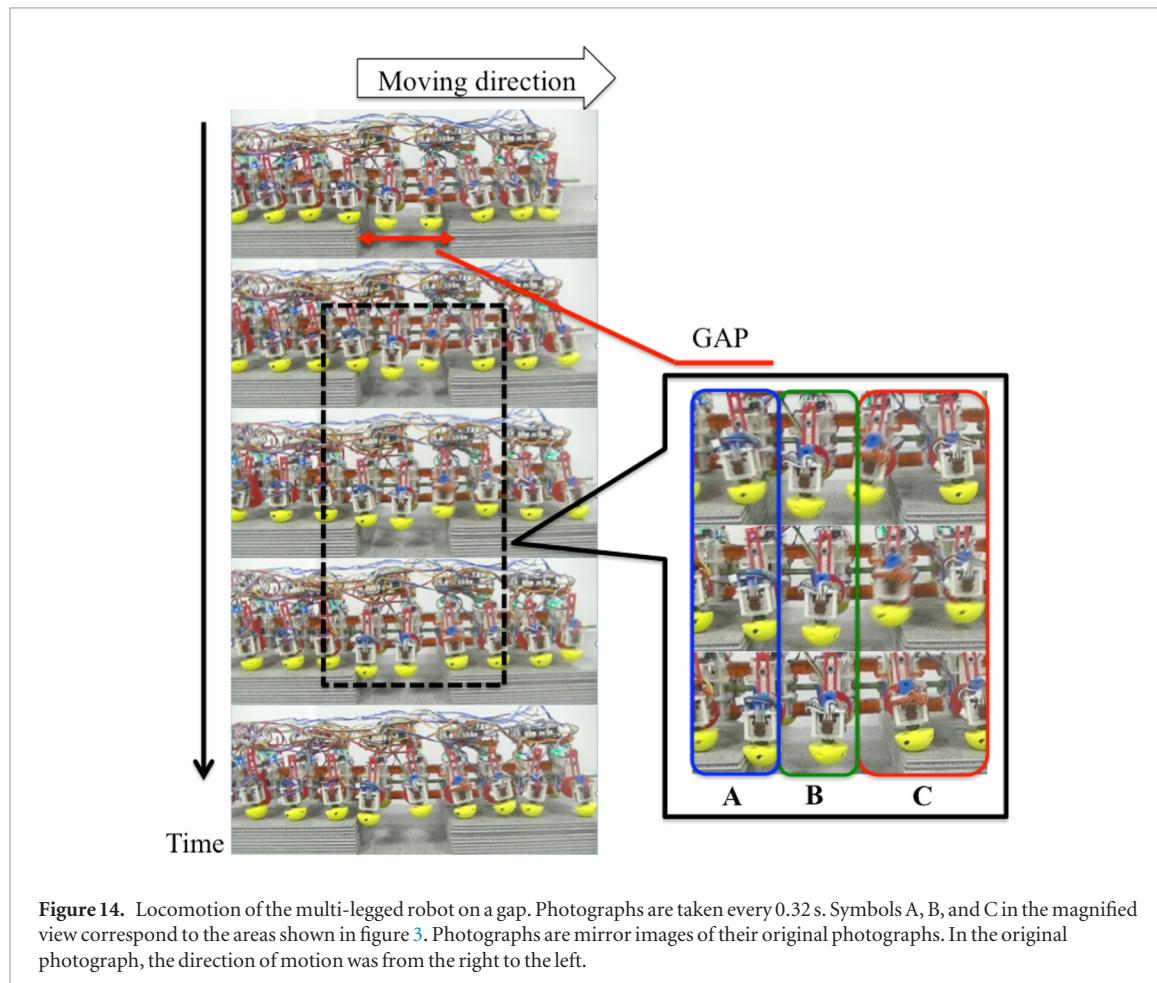
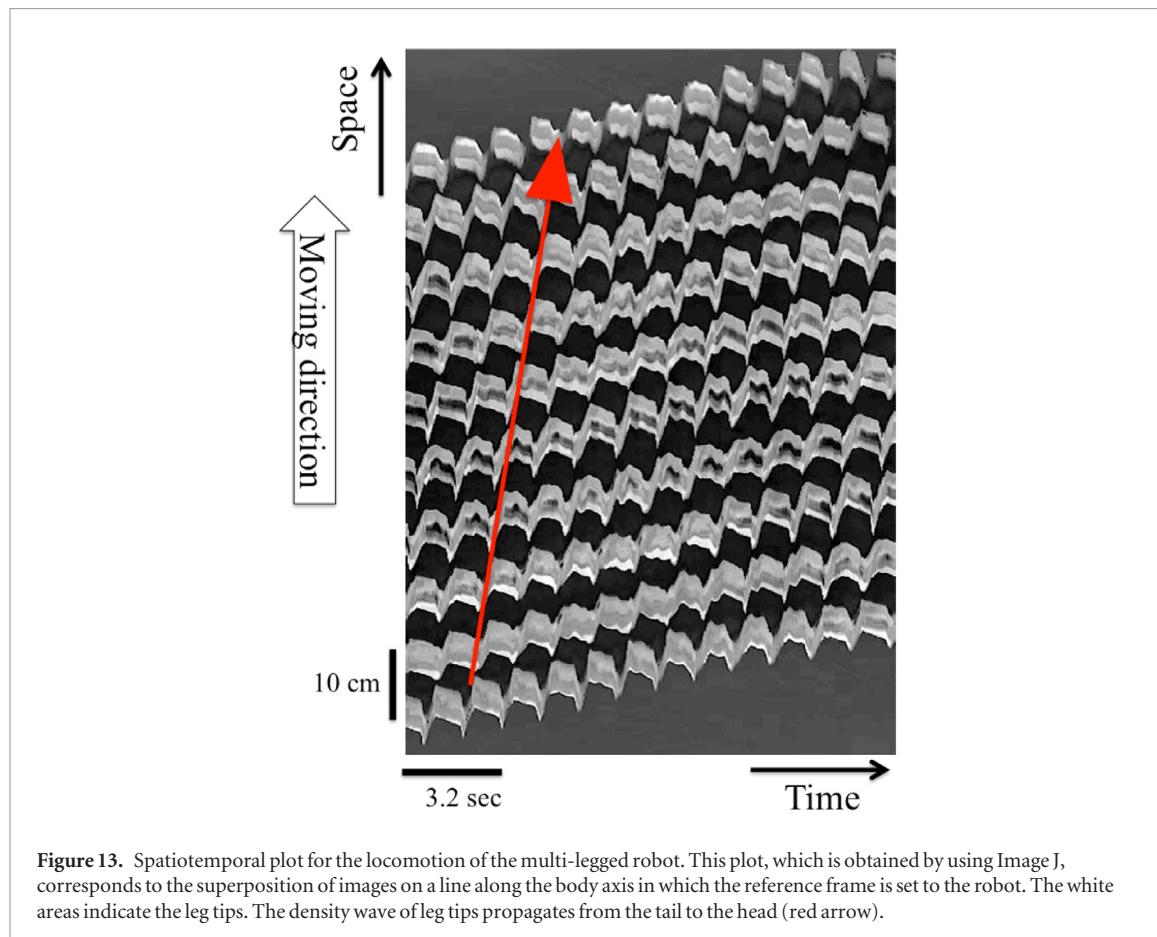


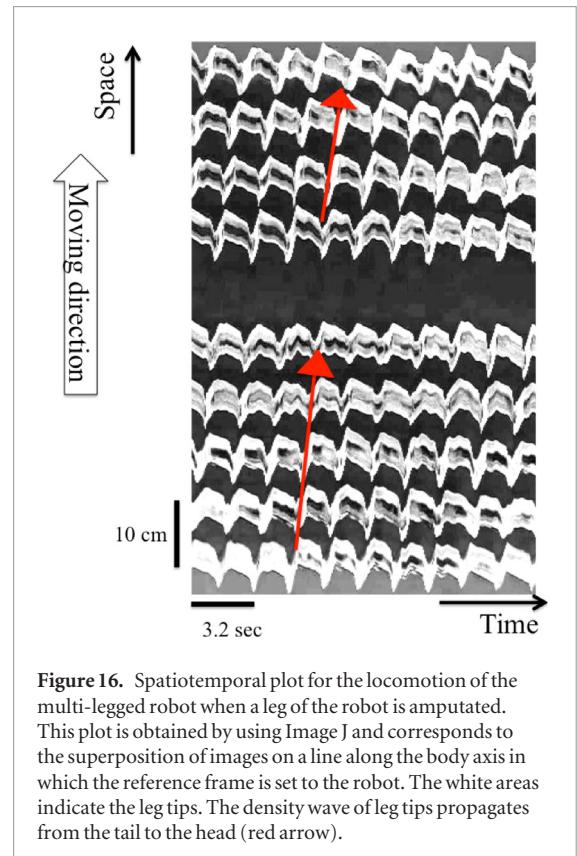
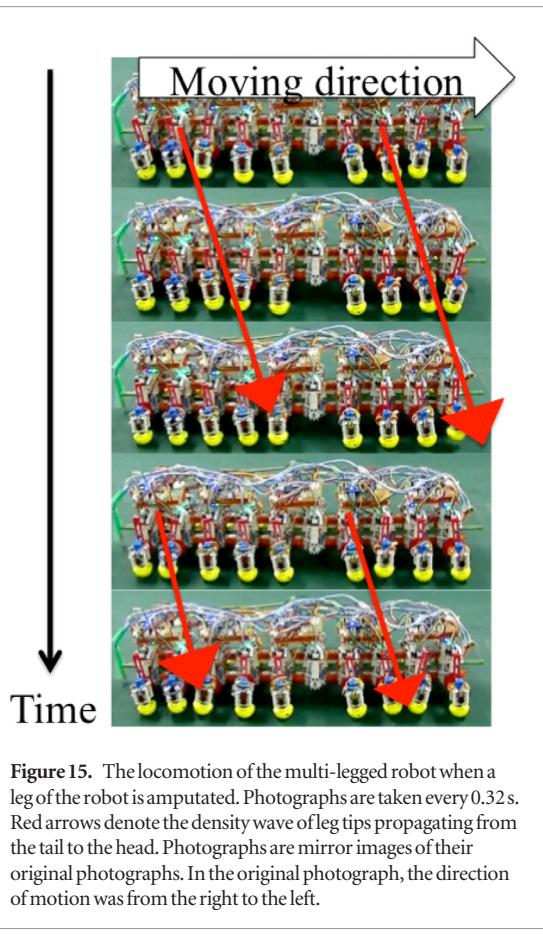
Figure 12. Photographs of the multi-legged robot during locomotion. Photographs are taken every 0.32 s. Red arrows denote the density wave of leg tips propagating from the tail to the head. Photographs are mirror images of their original photographs. In the original photograph, the direction of motion was from the right to the left.

4.2. Experimental results

4.2.1. Normal condition

First, the locomotion of the robot on an even terrain is observed. The parameter values are as follows: $\omega = 6 \text{ rad s}^{-1}$, $a = 10.5 \text{ rad s}^{-1}$, $\sigma_1 = 15 \text{ rad s}^{-1}$, and $\sigma_2 = 30 \text{ rad s}^{-1}$. Three trials are performed, and each trial consists of 6 or 7 cycles. In each trial, the robot is powered on with its body lifted off the ground. It





is placed on the ground after the phases of all legs converge to the stable solution of $\dot{\phi}_i = 0$.

The photographs, the movie, and the spatiotemporal plot of the leg tips for one of the trials are shown in figure 12, movie 3, and figure 13, respectively. The findings clearly indicate that the density waves of the leg tips propagated from the tail to the head. The legs in the dense and sparse parts are in the swing and stance phases, respectively. This result is in good agreement with the locomotion of real millipedes.

Real millipedes move the left and right legs in phase [9]. However, the phase difference between left and right legs of the developed robot drifts and does not converge to fixed values. To quantitatively evaluate the extent of synchronization, the following index is defined [28]:

$$R e^{i\Theta} = \langle \langle e^{i(\phi_{i,l} - \phi_{i,r})} \rangle_{\text{cycle}} \rangle_{\text{leg}}, \quad (4)$$

where i denotes an imaginary number and $\langle \cdot \cdot \cdot \rangle_{\text{cycle}}$ and $\langle \cdot \cdot \cdot \rangle_{\text{leg}}$ denote the average of the cycles for each leg in each trial and the legs in each trial, respectively. Parameter R characterizes the extent of synchronization. For example, $R = 1$ when $\phi_{i,l} - \phi_{i,r} = 0$ for all cycles and legs, and R approaches zero as $\phi_{i,l} - \phi_{i,r}$ distributes. Additionally, Θ characterizes the average phase difference between the legs. For example, $\Theta = \pi/2$ when $\phi_{i,l} - \phi_{i,r} = \pi/2$ for all cycles and legs.

The result for each trial corresponds to $R = 0.72$ and $\Theta = 0.21\pi$ (rad), $R = 0.62$ and $\Theta = 0.35\pi$ (rad), and $R = 0.62$ and $\Theta = 0.33\pi$ (rad). These results

indicate that the right and left legs tend to move in phase, although the movement is not completely synchronized.

4.2.2. Locomotion over a gap

The locomotion of the robot is observed over a gap. The parameter values are the same as those in section 4.2.1. The result is shown in figure 14 and movie 4. When a leg enters the gap, the leg moves for a short duration (figure 14(A)), and following this, the leg ceases to move (figure 14(B)). The leg begins to move again when the anterior leg comes into contact with the ground (figure 14(C)). This result is in qualitative agreement with the locomotion of a real millipede over a gap.

4.2.3. Fault tolerance

The locomotion of the robot is observed after a leg of the robot is removed. The parameter values are the same as those in section 4.2.1. The photographs, the movie, and the spatiotemporal plot are shown in figure 15, movie 5, and figure 16, respectively. The density waves of the leg tips successfully propagate from the tail to the head, and this is similar to the case of the locomotion of a millipede with several amputated legs (figures 5 and 6).

4.2.4. Changes in angular frequency

Extant research reports that the wavelengths of real millipedes increased with increases in the locomotion speed [9]. Experiments are performed by changing the angular frequency ω to investigate whether or not this finding can be reproduced using the control scheme proposed in the present study. Specifically, ω is changed from 3 rad s^{-1} to 6 rad s^{-1} and then to 9 rad s^{-1} during the experiment. The other parameter values are the

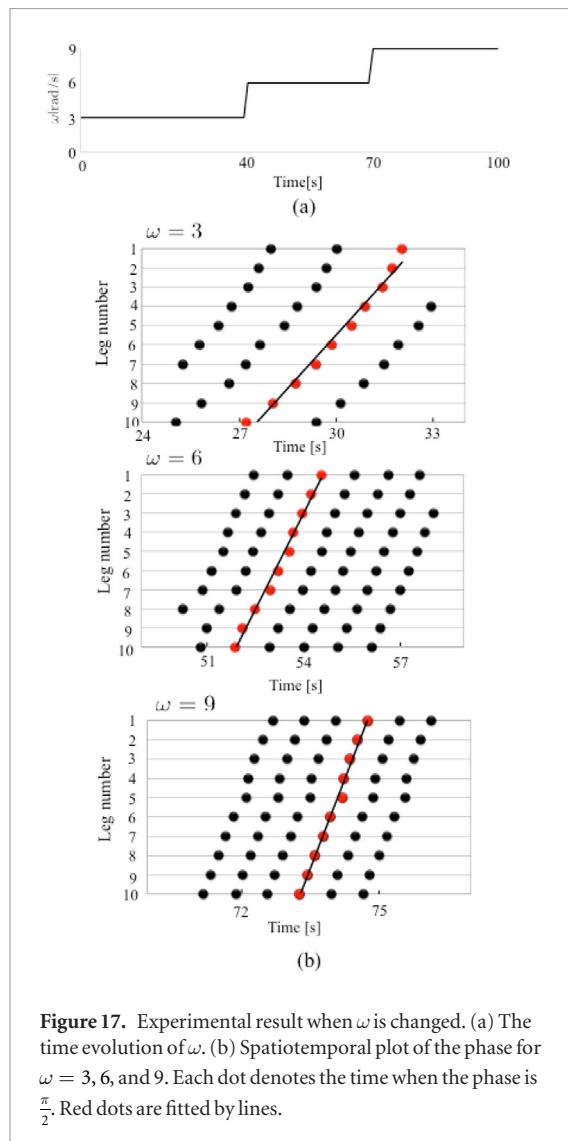


Figure 17. Experimental result when ω is changed. (a) The time evolution of ω . (b) Spatiotemporal plot of the phase for $\omega = 3, 6$, and 9 . Each dot denotes the time when the phase is $\frac{\pi}{2}$. Red dots are fitted by lines.

same as those in section 4.2.1. Figure 17 shows the plot of the oscillator phase. The wavelength increases with increases in ω , and this is in agreement with previously reported biological findings [9].

5. Discussion

The control scheme proposed by the present study reproduces the locomotion of real millipedes. The key point relates to the fact that the periodic motion of a leg is not generated when the anterior legs and the leg itself lift off the ground. This is described by rewriting equation (1) in the form of an active rotator model [29] as follows:

$$\dot{\phi}_{i,j} = \omega - A \cos \phi_{i,j} \quad (5)$$

where

$$A = a - \sigma_1 N_{i,j} - \sigma_2 N_{i-1,j} \quad (6)$$

When $\sigma_1 N_{i,j} + \sigma_2 N_{i-1,j} < a - \omega$, i.e. $A > \omega$, the leg state corresponds to an excitatory regime, and the leg does not move periodically. When $\sigma_1 N_{i,j} + \sigma_2 N_{i-1,j} > a - \omega$, i.e.

$A < \omega$, the leg state corresponds to an oscillatory regime, and the leg exhibits periodic motion.

A previous study proposed a decentralized control scheme for the interlimb coordination of quadrupeds [30], and the proposed scheme reproduces the gait patterns of quadrupeds. This control scheme can also be written in the form of the active rotator model (equation (3)). However, A in this case is given by the following equation:

$$A = \sigma N_{i,j}, \quad (7)$$

where σ denotes a positive constant. Thus, there are two main differences between quadrupeds and millipedes, and they can be expressed as follows:

- (i) As $N_{i,j}$ increases, the leg state changes from the excitatory regime to the oscillatory regime for millipedes and vice versa for quadrupeds.
- (ii) The leg motion is affected by the ground reaction forces acting on anterior legs in case of millipedes. However, the leg motion is not affected by the ground reaction forces acting on anterior legs in case of quadrupeds.

These facts suggest that the interlimb coordination mechanism changes with changes in the number of legs. However, the mechanism that underlies the interlimb coordination of animals with an intermediate number of legs, e.g. hexapods, octopods, etc, continues to warrant further investigation.

6. Conclusion

In conclusion, in this study, a decentralized control mechanism is proposed for the interlimb coordination of millipedes as the first step towards understanding the interlimb coordination mechanism of legged animals from a systematic viewpoint. The proposed model is based on the qualitative findings of behavioural experiments, which indicate that ground contact is essential for the generation of periodic leg motions. The proposed control mechanism is implemented in a developed robot. The results indicate that the proposed scheme can qualitatively reproduce millipede locomotion. The findings of this study offer a deeper understanding of the interlimb coordination mechanism of legged animals. It can also help in designing multi-legged robots that can adapt to changes in the environment as well as to changes in their own morphology.

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