Perspectives in Science (2016) 7, 101—108

Available online at www.sciencedirect.com

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Study on the motion control of snake-like robots on land and in water☆

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Received 26 October 2015; accepted 11 November 2015
Available online 10 December 2015

KEYWORDS
Snake-like robot;
Motion control;
Serpentince locomotion;
Swimming motion

Summary In order to fully use the advantage of legless body and rhythmic gaits to realize the inspection task, the snake-like robots and dynamic simulators are developed with components available online and open source software. The Serpenoid Curve formula is adopted to generate the joint rhythm of snake-like robot to realize serpentine locomotion. The serpentine locomotion of snake-like robots on land and in water is studied in details with experiments. This work wishes to provide the technical solution for researchers from different institutes to show the performance of the designed algorithm comparing to the other works and for the practical applications of snake-like robots in the near future.

☆ This article is part of a special issue entitled ''Proceedings of the 1st Czech-China Scientific Conference 2015''.
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http://dx.doi.org/10.1016/j.pisc.2015.11.017

Introduction

Snake-like robots were used to imitate the slim and legless body of snakes (Bauchot, 1994). Normally the orthogonal series (Zhenli et al., 2005), flexible cable-driven (Paap et al., 1996) and coupling-driven(Changlong et al., 2009) are adopted to construct the mechanical system of snake-like robots, as shown in Fig. 1.

Besides moving on ground with serpentine locomotion, concertina locomotion and side-winding locomotion, some amphibious snake-like robot can swim in the water, as show in Fig. 2 (Yamada et al., 2005; Shumei et al., 2012). Some fish-like robots or salamander-like robots are also developed with different kind of actuators, as shown in Fig. 3 (Crespi and Ijspeert, 2009; Westphal et al., 2011).

In recent years, with the development of computer software technology, the dynamic simulators of snake-like robots are also designed with ODE (Open Dynamics Engine)-based tools. It can give help on the real robot design and the efficiency study of robot motion.

Until now, there is no cheap snake-like robot available on market to provide the research platform for researchers from different places to show the performance of their designed algorithm comparing to the other works. In this paper, the mechanical system and control system constructed by the components available online are adopted to develop of the snake-like robot. The dynamic models of snake-like robots are also developed with open source software. The Serpenoid Curve formula is adopted to generate the rhythmic of joint for the snake-like robots to realize serpentine motion on land and in water. It is an option for researchers to represent the work of the other publications.

Snake-like robot for the motion control on land

The snake-like robot with orthogonal series joints, as shown in Fig. 4(a), is developed for the study of the serpentine locomotion on land (Zhenli et al., 2015a,b). The parameters of the snake-like robot are shown in Table 1. The parameters of the joint motors are shown in Table 2.

Table 1 Parameters of snake-like robot.

Number of orthogonal series joint	8
Number of joint motor	16
Weight (kg)	2.3
Length (mm)	1140

Table 2 Parameters of joint motor.

Demension (mm)	40*20*40.5
Weight (g)	60
Rotation range (deg)	0—300
Torque (kg cm)	14, 6v; 15, 7.2v
Joint rotation velocity (deg/s)	333, 6v; 375, 7.2v
Operation voltage (V)	4.8—7.2

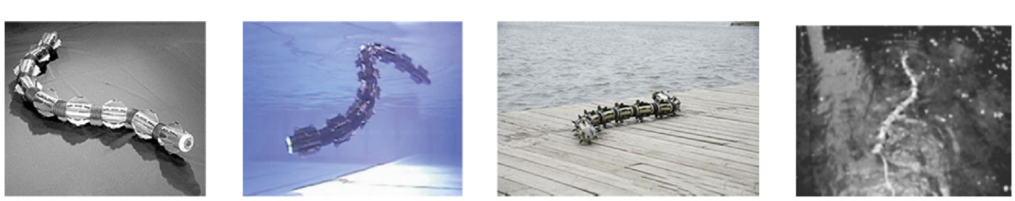
The orthogonal series joint is 2 DOF (Degree of Freedom), as shown in Fig. 4(b). The contacting mechanism of the snake-like robot is developed with bi-directional passive wheel or uni-directional passive wheel, as shown in Fig. 4(c) and (d).

Control system of the snake-like robot

The control system is mounted on the tail of the snake-like robot. The joint motors are controlled by a motor control board, which can control 24 motors, as shown in Fig. 5(a). The motor control board is connected with an ARDUINO UNO control board (ArduinoBoardUno, Documentation, 2015), as shown in Fig. 5(b). The blue tooth modular (Bluetooth, Documentation, 2015), as shown in Fig. 5(c), is connected with the serial port of ARDUINO UNO control board. It can exchange information with the other devices mounted another paired blue tooth modular.

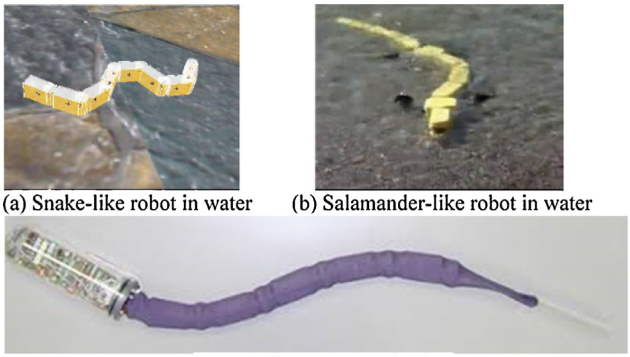
(a) Orthogonal series (b) Flexible cable-driven (c) Coupling-driven

Figure 1 Typical snake-like robots on land.



(a) ACM-R5 on land (b) ACM-R5 in water (c) SIA snake-like robot on land (d) SIA snake-like robot in water

Figure 2 Typical amphibious snake-like robots.



(a) Snake-like robot in water (b) Salamander-like robot in water

(c) Eel-like robot on land

Figure 3 Other similar type of robots in water.

Serpentine locomotion control

The Serpenoid Curve formula proposed by Prof.S. Hiros (Hiros, 1993) is adopted to generate the joint rhythm to control the snake-like robot to realize serpentine locomotion. The formula is shown in (1).

$$Servoangle[i] = -2\alpha(\sin(kn\pi/N))(\sin(2kn\pi arcs/L + 2kn\pi i/N)) \quad (1)$$

where $Servoangle[i]$ is the joint angle of ith joint, $i = 1, \ldots, 8$;α is the bending angle of the Serpenoid Curve; kn is the number of S-shape; $arcs$ is the arc length of Serpenoid Curve, which is changed with changing speed of Δs; N is the number of joint; L is the total length. With the parameters shown in Table 3, the snake-like robot can realize serpentine locomotion. The average speed of the snake-like robot with the bi-directional passive contacting mechanism is 0.3054 m/s, the experimental result is shown in Fig. 6. The average speed of the snake-like robot with the uni-directional passive contacting mechanism is 0.076 m/s, the experimental result is shown in Fig. 7.

Table 3 Parameters of Serpenoid Curve formula.

α (*rad*)	0.8
kn	1
Δs (mm)	200
L (mm)	1440
arcs(mm)	20,000
N	8

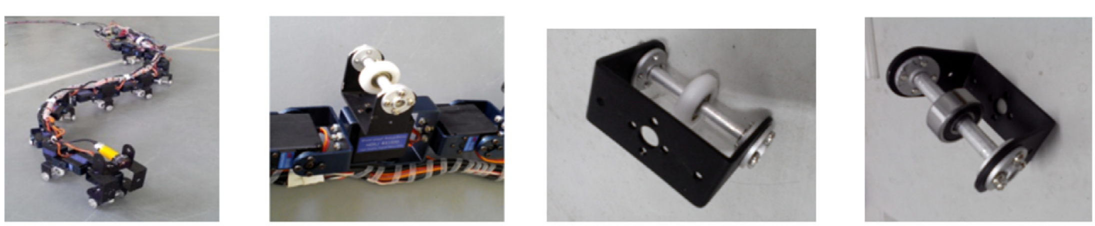
Infrared sensor-based obstacle avoidance

The infrared sensor (E18-D80NK) (E18-D80NK infrared Sensor Documentation, 2015) with three cables (power, ground, signal) connected with ARDURINO UNO control board, as shown in Fig. 8(a), is mounted on the top of snake-like robot, as shown in Fig. 8(b).

Through adding a bias in formula (1), the snake-like robot can realize the turn motion during serpentine locomotion. The formula is shown in (2).

$$Servoangle[i] = -2\alpha(\sin(kn\pi/N))(\sin(2kn\pi arcs/L + 2kn\pi i/N)) + k1unit\_len \quad (2)$$

where $unit\_len = 130.0$ mm, $k1$ is a parameter to regulate the amplitute of turn motion. The infrared sensor can generate different value of $k1$. In the following experiment, if there is no obstacles ($k1 = 0$), the snake-like robot will move toward a line direction; if the snake-like robot detects the obstacle through the infrared sensor, the control system will set $k1 = 0.013$ to drive the snake-like robot to turn left. The experimental result of infrared sensor-based obstacle function is shown in Fig. 9.

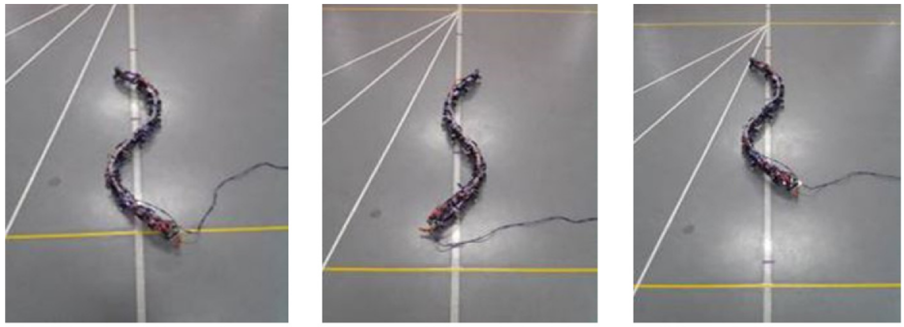


(a) Whole robot (b) The orthogonal series joint (c) Bi-directional passive wheel (d) Uni-directional passive wheel

Figure 4 Mechanical components.

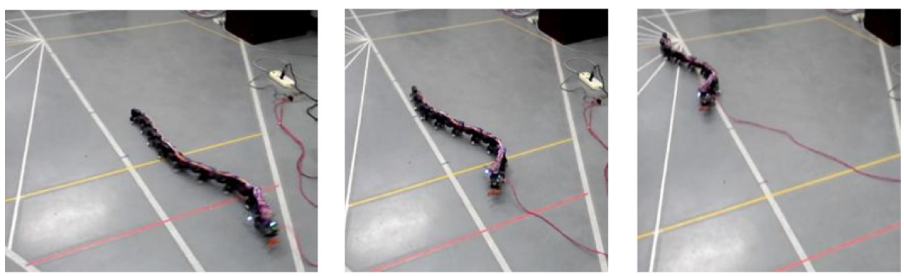
(a)Motor control board. (b)ARDUINO UNO control board. (c) Bluetooth modular.

Figure 5 Hardware of control system.



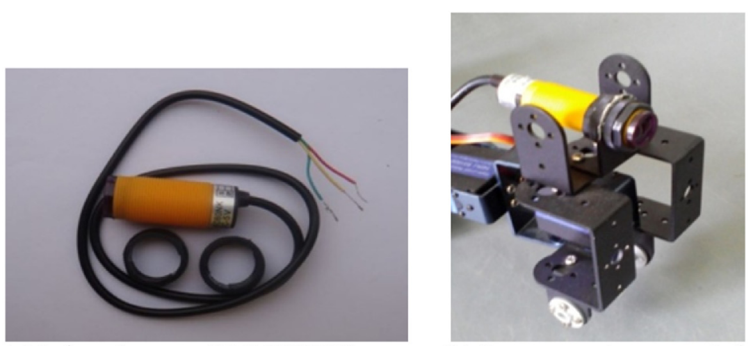
(a) t=1 (b) t=3 (c) t=5

Figure 6 Experimental result with bi-directional contacting mechanism.



(a) t=1 (b) t=3 (c) t=5

Figure 7 Experimental result with uni-directional contacting mechanism.



(a) Infrared sensor (E18-D80NK) (b) Sensory system mounted on head

Figure 8 Sensor system for obstacle avoidance.

Comparisons of locomotion speed under different ground surface friction coefficient

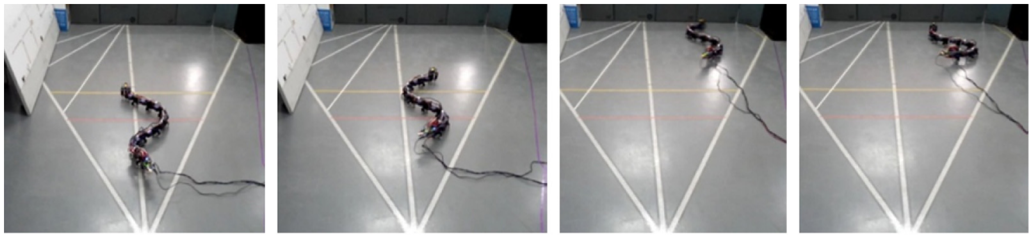
In order to study on the performance of the snake-like robot under different ground surface friction coefficient environment, a device is developed, as shown in Fig. 10(a). The experiments to measure the force of rolling friction and the force of sliding friction are shown in Fig. 10(b) and (c) respectively.

Different tapes, as shown in Fig. 11, are stuck to the surface of the passive wheels to get the serpentine locomotion speed of the snake-like robot under different ground surface friction coefficient enviroment. The results for the snake-like robot with bi-directional passive wheel contacting mechanism are shown in Tables 4—6.

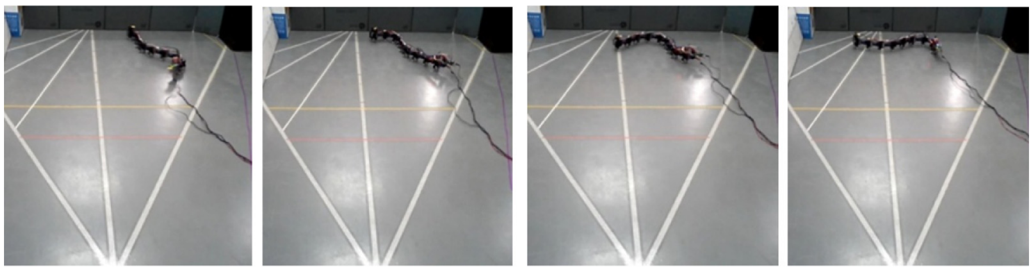
Table 4 $\mu\{\text{rolling}\} = 0.048757$, $\mu\{\text{sliding}\} = 0.463189$.

α (rad)	Average speed (m/s)
0.6	0.236
0.7	0.2795
0.8	0.3054
0.9	0.3061

When the cloth adhensive tape, as shown in Fig. 11(d), is used to put on the surface of the passive wheel, the robot cannot move normally, as shown in Fig. 12. The parameters is as follow: $\mu_{\{\text{ROLLING}\}} = 0.32$, $\mu_{\{\text{SLIDING}\}} = 0.56$.



(a) t=1 (b) t=3 (c) t=5 (d) t=7



(e) t=9 (f) t=11 (g) t=13 (h) t=15

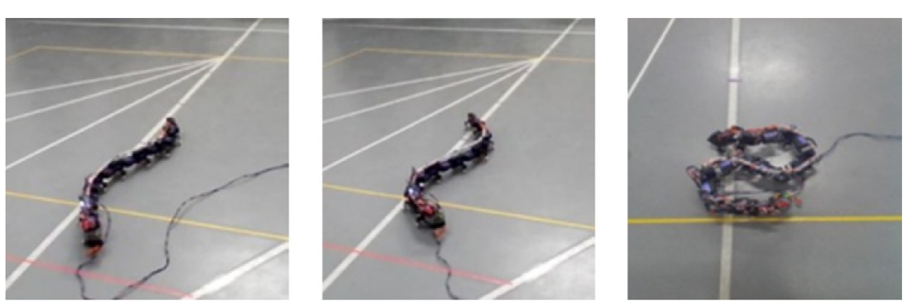
Figure 9 Infrared sensor-based obstacle avoidance.

(a) Measure the device weight (b) Measure the force of rolling friction (c) Measure the force of sliding friction

Figure 10 Measurement of ground surface friction coefficient.

(a) Smooth plastic tape (b) Plastic insulating tape (c) Double-sided tape (d) Electrical adhesive tape

Figure 11 Tapes with different surfaces.



(a) t=1 (b) t=3 (c) t=5

Figure 12 Abnormal situation of the snake-like robot.

Table 5 $\mu\{\text{rolling}\} = 0.048780$, $\mu\{\text{sliding}\} = 0.439024$.

α (rad)	Average speed (m/s)
0.6	0.2750
0.7	0.2951
0.8	0.3061
0.9	0.3064

Table 6 $\mu\{\text{rolling}\} = 0.097513$, $\mu\{\text{sliding}\} = 0.536324$.

α (rad)	Average speed (m/s)
0.6	0.1815
0.7	0.2352
0.8	0.2719
0.9	0.2724

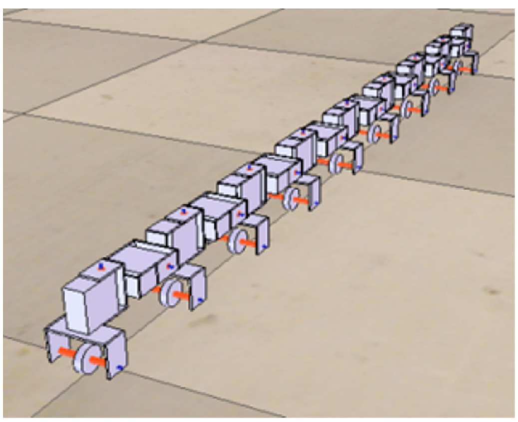


Figure 13 Dynamic simulator of the snake-like robot.

Dynamic simulator of the snake-like robot for the motion control on land

In order to avoid the error from the mechanical system and other devices in the real system, a dynamic simulator of the snake-like robot is developed within V-REP (Virtual Robot Experimentation Platform) (V-REP Documentation, 2015), as shown in Fig. 13.

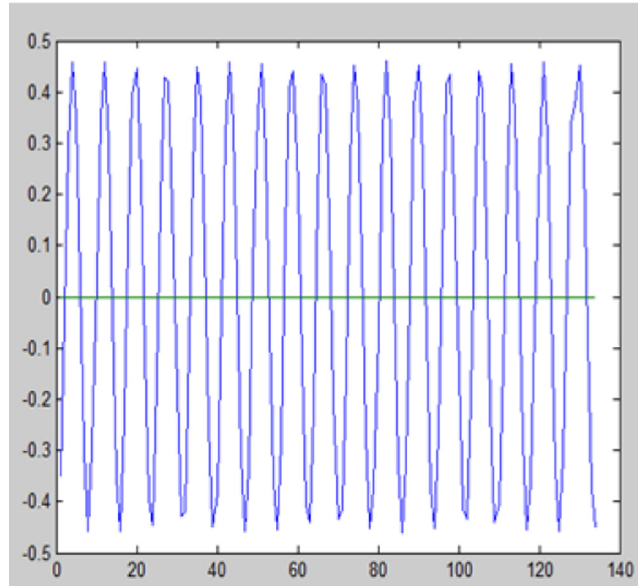


Figure 15 Joint angle during the movement.

With the parameters shown in Table 3, the simulator can realize serpentine locomotion, as shown in Fig. 14, and the average speed is about 0.086 m/s.

In the simulator, we can also get the joint position during the movement. The angle value of joint 1 is shown in Fig. 15, where vertical axis is joint angle in deg, and horizontal axis is time in second.

Dynamic simulator of the snake-like robot for the motion control in water

Snakes can swim elegantly in water, as shown in Fig. 16. It is very important to know how to control snake-like robot to swim in water (Zhenli et al., 2008, 2015c; Crespi and Ijspeert, 2006).

Another dynamic simulator of the snake-like robot is also developed within V-REP for the study of swimming motion in water, as shown in Fig. 17.

With the same parameters shown in Table 3, the simulator realized serpentine swimming motion in water, as shown in Fig. 18, and the average speed is about 0.036 m/s.

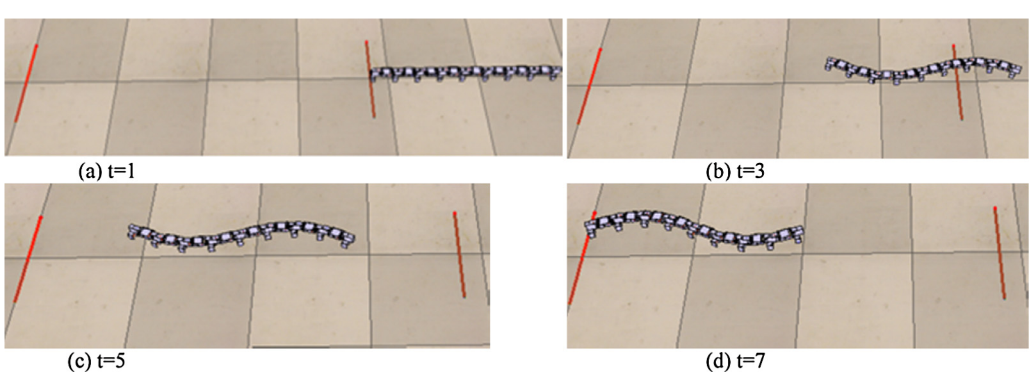
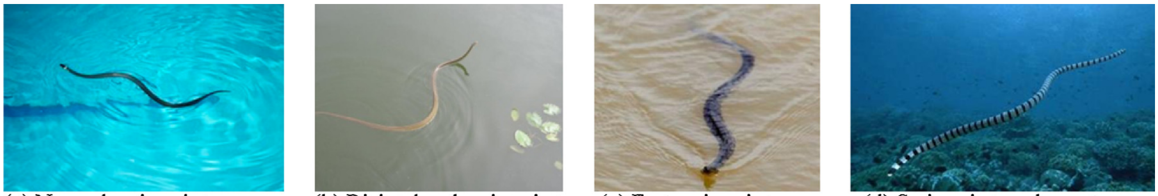


Figure 14 Serpentine locomotion.



(a) Normal swimming (b) Rising head swimming (c) Fast swimming (d) Swimming under water

Figure 16 Swimming motion of snakes.

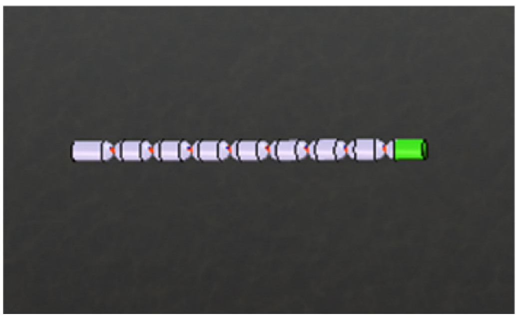
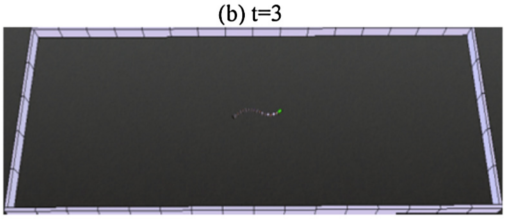


Figure 17 Snake-like robot model in V-REP.

(a) t= 1

(b) t=3



(c) t=5

Figure 18 Swimming motion of the snake-like robot simulator.

Conclusion

In this paper, the practical solutions to develop of snake-like robots with all components available online and dynamic simulators of snake-like robots with open source software have been presented. The Serpenoid Curve formula is adopted to generate the joint rhythm for the snake-like robot to realize serpentine locomotion on land and swimming motion in water. The infrared sensor based obstacle avoidance function and comparisons of locomotion speed under different ground surface friction coefficient environment have been studied through experiments. This work wishes to provide the benefits for researchers from different area to develop of snake-like robot platform to show the performance of their designed algorithm comparing to the other works and represent the experimental results in existing publications.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgements

This work is supported by the National Science Foundation of China under Grant 61333016. Results achieved in this research received funding from the Moravian-Silesian Region within the project VSB-Technical University of Ostrava activities with China and partially was supported by the grant SGS reg. no. SP2015/82 conducted at VSB-Technical University of Ostrava, Czech Republic. This work is also funded by State Key Laboratory of Robotics (Grant No. 2014-O08), and FEDER through the Operational Program Competitiveness Factors — COMPETE and by National Funds through FCT — Foundation for Science and Technology in the context of the project FCOMP-01-0124-FEDER-022682 (FCT reference PEst-C/EEI/UI0127/2011), also by the Funds of Changshu Institute of Technology (Grant No. XZ1306). The first author is supported by the FCT grant under CIENCIA2007 (Post Doctoral Research Positions for the National Scientific and Technological System).

References

ArduinoBoardUno, Documentation, 2015. Available at: https://www.arduino.cc/en/Main/ArduinoBoardUno.

Bauchot, R., 1994. Snakes—A Nature History. Sterling Publishing Company, Inc., New York.

Bluetooth, Documentation, 2015. Available at: https://www.bluetooth.org/en-us.

Changlong, Y., Shugen, M., Bin, L., Yuechao, W., 2009. Modular universal unit for a snake-like robot and reconfigurable robots. Robot.: Int. J. Robot. Soc. Jpn. 23 (7), 865—887, Available at: http://www.tandfonline.com/doi/abs/10.1163/156855309X443061#.Vhvrpfmqqko.

Crespi, A., Ijspeert, A.J., 2006. AmphiBot II: An amphibious snake robot that crawls and swims using a central pattern generator. In: Proceedings of the 9th International Conference on Climbing and Walking Robots,CLAWA2006, pp. 19—27, Available at: http://libra.msra.cn/Publication/4555225/amphibot-ii-an-amphibious-snake-robot-that-crawls-and-swims-using-a-central-pattern-generator.

Crespi, A., Ijspeert, A.J., 2009. Salamandra robotica: a biologically inspired amphibious robot that swims and walks. Artif. Life Models Hardw., 35—64, Available at: http://link.springer.com/chapter/10.1007/978-1-84882-530-7_3.

E18-D80NK infrared Sensor Documentation, 2015. Available at: http://www.chipskeytech.com/.

Hiros, S., 1993. Inspired Robots—Snake-Like Locomotors and Manipulators [M]. Oxford University Press, Oxford.

Paap, L.K., Dehlwisch, M., Klaassen, B., 1996. GMDSnake: A Semi-Autonomous Snake-like Robot. In: Distributed Autonomous Robotic Systems 2. Springer Verlag, pp. 71—77.

Shumei, Y., Minghui, W., Shugen, M., Bin, L., Yuechao, W., 2012. Development of an amphibious snake-like robot and its gaits on ground and in water. J. Mech. Eng. 48 (9), 18—27 (in Chinese with English abstract). Available at: http://www.doc88.com/p-7438302972705.html.

V-REP Documentation, 2015. Available at: http://www.v-rep.eu/helpFiles/index.html.

Westphal, A., Rulkov, N., Ayers, J., Brady, D., Hunt, M., 2011. Controlling a lamprey-based robot with an electronic nervous system. Smart Struct. Syst. 7 (6), 471—484, Available at: http://www.neurotechnology.neu.edu/WestphalEtAl2011.pdf.

Yamada, H., Chigisaki, S., Mori, M., Takita, K., Ogami, K., Hirose, S., 2005. Development of amphibious snake-like robot ACMR5. In: Proceedings of the International Symposium on Robotics, ISR '05, p. 133.

Zhenli, L., Shugen, M., Bin, L., Yuechao, W., 2005. Serpentine locomotion of a snake-like robot controlled by cyclic inhibitory CPG Model. In: Proceedings of 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems,IROS2005,3019-3024, Available at: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=1545435.

Zhenli, L., Shugen, M., Bin, L., Yuechao, W., 2008. Gaits-transferable CPG controller for a snake-like robot. Sci. China Ser. F: Inf. Sci., 293—305, Available at: http://link.springer.com/article/10.1007%2Fs11432-008-0026-0.

Zhenli, L., Chao, L., Yafei, X., Chenxi, W., Limin, M., Bin, L., 2015a. Design of a snake-like robot and analysis of friction infuluence on its motion performance. High Technol. Lett. 25 (3), 293—299 (in Chinese with English abstract). Available at: http://www.hitech863.com/gjstxcn/ch/reader/view_abstract.aspx?flag=1&file_no=201503010&journal_id=gjstxcn.

Zhenli, L., Chao, L., Yafei, X., Huigang, X., Changkao, S., Xianzhen, X., Bin, L., 2015b. Using phase adjustment method to achieve snake-like robot's obstacle avoidance function. High Technol. Lett. 25 (5), 508—514 (in Chinese with English abstract). Available at: http://www.hitech863.com/gjstxcn/ch/reader/view_abstract.aspx?flag=1&file_no=201505010&journal_id=gjstxcn.

Zhenli, L., Yafei, X., Huigang, X., Jun, L., Limin, M., Changkao, S., Bin, L., 2015c. Design of a MNSM-based controller for the swimming motion of a snake-like robot. In: Proceedings of the 5th Annual IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems,CYBER2015, pp. 2050—2055.