Application of bio-inspired control of AmphiHex-I in detection of *Oncomelania hupensis*, the amphibious snail intermediate host of *Schistosoma japonicum*

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Abstract

Purpose – This paper aims to construct a central pattern generator (CPG) network that comprises coupled nonlinear oscillators to implement diversified locomotion gaits of robot AmphiHex-I. With the gaits, AmphiHex-I will have a strong locomotion ability in an amphibious environment, which is motivated by a novel public health application to detect the amphibious snail, *Oncomelania hupensis*, the snail intermediate host of *Schistosoma japonicum*, as an amphibious robot-based tool for schistosomiasis surveillance and response in the future.

Design/methodology/approach – First, the basis neural network was built by adopting six Hopf nonlinear oscillators which corresponded to six legs. Then, the correlation between the self-excited harmonic output signals generated from CPGs and various gaits was established. In view of requirements on its field application, the authors added a telecontrol system and an on-board battery to support the real-life remote control and a high-definition camera and a global positioning system module to acquire images and position information. Finally, the authors conducted the testing experiments on several tasks, e.g. detecting the distribution of *Oncomelania hupensis* snails.

Findings – The results demonstrate that the CPG is effective in controlling the robot's diversified locomotion gaits. In addition, the robot is capable of fulfilling several testing tasks in the experiments.

Originality/value – The research provides a method based on CPG to control a hexapod robot with multiple motion patterns, which can effectively overcome the difficulty of motion control simply by changing certain mathematical parameters of a nonlinear equation, such as frequency, phase difference and offset angle, so as to realize the gait transitions. Also, using such a robot to probe the distribution of snails offers another way to tackle this laborious job, especially in some odious terrains, which will hence broaden the application of AmphiHex-I to vector surveillance in the fields of public health.

Keywords Central pattern generator, Motion control, Amphibious robot, Disease surveillance, Gait, *Oncomelania hupensis*

Paper type Research paper

1. Introduction

Research on amphibious robots has been undertaken for many decades. Many research groups are attracted by its broad prospect and application, such as resource exploration, disaster rescue, military surveillance, etc. Some remarkable amphibious robots have been developed around the world in recent years. Whegs, a biologically inspired amphibious robot with the combination of propellers and legs, has good locomotion abilities to navigate on rough terrain and underwater (Boxerbaum *et al.*, 2005). RHex series robot, a cockroach-like hexapod robot with six curved legs which incorporates the advantages of legged and wheeled locomotion, has shown outstanding performance on terrestrial terrains (Saranli *et al.*, 2000, 2001). AQUA series robot, which stems from the RHex robot, can achieve aquatic maneuvers such as hovering, descending, lift-off, yawing and

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rolling by utilizing six flippers oscillating as propulsion mechanisms (Prahacs *et al.*, 2004; Dudek *et al.*, 2007). Compared with the aforementioned robots, AmphiHex-I performs a good locomotion performance not only in the rough terrains and aquatic environments but also in muddy or sandy substrates, because of its unique transformable leg-flipper composite propulsion mechanism (Liang *et al.*, 2012; Zhang *et al.*, 2013, 2015). However, there are some control difficulties with the novel leg-flipper mechanism and motion patterns, such as being hard to change the velocity timely and the complex control program, which is due to multiple gaits, which has hindered the field application of the robot. Thus, a new control strategy is required to simplify the gait control to adapt the field applications.

As traditional model-based control strategies have limitations in flexibility, stability, adaptability and motion modulation, researchers have been turning to bio-based control methods (Ijspeert, 2008). Neurobiology studies have demonstrated that the rhythmic actions of animals (running, chewing, swimming, flying, etc.) are mainly controlled by central pattern generators (CPGs), which are neural circuits found in both invertebrate and vertebrate animals that can produce robust, coordinated rhythmic signal without any inputs from higher control centers (Hooper, 2000; Rosenberger, 2001; Ijspeert *et al.*, 2007). So, the method of building an artificial network of nonlinear oscillating neurons to control the rhythmic motions of robots has received more and more attention during past few years, such as the locomotion of bipedal robot (Endo *et al.*, 2008; Shahbazi *et al.*, 2012), the quadrupedal legged locomotion (Liu *et al.*, 2011), the hexapod robot (Chung *et al.*, 2015), the swimming of RoMan-II (Zhou and Low, 2012) and Robo-Ray (Cao *et al.*, 2015), the swimming and land locomotion of Salamander (Ijspeert *et al.*, 2007) and AmphiRobot-1 (Yu *et al.*, 2013). The successful applications of robots indicate that CPG-based control is suitable for handling the multiple degrees of freedom (DOFs) associated rhythmic locomotion control, and it has considerable advantages in stability and smoothness of the transition process among different movements. Also, with CPG-based control, the chief motion control mission is managed by bottom control layer, which can liberate the upper levels to do something more sensible, such as image processing, which consumes massive memory resources. In view of the characteristics of CPG-based control, we adopt the Hopf nonlinear oscillators as the neurons to construct the neural network of the control system, which can be used to fulfill the task of moving in various terrains by choosing the corresponding gaits.

Another highlight of this paper is the novel public health application that motivates the bio-inspired controlling strategy, namely, amphibious robot-based distribution probing of snails; *Oncomelania hupensis*, the snail intermediated host of *Schistosoma japonicum*, which can cause zoonotic schistosomiasis both in human and domestic animals, which finally can be used for the timely disease surveillance and response. Schistosomiasis is a serious parasitic disease that affects more than 70 million populations in the endemic areas of China (Chen, 2014). One of the most important control approach in the national schistosomiasis control program is to eliminate *Oncomelania hupensis*, the snail intermediated host of *Schistosoma japonicum*. Up to now, the distribution of *Oncomelania hupensis* is still detected manually by human eyes, which is not only labor-intensive but also practically inefficient because of the sludge terrain and tiny body; this hinders the control program significantly (Collins *et al.*, 2012). *Oncomelania hupensis* is an amphibious snail distributed mainly in the marshland along the Yangtze River and connected lakes, such as Puyang Lake and Dongting Lake. Therefore, it is worthwhile to detect the distribution of *Oncomelania hupensis* snail by amphibious robot-based tools, which can promote the efficiency to guide the disease surveillance and intervention of schistosomiasis (Zheng *et al.*, 2013). Our robot equipped with a high-definition (HD) camera and a global positioning system (GPS) unit provides an efficient method for probing the snails owing to its motion performance in an amphibious environment, which can enhance its practicability to the fields of epidemiology and public health.

The remainder of the paper is organized as follows. The design of mechanism and electrical control system are briefly described in Section 2. The CPG-based control method that utilizes the signal produced by CPGs to implement the gaits transition is introduced in Section 3. Section 4 presents a real-world experiment of probing the distribution of snails with AmphiHex-I, which can be viewed as an application in some fields of epidemic prevention. Finally, the conclusions of the paper with an outline of future work are offered in Section 5.

2. Locomotion platform for field application

AmphiHex-I has incorporated the merits of the RHex robots and AQUA robots by mounting six actively transformable leg-flippers (Saranli *et al.*, 2000; Prahacs *et al.*, 2004). The robot imitates wheeled movement on rough land and soft substrates (e.g. sandy and muddy terrain) by rotating the curved legs, and it also imitates fin propulsion with the vectored thrust produced by oscillating the straight flippers (Zhang *et al.*, 2013, 2015). The transformation and propulsion motions are realized by six sets of driving mechanisms that delicately integrate driving motors and assisting motors. However, the active transformation process and versatile propulsion gaits increase the controlling complexity of the robot. In view of requirements on its field application, some improvements of the robot should be fulfilled.

2.1 Modification of AmphiHex-I

To fulfill a field detection task, we have conducted some improvements on AmphiHex-I. First, the command signal was sent through wireless communication from a telecontrol system, meanwhile two pieces of Li-pol batteries with the rated current and capacity of 10 A and 10 Ah, respectively, were added as the power supply of the robot, which removes the power and signal tether of the robot. Based on the improvements, the maneuverability has enhanced greatly and real-life remote control has come true. Second, an HD waterproof camera is equipped on the front body of robot, which can capture ground image and deliver it to upper smart phone by Wi-Fi or store in its own memory card. Finally, we also install a GPS module in the robot, which can collect the location information when the robot runs in the field environment. On the strength of these modifications, our robot can fulfill the field task of detecting the distribution/

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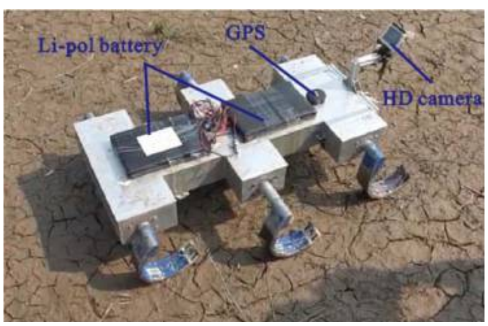
density of snails in real-world scenarios. Figure 1 shows the prototype of the improved robot.

2.2 Electrical control system

The overall control architecture of the electrical system is organized by a hierarchical control structure that includes top control layer, central control layer and bottom control layer from top to bottom, as shown in Figure 2. The top control layer comprises a remote control board based on a digital signal processing (DSP) chip of TMS320F2407A and a smart phone used for obtaining the position information from the GPS and communicating between the robot and the HD camera with Wi-Fi. The central control layer delivers suitable parameters about frequency, phase difference and offset angle to the bottom control layer by a controller area network (CAN) interface embedded in DSP according to the received gait pattern from the top control layer and gives some feedbacks upwardly to judge the correctness of receiving. There are two sets of wireless modules called RF1100-232 used for communicating between the top and central control layer with serial communications interface (SCI) interface embedded in DSP.

The bottom control layer is composed of three groups of motor control units with the same priority level, which are called front, middle and rear control unit. Each group of motor control unit utilizes a DSP chip to simultaneously actuate a MC33886 circuit board used for controlling the main drive motor and an L298 circuit board used for controlling the assistant motor. Each drive motor is equipped with an encoder which can send 1,024 pulses per cycle; the pulses are received by the quadrature encoder pulse (QEP) module embedded in DSP, then the information about the position and velocity of the leg can be determined exactly by counting the number of the pulses during every interrupt routine, while the state of the assistant motor is estimated through gathering the peak current realized by Analog-to-Digital (AD) module of DSP. Also, we take a set of photoelectric encoders at the end of each main output shaft as an absolute zero reference point used for judging the synchronous state of all legs at the first. The circuit boards of one set of motor control unit are shown in Figure 3.

Figure 1 Improved AmphiHex-I prototype



3. Central pattern generator-based gait generator

With the purpose of implementing the diverse motion patterns of AmphiHex-I and reducing the control difficulty, we construct a CPG network and establish the correlation between the self-excited harmonic output signals and various gaits and then implement the motion control by adjusting certain mathematical parameters of a nonlinear equation.

3.1 Control theme and mathematic model

As mentioned in Section 1, the rhythmic motions of animals, such as walking, swimming, flying, etc., are mainly governed by self-excited oscillation signals generated from a low-lever neural, and a high-lever neural just gives some stimulus about exercise intensity and does not concern on the locomotion details, which can reduce resource consumption greatly. Considering this, we construct an artificial network coupled with nonlinear oscillating neurons producing the self-excited oscillation signals to control the corresponding motors in the

Figure 2 Block diagram of the control system of AmphiHex-I

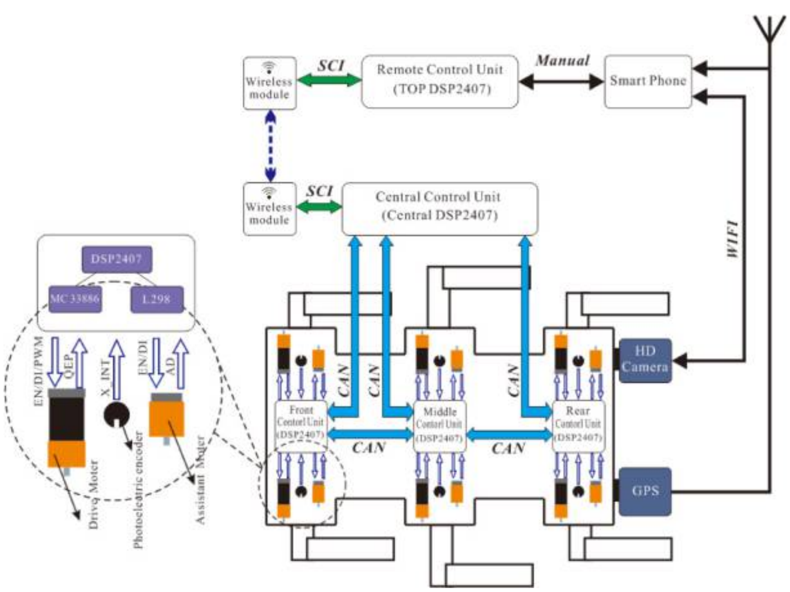
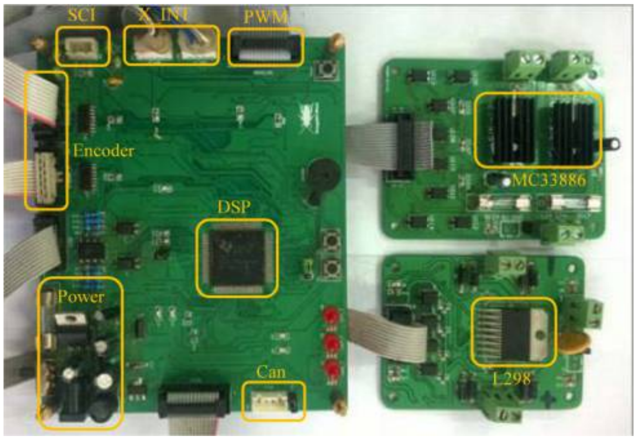


Figure 3 Printed circuit board (PCB) of one motor control unit



bottom control layer, while the top and middle control layers just provide the required stimulus, such as frequency, phase difference, offset angle, etc., and concentrate resources on image processing, which can realize snail recognition on-line in future. Therefore, a CPG-based control is a suitable way for our field probing experiment of robot implementation, which can also optimize the resource distribution and improve the robots' utilization efficiency.

Multiple nonlinear oscillators have been used in modeling CPG systems for motion control, such as Matsuoka oscillator (Kamimura *et al.*, 2005; Sfakiotakis and Tsakiris, 2007), Van Der Pol oscillator (Zhao *et al.*, 2006) and ACPOs oscillator (Torrealba *et al.*, 2012). In this paper, we adopt the Hopf nonlinear oscillator as a basic pattern generator to build the CPG network. The mathematical model of the control system can be described as the following nonlinear equation set:

$$\begin{cases} \dot{X} = f(X) + g(X, \theta) \\ Y = C(t)X + D \end{cases} . \qquad (1.1\text{-}1.2)$$

Equations (1.1) and (1.2) represent the state equation of nonlinear system and output equation, respectively. Here, $f(X)$ is a typical autonomous system which means that its parameters have nothing to do with the time t, $g(X, \theta)$ shows the coupling relationship between different neurons and the state equation of the ith neuron can be expressed as the following nonlinear differential equation set:

$$\dot{X}_i = \begin{bmatrix} \dot{u}_i \\ \dot{v}_i \end{bmatrix} = \begin{bmatrix} \sigma\,(\mathrm{R}^2 - u_i^2 - v_i^2)\,u_i - \omega\,v_i \\ \sigma\,(\mathrm{R}^2 - u_i^2 - v_i^2)\,v_i + \omega\,u_i \end{bmatrix} + \begin{bmatrix} 0 \\ \lambda\,(u_{i-1}\,sin\,\theta_i + v_{i-1}\cos\,\theta_i) \end{bmatrix}, \qquad (2)$$

where $X_i = [u_i, v_i]^T$ represents the state vector of the ith oscillating neuron; σ is a positive constant that adjusts the velocity of convergence; and R and ω denote the amplitude of convergence radius and oscillation frequency, respectively. The content in the third bracket describes the phase relationship between the corresponding neurons, where λ and θ represent the strength of coupling and phase difference between neurons, respectively. A time-domain plot about the transition of frequency, amplitude and phase between two neurons is illustrated in Figure 4. We can find that the process of transition is very smooth, which is a huge advantage about application with the CPG-based control.

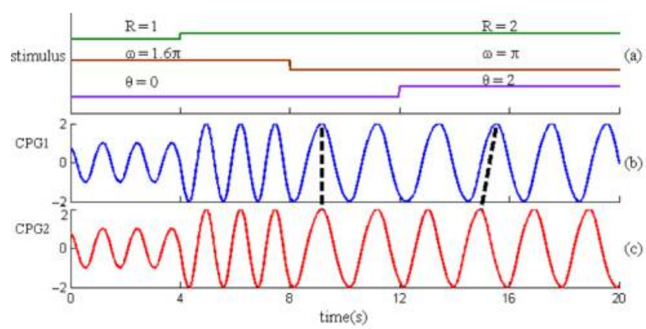
3.2 Central pattern generator topology

In views of aforementioned characteristics about control architecture and Hopf model, we construct the bottom neural network by adopting six Hopf oscillators corresponding to six legs rightly and number them from CPG1 to CPG6. The topology structure is shown in Figure 5, where the contralateral oscillators couple mutually to constitute front, middle and rear neuron pair. The phase difference inside the neuron pair are opposite, for example, $\theta_{14} = -\theta_{41}$. The middle and rear neuron pairs couple with the front neuron pair through the left oscillator of their own. Every oscillator has two output signals that can actuate the drive motor and assistant motor. So, we change equation (1.2) into:

$$\begin{cases} Y_u = C_1(t)U + \tanh\,(t)\Phi \\ Y_v = \mathrm{sgn}\,(v)C_2(t)V \end{cases}, \qquad (1.2.1\text{-}1.2.2)$$

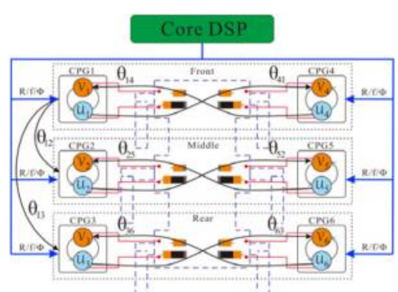
where C_1(t) represents the customized mapping relationsh ip between the value of state vector U and corresponding legs movement position, Φ is an offset angle vector which can modulate the underwater gaits and always equals to 0 when walking on land, *tanh*(t) is a hyperbolic tangent func tion used for smoothing the mutation of Φ and C_2(t) is a customized function which states the relationship between the value of state vector V and corresponding inputs Y_v for assistant motors. Considering that the assistant motor just

Figure 4 The parameter transition between two neurons



Notes: (a) Control stimulus; (b) and (c) represent the value of two neurons, and the phase transition can be reflected clearly by the referenced black dotted line

Figure 5 The topology structure of the bottom control layer



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works in the process of the transformation between curved leg and straight flipper, we set the function *sgn(v)* as the following equation to control the switch of output signal Y_v:

$$\mathrm{sgn}\,(v) = \begin{cases} 1 & \textit{strain wire rope} \\ -1 & \textit{loosen wire rope} \\ 0 & \textit{otherwise} \end{cases}. \quad (3)$$

3.3 Central pattern generator-based control strategy

When AmphiHex-I walks on land, the movement status of the leg can be divided into the support phase contacted with ground and the aerial phase rotated in air, while the underwater motion can be regarded as another two stages: up-stroke and down-stroke. The staged timing sequence relationship between the CPG harmonic output and motion status is illustrated in Figure 6.

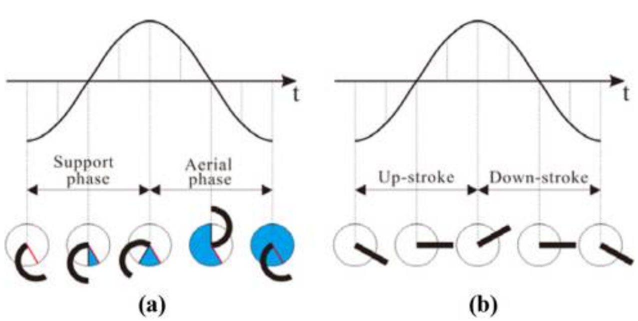
For the purpose of clearly describing the phase relationship between different legs, we define θ as a 6×6 symmetric matrix over the set $\{0, \pi, -\pi, {}^*\}$, if $\theta_{i\,j} = 0$, then it is desired that oscillators i and j be in-phase, if $\theta_{i\,j} = \pi$ or $-\pi$ (when $\theta_{i\,j} = \pi$, then $\theta_{j\,i} = -\pi$), it is desired that oscillators i and j be out-of-phase, if $\theta_{i\,j} = {}^*$ ($\theta_{i\,i} = {}^*$ for all i), then no phase difference is specified but can be deduced easily via topology structure. So, we define the phase difference matrix of tripod gait, tetrapod gait and hexapod gait as follows:

$$\theta_{Tri} = \begin{bmatrix} * & \pi & 0 & \pi & * & * \\ -\pi & * & * & * & \pi & * \\ 0 & * & * & * & * & \pi \\ -\pi & * & * & * & * & * \\ * & -\pi & * & * & * & * \\ * & * & -\pi & * & * & * \end{bmatrix} \theta_{Tetr} = \begin{bmatrix} * & * & * & 0 & * & * \\ * & * & * & * & 0 & * \\ * & * & * & * & * & 0 \\ 0 & * & * & * & * & * \\ * & 0 & * & * & * & * \\ * & * & 0 & * & * & * \end{bmatrix}$$

$$\theta_{Hex} = \begin{bmatrix} * & 0 & 0 & 0 & * & * \\ 0 & * & * & * & 0 & * \\ 0 & * & * & * & * & 0 \\ 0 & * & * & * & * & * \\ * & 0 & * & * & * & * \\ * & * & 0 & * & * & * \end{bmatrix}$$

From the matrix, we can effortlessly find that the groups of legs 1, 3 and 5 and legs 2, 4 and 6 will walk in-phase inside, while out-of-phase between each other in a tripod gait, but with a hexapod gait, all legs will be in-phase. Because there is an additional waiting phase in a tetrapod gait (Kong *et al.*, 2014), which means disordering our timing sequence correspondence mentioned before, we abolish the phase difference among different neuron pairs and just specify inside neuron pair that the command of waiting phase is charged by the central control layer according to the interrupt signal from photoelectric encoder placed at the end of each main output shaft. Figure 7 gives an example about terrestrial gait transition accompanying speed variation.

Figure 6 Timing sequence relationship between CPG harmonic wave and move status of leg-flipper



Notes: (a) Walking on land, the rising edge corresponds to support phase; (b) Swimming in water, the rising edge equals to up-stroke

To easily introduce various motion patterns underwater, we define Φ as a 6×5 matrix comprising five different column vectors that correspond to various underwater motions described in Figure 8. Each column vector has six elements that represent the offset angle of the six legs, where the offset angle means the degree from zero position to the central line of waving state (Kong *et al.*, 2014):

$$\Phi = \begin{bmatrix} \Phi_{Forward} \\ \Phi_{Backward} \\ \Phi_{Turning} \\ \Phi_{Ascending} \\ \Phi_{Descending} \end{bmatrix}^T = \begin{bmatrix} \pi/2 & 3\pi/2 & \pi/2 & 3\pi/4 & \pi/4 \\ \pi/2 & 3\pi/2 & \pi/2 & 3\pi/4 & \pi/4 \\ \pi/2 & 3\pi/2 & \pi/2 & 3\pi/4 & \pi/4 \\ \pi/2 & 3\pi/2 & 3\pi/2 & 3\pi/4 & \pi/4 \\ \pi/2 & 3\pi/2 & 3\pi/2 & 3\pi/4 & \pi/4 \\ \pi/2 & 3\pi/2 & 3\pi/2 & 3\pi/4 & \pi/4 \end{bmatrix}$$

When AmphiHex-I adopts the offset angle vector like $\Phi_{Forward,}$ all legs present equi-amplitude vibration at the central line of waving state, which can propel the robot to swim forward steadily. The other offset angle vectors can also be understood in a similar way. An example about the pattern transition of aquatic locomotion is given in Figure 8.

Based on this control strategy, we can simplify the complex motion patterns and velocity modulation to regulate some mathematical parameters, such as ω, θ and Φ. Moreover, the output signal of the CPG system is stable, and the parameter transition is smooth because of its inherent characteristics. These advantages reduce the control difficulty greatly and facilitate the robot to be applied in a real world.

4. Field application

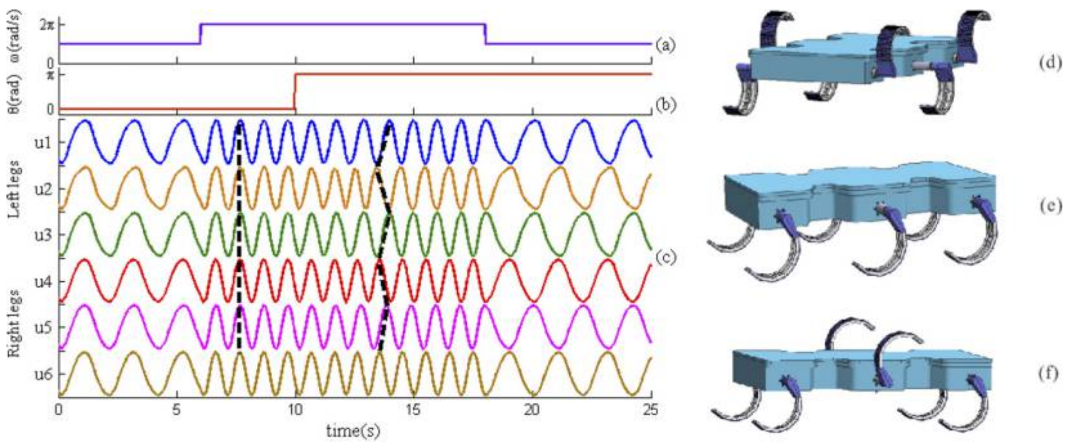
4.1 Validation experiments

To investigate the applicability of a CPG-based control and various gaits, we carried out abundant experiments on diverse environments, including rough land, grassland, slope, sand, mud and underwater, which are illustrated in Figure 9. The results demonstrated that our improved robot can adapt to diversified terrains and exhibit well locomotion ability in various kinds of environments.

4.2 Snail detection

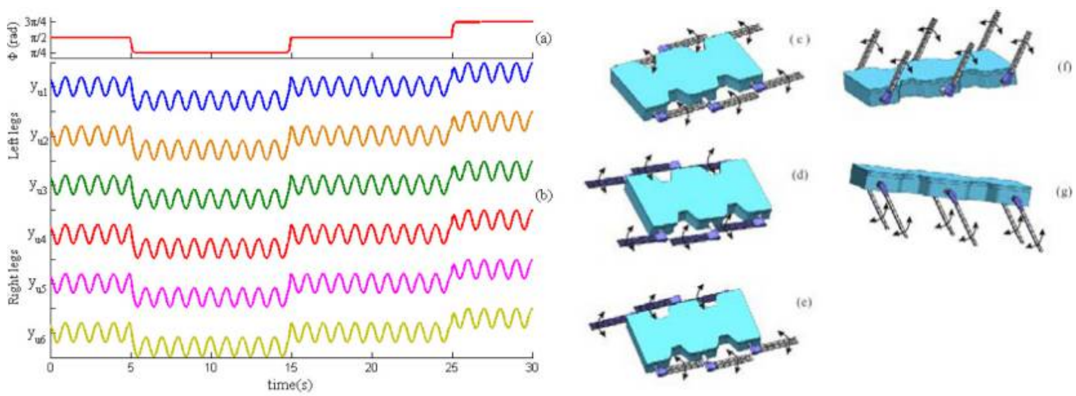
Oncomelania hupensis, an amphibious freshwater snail with a spiral shell, is distributed in the marshland of lake and water-pond or in river bank rich in humus. It is very inconvenient for people to probe the snails by their own because the snails are quite small (<10 mm in length) and the living sludge terrain is hardly passable. To our robot, all this challenges can be conquered because of its maneuverability in amphibious environment. Figure 10 shows the experiment of

Figure 7 Hexapod gait transforms to tripod gait accompanying speed variation (left), gaits of terrestrial locomotion (right)



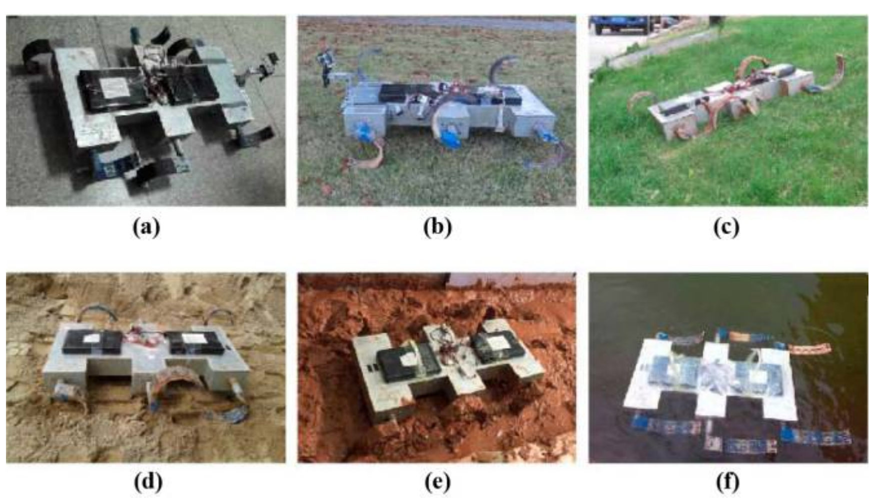
Notes: (a) Control input ω; (b) Control input θ; (c) Harmonic wave of state vector U, the black dashed lines represent the transition between hexapod gait and tripod gait; (d) Tripod gait; (e) Hexapod gait; (f) Tetrapod gait

Figure 8 The motion patterns transition between swimming forward, descending and ascending (left), underwater locomotion patterns (right)



Notes: (a) Control input Φ, (b) Harmonic output of six legs, (c) Swimming forward, (d) Swimming backward, (e) Turning underwater, (f) Descending, (g) Ascending

Figure 9 AmphiHex-I move on various environments



Notes: (a) Rough land; (b) Grassland; (c) Slope; (d) Sand; (e) Mud; (f) Underwater

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Figure 10 Snapshot sequence of the robot moving in field muddy terrain with hexapod gait

probing the distribution of snails in one area of the river bank located in Tongling, Anhui Province, China.

With the equipped HD camera onboard the robot, we can acquire the spot images and then store it to accompany the position information that comes from the GPS and process it to count the number of snails in a certain area for detecting the distribution and density of snails, which can be used as a gist of epidemic prevention and liquid medicine spraying in some degree. We select a specific region nearby river bank in which identifying the snails does not need too much effort. Three typical sample photos and corresponding image processing results are listed in Figure 11.

To process the images we have collected, the following steps are generally needed. First of all, images should be converted to grayscales. Second, an appropriate threshold should be chosen to convert the images into binary images. Because of the complex environments that the snails live in, an appropriate threshold is a key factor to extract the edge of the snails in the images successfully. The next step is to remove the small area in the binary image. As the snails in the images occupied roughly the same size, we can determine an approximate area threshold for removing small areas. Then, large connected domains need to be removed, the remaining areas basically correspond to the snails. In the final two steps, there exist situations in which interference domains that are difficult to remove arise occasionally, so we also need to add some expansion and corrosion processes to detect the snails more accurately.

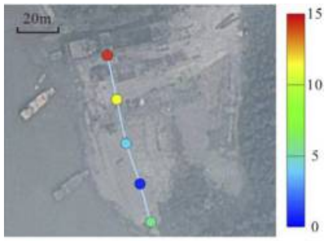
In the field experiment, we took a photo every 20 m in a selected range to add up the number of snails as a reference of epidemic prevention. The processed data are illustrated in Figure 12, which is a Google Earth map with scale 1:833. The colored dot represents a captured photo in the experimental range, the color value is related to the number of snails in each photo and the position information is generated from the GPS unit.

5. Conclusion

Motivated by a novel public health application, amphibious robot-based distribution probing of snails, a CPG-based control method aimed at the mechanical feature and the control architecture of the AmphiHex-I have been presented in this paper. We used the stable harmonic output signals that come from the CPGs network coupled with Hopf nonlinear oscillators to implement the various locomotion patterns in amphibious environment. It is worth mentioning that the research provides a method based on CPG to control a hexapod robot with multiple motion patterns, which can effectively overcome the difficulty of motion control simply by changing certain mathematical parameters of a nonlinear equation, such as frequency,

Figure 11 Sample photos of snails and process results

Figure 12 Processed result about snail data in the field experiment



Notes: The color lump bar on the right indicates the mapping relation between the number of snails and the color value based on red green and blue (RGB)

phase difference and offset angle, to realize the gait transitions smoothly.

The locomotion performance of AmphiHex-I in all kinds of amphibious terrains has been verified in field experiments. Also, we presented an outdoor experiment using such a robot to probe the distribution of snails. The field application offers another way to tackle the laborious job, especially in some odious terrains, which will hence broaden the application of AmphiHex-I to vector management and disease surveillance in the fields of epidemiology and public health.

Future research will be carried out in the following aspects. First, the weight of the robot should be decreased by choosing a lighter shell or by optimizing the overall structure to improve its flexibility, maneuverability and cruising ability. Second, combining the sensory feedback into the CPG network will be taken into account to make the robot choose a more suitable gait autonomously according to a specific terrain. Third, enhancing the resolution of snails especially under some difficult conditions and realizing online data processing automatically with a GPU is a forthcoming task.

References

Boxerbaum, A.S., Werk, P., Quinn, R.D. and Vaidyanathan, R. (2005), "Design of an autonomous amphibious robot for surf zone operation: part I mechanical design for multi-mode mobility", *Proceedings of 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, CA, pp. 1459-1464.

Cao, Y., Bi, S., Cai, Y. and Wang, Y. (2015), "Applying central pattern generators to control the robofish with oscillating pectoral fins", *Industrial Robot: An International Journal*, Vol. 42 No. 5, pp. 392-405.

Chen, M.G. (2014), "Assessment of morbidity due to Schistosoma japonicum infection in China", *Infectious Diseases of Poverty*, Vol. 3 No. 1.

Chung, H., Hou, C. and Hsu, S. (2015), "Hexapod moving in complex terrains via a new adaptive CPG gait design", *Industrial Robot: An International Journal*, Vol. 42 No. 2, pp. 129-141.

Collins, C., Xu, J. and Tang, S. (2012), "Schistosomiasis control and the health system in P.R. China", *Infectious Diseases of Poverty*, Vol. 1 No. 1, p. 8.

Dudek, G., Giguere, P., Prahacs, C., Saunderson, S., Sattar, J., Torres-Mendez, L.A., Jenkin, M., German, A., Hogue, A., Ripsman, A., Zacher, J., Milios, E., Liu, H., Zhang, P., Buehler, M. and Georgiades, C. (2007), "AQUA: an amphibious autonomous robot", *Computer*, Vol. 40, pp. 46-53.

Endo, G., Morimoto, J., Matsubara, T., Nakanishi, J. and Cheng, G. (2008), "Learning CPG-based biped locomotion with a policy gradient method: application to a humanoid robot", *The International Journal of Robotics Research*, Vol. 27 No. 2, pp. 213-228.

Hooper, S.L. (2000), "Central pattern generators", *Current Biology*, Vol. 10 No. 2, pp. 176-177.

Ijspeert, A.J. (2008), "Central pattern generators for locomotion control in animals and robots: a review", *Neural Networks*, Vol. 21 No. 4, pp. 642-653.

Ijspeert, A.J., Crespi, A., Ryczko, D. and Cabelguen, J. (2007), "From swimming to walking with a salamander robot driven by a spinal cord model", *Science*, Vol. 315 No. 5817, pp. 1416-1420.

Kamimura, A., Kurokawa, H., Yoshida, E., Murata, S., Tomita, K. and Kokaji, S. (2005), "Automatic locomotion design and experiments for a modular robotic system", *IEEE/ASME Transctions on Mechatronics*, Vol. 10 No. 3, pp. 314-325.

Kong, Z., Xu, M., Wang, X., Zhou, Y. and Zhang, S. (2014), "Gait planning and Gait transition of AmphiHex-I", *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Besançon.

Liang, X., Xu, M., Xu, L., Liu, P., Ren, X., Kong, Z., Yang, J. and Zhang, S. (2012), "The amphihex: a novel amphibious robot with transformable leg-flipper composite propulsion mechanism", *Proceedings of International Conference on Intelligent Robots and Systems*, Algarve, pp. 3667-3672.

Liu, C., Chen, Q. and Wang, D. (2011), "CPG-inspired workspace trajectory generation and adaptive locomotion control for quadruped robots", *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, Vol. 41, pp. 867-880.

Prahacs, C., Saunders, A., Smith, M., McMordie, D. and Buehler, M. (2004), "Towards legged amphibious mobile robotics", *Proceedings of the Canadian Engineering Education Association*, Southampton.

Rosenberger, L.J. (2001), "Pectoral fin locomotion in batoid fishes: undulation versus oscillation", *Journal of Experimental Biology*, Vol. 204, pp. 379-394.

Saranli, U., Buehler, M. and Koditschek, D.E. (2000), "Design, modeling and preliminary control of a compliant hexapod robot", *Proceedings of 2000 IEEE International Conference on Robotics and Automation, San Francisco, CA*, pp. 2589-2596.

Saranli, U., Buehler, M. and Koditschek, D.E. (2001), "RHex: a simple and highly mobile hexapod robot", *The International Journal of Robotics Research*, Vol. 20 No. 7, pp. 616-631.

Sfakiotakis, M. and Tsakiris, D.P. (2007), "Biomimetic centering for undulatory robots", *International Journal of Robotics Research*, Vol. 26 Nos 11/12, pp. 1267-1282.

Shahbazi, H., Jamshidi, K. and Monadjemi, A. (2012), "Modeling of mesencephalic locomotor region for Nao humanoid robot", *Industrial Robot: An International Journal*, Vol. 39 No. 2, pp. 136-145.

Torrealba, R., Cappelletto, J., Leonardo, F., Fernández-López, G. and Grieco, J. (2012), "Cybernetic knee prosthesis: application of an adaptive central pattern generator", *Industrial Robot: An International Journal*, Vol. 41 Nos 1/2, pp. 192-205.

Yu, J., Ding, R., Yang, Q. and Tan, M. (2013), "Amphibious pattern design of a robotic fish with wheel-propeller-fin mechanisms", *Journal of Field Robotics*, Vol. 30 No. 5, pp. 702-716.

Zhang, S., Liang, X., Xu, L. and Xu, M. (2013), "Initial development of a novel amphibious robot with transformable fin-leg composite propulsion mechanisms", *Journal of Bionic Engineering*, Vol. 10 No. 4, pp. 434-445.

Zhang, S., Zhou, Y., Xu, M., Liang, X., Liu, J. and Yang, J. (2015), "AmphiHex-I: locomotory performance in amphibious environments with specially designed transformable flipper-leg", *IEEE/ASME Transactions on Mechatronics*, Vol. 21 No. 3, pp. 1720-1731.

Zhao, W., Yu, J., Fang, Y. and Wang, L. (2006), "Development of multi-mode biomimetic robotic fish based on central pattern generator", *Proceedings of 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing*, pp. 3891-3896.

Zheng, Q., Vanderslott, S., Jiang, B., Xu, L.L., Liu, C.S., Huo, L.L., Duan, L.P., Wu, N.B., Li, S.Z., Xia, Z.G., et al. (2013), "Research gaps for three main tropical diseases in the people's Republic of China", *Infectious Diseases of Poverty*, Vol. 2 No. 1, p. 15.

Zhou, C. and Low, K.H. (2012), "Design and locomotion control of a biomimetic underwater vehicle with fin propulsion", *IEEE/ASME Transactions on Mechatronics*, Vol. 17 No. 1, pp. 25-35.

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