UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS

JUDUL: **REALIZATION OF MULTI-OBJECTIVE EVOLVED CONTINUUM ROBOTS USING 3D PRINTING**

IJAZAH: **MASTER OF ENGINEERING (ELECTRICAL AND ELECTRONIC)**

Saya **CHEE WEI SHUN**, Sesi Pengajian **2013-2015**, mengaku membenarkan tesis Doktor Falsafah ini disimpan di Perpustakaan Universiti Malaysia Sabah dengan syarat-syarat kegunaan seperti berikut:

1. Tesis ini adalah hak milik Universiti Malaysia Sabah.
2. Perpustakaan Universiti Malaysia Sabah dibenarkan membuat Salinan untuk tujuan penajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. Sila tandakan (/)

☐ SULIT	(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA 1972)
☐ TERHAD	(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)
☑ TIDAK TERHAD	

Disahkan oleh,

NURULAIN BINTI ISMAIL
LIBRARIAN
UNIVERSITI MALAYSIA SABAH

Chee Wei Shun

(Tandatangan Pustakawan)

Tarikh: 30 Jun 2015

(Assoc. Prof. Dr. Jason Teo Tze Wi)
Penyelia

DECLARATION

I hereby declare that this thesis submitted to Universiti Malaysia Sabah as fulfilment of the requirements for the degree of Master of Engineering, has not been submitted to any other university for any degree. I also certify that the work described herein is entirely my own except for quotations, equations, summaries and references, which have been duly acknowledged.

30 June 2015

Chee Wei Shun
(MK1221005T)

CERTIFICATION

NAME : **CHEE WEI SHUN**

MATRIK NO. : **MK1221005T**

TITLE : **REALIZATION OF MULTI-OBJECTIVE EVOLVED CONTINUUM ROBOTS USING 3D PRINTING**

DEGREE : **MASTER OF ENGINEERING (ELECTRICAL AND ELECTRONIC)**

VIVA DATE : **09 NOVEMBER 2015**

CERTIFIED BY

Signature

1. **SUPERVISOR**
   Assoc. Prof. Dr. Jason Teo Tze Wi

2. **CO-SUPERVISOR**
   Kenneth Teo Tze Kin

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude and appreciation to my supervisor Assoc. Prof. Dr. Jason Teo Tze Wi for all his advice, supervision, and support in this research whilst providing me with an excellent atmosphere for doing research. Without his assistance and aspiring guidance throughout the process, this research work would have never been accomplished. His patience and willingness to share his knowledge not only helped me a lot in the process of achieving the objectives of this research but also aided me to improve myself.

Besides that, I would like to acknowledge my gratitude to my co-supervisor Mr. Kenneth Teo Tze Kin for his guidance and assistance in this research work that lead to the completion of this thesis. I am sincerely grateful to him for his constant help and invaluably constructive criticism on a number of issues related to the research. I would also like to thank Mr. Yoong Hou Pin who introduced me to this research and helping me to develop my background in robotics design and engineering working attitude.

Last but not least the special thanks go to my family. Their assistance, encouragement and contribution had become the major support for me to accomplish this Master's research.

Chee Wei Shun

30 June 2015

ABSTRACT

Continuum robots are recognized as one of the most flexible and versatile mobile robots that are capable of performing various kinds of motions to navigate in unknown and challenging environments. However, the large number of degrees of freedom leads to the difficulty in designing a continuum robot. Moreover, an open-ended synthesis problem arises whereby there exists no formal models thus far for a designer to determine the optimum control strategy, body structure, number of segments and suitable segment lengths during the design stage. Additionally, conventional methods for designing continuum robots do not consider the optimization of multiple objectives. As such, there has not been any research carried out thus far on co-evolving both the morphology and controller of continuum robots using a multi-objective evolutionary optimization approach. Therefore, in this research work, a system is developed to automatically design and optimize both the morphology and controller of continuum robots by employing a novel hybridized Genetic Programming and self-adaptive Differential Evolution algorithm. A multi-objective evolutionary algorithm is incorporated into the artificial evolutionary optimization process to simultaneously maximize the locomotion performance and minimize the complexity of the continuum robots. In addition, a novel GP tree-based encoding structure is proposed to allow for the representation of the continuum robot's morphology and controller to be optimized simultaneously during co-evolution. The artificial co-evolutionary process is carried out by using the Webots physics simulation software. Two types of continuum robots are to be evolved in this research, namely the snake-like continuum robot (SLCR) and multi-branching continuum robot (MBCR). The outcome of this work shows that the Pareto-optimal front of evolved solutions are successfully obtained for the simulated SLCRs where the evolved heterogeneous SLCRs can perform lateral undulation, narrow path crawling, vertical undulation and lateral rolling moving behaviours for locomotion. Additionally, the evolved solutions of the MBCRs are converging to a point where the MBCR with the least number of segments turns out to be the dominating solution. In order to validate the simulated results, the evolved SLCRs are transferred to real world for physical testing using 3D printing technology. The physical testing results demonstrate that the evolved SLCRs can be successfully transferred from simulation to the real world for actual physical deployment in its task environment. An 82.55% transference accuracy is achieved in this work which demonstrates that the proposed multi-objective co-evolutionary algorithm is feasible and practical to be employed for the automatic design of continuum robots.

ABSTRAK

REALISASI REKA BENTUK MULTI-OBJEKTIF ROBOT KONTINUM PENGGUNAAN PENCETAKAN 3D

Robot kontinum adalah antara jenis robot mudah alih yang amat fleksibel dan serba berguna yang mampu melakukan pelbagai jenis pergerakan untuk menyeberangi persekitaran yang tidak diketahui dan mencabar. Namun demikian, kepunyaan bilangan banyak darjah kebebasan pergerakan menyebabkan robot kontinum sukar direka bentuk. Selain itu, masalah sintesis terbuka akan terbangkit oleh sebab setakat ini tiada model rasmi wujud untuk pencipta robot menentukan strategi kawalan, struktur badan, bilangan segmen dan ukuran segmen yang bersesuaian di peringkat reka bentuk robot kontinum. Seterusnya, kaedah konvensional untuk mereka bentuk robot kontinum tidak mempertimbangkan pengoptimuman pelbagai objektif. Oleh demikian, tiada sebarang penyelidikan yang telah menceburi bidang evolusi kedua-dua reka bentuk struktur dan sistem kawalan robot kontinum dengan menggunakan kaedah evolusi pengkomputeran. Oleh sebab itu, satu sistem telah dicipta dalam kerja penyelidikan ini untuk mereka bentuk dan mengoptimumkan kedua-dua reka bentuk struktur dan sistem kawalan robot kontinum secara automatik degan menggunakan kaedah novel kombinasi Pengaturcaraan Genetik dan Pengkamiran Evolusi penyesuaian diri. Algoritma evolusi multi-objektif juga digabung bersama dengan proses pengoptimuman evolusi untuk meningkatkan prestasi pergerakan di samping mengurangkan kerumitan reka bentuk robot kontinum secara serentak. Selain itu, struktur berasaskan GP yang novel telah dicadangkan untuk membenarkan pengwakilan reka bentuk struktur dan sistem kawalan robot kontinum supaya kedua-dua ciri reka bentuk ini dapat dioptimumkan serentak dalam proses evolusi. Proses evolusi adalah dilaksanakan dengan penggunaan perisian fizik simulasi Webots. Dua jenis robot kontinum adalah direka bentuk dalam kajian penyelidikan ini, iaitu robot kontinum berbentuk ular (SLCR) dan robot kontinum bercabang (MBCR). Hasil kerja ini menunjukkan bahawa penyelesaian Pareto-optimum evolusi SLCR adalah berjaya diperolehi melalui simulasi di mana pelbagai SLCR yang berbeza dapat direka bentuk untuk melakukan gerakan lateral, gerakan merangkak, gerakan mengombak tegak dan gerakan menggulung untuk pergerakan. Di samping itu, keputusan kajian evolusi menunjukkan penyelesaian MBCR menumpu ke satu penghujung di mana MBCR yang mempunyai segmen yang paling kurang menjadi penyelesaian tunggal dan mendominasi penyelesaian lain. Dalam usaha untuk mengesahkan keputusan simulasi, SLCR yang direka bentuk melalui proses evolusi telah dipindah ke dunia sebenar untuk menjalankan ujian fizikal degan menggunkan teknologi pencetakan 3D. Keputusan ujian fizikal menunjukkan bahawa SLCR yang direka bentuk melalui proses evolusi berjaya dipindahkan dari simulasi ke dunia sebenar untuk penggunaan realistik dalam persekitaran tugasan. Ketepatan pemindahan robot sebanyak 82.55%telah dicapai dalam kerja kajian dan ini menunjukkan bahawa algoritma evolusi multi-objektif yang dicadangkan adalah realistik dan praktikal untuk digunakan dalam mereka bentuk robot kontinum secara automatik.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ANN	Artificial Neural Network
CPG	Central Pattern Generator
EP	Evolutionary Programming
ES	Evolutionary Strategies
FDM	Fused Deposition Modelling
GA	Genetic Algorithm
GP	Genetic Programming
HIPS	High Impact Polystyrene
jDE	Self-adaptive Differential Evolutionary Algorithm
MBCR	Multi-branching Continuum Robot
MOEA	Multi-objective Evolutionary Algorithm
ODE	Open Dynamics Engine
PC	Polycarbonate
PID	Proportional-integral-derivative
PLA	Polylactic Acid

SLA	Stereolithography
SLCR	Snake-like Continuum Robot
SLS	Selective Laser Sintering

LIST OF SYMBOLS

$\emptyset_{i,ref}$	Joint reference angle
α	Amplitude
ω	Frequency
δ	Phase shift
$\emptyset_o$	Offset control parameter
r	Individual
G	Generation
F	Weighting factor
F_l	Weighting factor lower limit
F_u	Weighting factor upper limit
CR	Crossover probability
$rand$	Random number
τ	Control Parameter Probability Threshold
U	Trial vector
X	Target vector
V	Mutant Vector

j_{rand}	Random structure number
N_{rand}	Scale random number
m	Segment mass
l	Segment length
θ	Motor position angle
O	Output
t	Time

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this modern era, autonomous robots are not only used for operations in factories and technology-related environments, instead they have become part of human lives in which they are customized to assist humans in daily jobs or other repetitive tasks. Different types of robots are also designed to replace humans to work in hazardous environments and tasks that are beyond the humans' capability. The usage of search and rescue robots during the incidents of the 9/11 World Trade Centre attack and the 2004 tsunami strike had exhibited the importance of the role of robots in locating the victims within the golden time rescue period (Albert and Henry, 2009). Rescue robots are either designed to overcome obstacles or are small in size in order to pass through narrow gaps which are unreachable for humans. Modular robots or more specifically known as continuum robots are becoming increasingly popular in search and rescue mission as they possess the ability to perform multiple movements, and thus have grown into one of the most flexible and versatile mobile robots (Crespi, Badertscher, Guignard, and Ijspeert, 2005). As the continuum robots are highly versatile and compact in size, they can easily navigate across narrow holes or pipes to carry out the assigned tasks or investigations. If there is an existence of obstacles, continuum robots can climb up and over the obstacles which might even be higher than the robot itself. Besides that, the continuum robots are also equipped with multiple degrees of freedom which make them capable to carry out various kinds of motions and can act as either locomotors or manipulators. Since the continuum robots are modular in form comprising of combinations of different module units, they are redundant in design, which means that the continuum robots can continue their locomotion even though one particular module is malfunctioning. Due to all these unique features, continuum robots possess the potential of meeting the needs for robotic mobility to travel and perform tasks in unknown and challenging environments.

However, in the field of robotic design, the open-ended synthesis problem is still a meta-challenge. This is due to the fact that there is no formal model that exists thus far for a designer to determine the optimized solutions on the combination of building blocks, in addition to their controllers (Lipson, 2006). Due to the limitations of understanding and the bias of the human designer, people tend to design robots with pre-defined morphologies where most of them are designed according to human experimental trials and errors. Thereafter, the control system is usually restricted to function within the morphologies designed. By using this method, the optimization problem will arise where the designer cannot ensure if the pre-defined robot morphologies and controller are able to provide the optimal performance in its task environment. Furthermore, most of the designs implementing this method are only aiming on achieving a single objective which is to accomplish the allocated task. Unfortunately, due to optimization problems in real world situations, designing of robots naturally involve multiple objectives which are equally important and eventually may lead to conflicting scenarios among them (Deb, 2004).

In the field of continuum robot design, numerous researches have been carried out in modelling and designing the continuum robots' morphology and controller inspired from the snake movements and neuronal control mechanism. From these studies, it was found that both morphology and control mechanism are contributing to the overall moving behaviour of the continuum robots (Lipson, 2006). Yet, there is still a lack of relevant information regarding how a continuum robot morphology and controller relates to its behaviour. This issue turns out to be an open-ended design problem where humans are unsure of the optimum control strategy, body structure, number of segments and suitable segment length in order to provide the best versatility of the continuum robots. Apart from that, the continuum robots possess large number of degrees of freedom which require significant effort from the designer to model and tune the predetermined parameters so that the continuum robots can perform according to their respective initial design. Most of the time, such a process is very time consuming and costly. In order to overcome this open-ended design and optimization problem, a novel system is developed in this research by implementing the multi-objective co-evolutionary approach to design and optimize automatically both morphology and controller of continuum robots via an artificial evolutionary process with the aim to maximize the moving behaviour and minimize the complexity of continuum robots. Using this method, heterogeneous continuum robots with different morphologies along with the control system are able to be automatically designed and optimized. The continuum robots which were evolved with different morphologies and control systems for similar functionalities are referred to as heterogeneous continuum robots.

In evolutionary robotics, evolutionary optimization is carried out on the autonomous robots' candidate solutions. The population is repeatedly modified and selected according to the formulated fitness function. The favourable genetic traits will develop repeatedly and will be passed on to their offspring generation by generation and thus eventually resulting in better performance in subsequent generations. Hence, a large number of evolutionary iterations are involved in order to obtain the final optimum design. As a result, it is impractical to carry out such trials directly in the real world. For this purpose, a physical simulation software is used in this research to perform the evolutionary computation where a virtual environment will be created in the simulator for the autonomous robots to evolve. In most similar studies, the research is conducted up to the simulation stage only. This is because the fabrication of the designed robots involves high manufacturing cost and numerous manufacturing constraints will arise in fabricating heterogeneous body parts. However, the invention of 3D printers provides a solution for rapid prototyping with a relatively low cost. A prototype can be easily fabricated from a 3D printer within a short period. For that reason, 3D printers are being used in this research to fabricate heterogeneous robot bodies such that the evolved morphologies and controllers are able to be transferred into the real world for physical testing in order to validate on the feasibility of the system and to make the robotic design more practical whereby the robot is not constrained to the simulation world only.

REFERENCES

Albert, W. Y. K. and Henry, Y. K. L. 2009. Intelligent Robot-assisted Humanitarian Search and Rescue System. *International Journal of Advanced Robotic Systems,* **6**(2), pp. 121-128.

Baba, T., Kameyama, Y., Kamegawa, T. and Gofuku, A. 2010. A Snake Robot Propelling Inside of A Pipe with Helical Rolling Motion. *SICE Annual Conference,* pp. 2319 - 2325.

Basheer, I. A. and Hajmeer, M. 2000. Artificial Neural Networks: Fundamentals, Computing, Design, and Application. *Journal of Microbiological Methods,* **43**(1), pp. 3-31.

Bath, Avon, B. & Devizes. 2015. "Snake-arm Robots: Robot for Confine Spaces" (online), http://www.ocrobotics.com/applications--solutions/aerospace/.

Berman, B. 2012. 3-D printing: The new industrial revolution. *Business Horizons,* **55**(2), p. 155–162.

Berry, M. J. A. and Linoff, G. S., 1997. Data Mining Techniques. New York: John Wiley & Sons.

Beyer, H. G. and Schwefel, H. P. 2002. Evolution Strategies: A Comprehensive Introduction. *Natural Computing,* **1**(1), pp. 3-52.

Boger, Z. and Guterman, H., 1997. Knowledge Extraction from Artificial Neural Network Models. IEEE Systems, Man, and Cybernetics, Volume 4, pp. 3030 - 3035.

Bongard, J. and Lipson, H. 2004. *Integrated Design, Deployment and Inference for Robot.* California, Robosphere.

Brest, J. et al. 2006. Self-Adapting Control Parameters in Differential Evolution: A Comparative Study on Numerical Benchmark Problems. *IEEE Transactions on Evolutionary Computation,* **10**(6), pp. 646 - 657.

Brest, J. et al. 2008. An Analysis of the Control Parameters' Adaptation in DE. In: U. K. Chakraborty, ed. *Advances in Differential Evolution.* s.l.:Springer Berlin Heidelberg, pp. 89-110.

Chakraborty, R. C. 2010. *Fundamental of Neural Networks: AI Course Lecture 37 Notes,* Guna: s.n.

Chen, L., Wang, Y. C., Ma, S. and Li, B. 2004. Studies on Lateral Rolling Locomotion of A Snake Robot. *Robotics and Automation,* pp. 5070 - 5074.

Chen, Y., Qiu, Z., Lu, Z. & Mao, L., 2015. *Numerical Simulation of Hydrodynamic Characteristics of Underwater Snake-like Robot.* Changshu, IEEE, pp. 491-495.

Chua, C. K., Leong, K. F. and Lim, C. S. 2010. *Rapid Prototyping.* 3rd ed. Singapore: World Scientific.

Crespi, A., Badertscher, A., Guignard, A. and Ijspeert, A. J. 2005. AmphiBot I: An Amphibious Snake-like Robot. *Robotics and Autonomous Systems,* **50**(4), pp. 163-175.

Deb, K. 2004. *Multi-Objective Optimization using Evolutionary Algorithms.* England: John Wiley & Sons Ltd.

Delcomyn, F. 1980. Neural Basis of Rhythmic Behavior In Animals. *Science,* **210**(4469), pp. 492-498.

Eiben, A. E. and Smith, J. E. 2003. *Introduction to Evolutionary Computing.* 1st ed. Berlin: Springer.

Fogel, L. J. 1999. *Intelligence Through Simulated Evolution: Forty Years of Evolutionary Programming.* New York: John Wiley & Sons.

Gardner, M. W. and Dorling, S. R. 1998. Artificial Neural Networks (The Multilayer Perceptron)—A Review of Applications in The Atmospheric Sciences. *Atmospheric Environment,* **32**(14-15), pp. 2627-2636.

Goldberg, D. E. 1989. *Genetic Algorithms in Search, Optimization, and Machine Learning.* Redwood City: Addison-Wesley.

Gray, J. 1946. The Mechanism of Locomotion in Snakes. *Journal of Experimental Biology,* **23**(2), pp. 101-120.

Gregor, M., Spalek, J. and Capak, J. 2012. Use of Context Blocks in Genetic Programming for Evolution of Robot Morphology. *ELEKTRO,* pp. 286-291.

Guettas, C., Cherif, F., Breton, T. and Duthen, Y. 2014. Cooperative Co-evolution of Configuration And Control for Modular Robots. *Multimedia Computing and Systems,* pp. 26 - 31.

Haller, B. v., Ijspeert, A. and Floreano, D. 2005. Co-evolution of Structures and Controllers for Neubot Underwater Modular Robots. In: M. S. Capcarrère, et al. eds. *Advances in Artificial Life.* Berlin: Springer Berlin Heidelberg, pp. 189-199.

Harvey, I. et al. 2005. Evolutionary Robotics: A New Scientific Tool for Studying Cognition. *Artificial Life,* **11**(1-2), pp. 79-98.

Haykin, S. 1998. *Neural Networks: A Comprehensive Foundation.* 2nd ed. New Jersey: Prentice Hall.

Hecht-Nielsen, R. 1990. *Neurocomputing.* Boston: Addison-Wesley.

Hirose, S. 1993. *Biologically Inspired Robots: Snake-like Locomotors and Manipulators.* New York: Oxford University Press.

Holland, J. H. 1992. *Adaptation in Natural and Artificial Systems.* Cambridge: MIT Press.

Hopkins, J. K., Spranklin, B. W. and Gupta, S. K. 2009. A Survey of Snake-inspired Robot Designs. *Bionispiration and Biomimetics,* **4**(2).

Howard, L. M. and D'Angelo, D. J. 1995. The GA-P: A Genetic Algorithm And Genetic Programming Hybrid. *IEEE Expert,* **10**(3), pp. 11-15.

Hull, C. W. 1986. *Apparatus for Production of Three-dimensional Objects by Stereolithography.* US, Patent No. 4,575,330.

Jakobi, N. 1997. Evolutionary Robotics And The Radical Envelope-of-noise Hypothesis. *Adaptive Behavior,* **6**(2), pp. 325-368.

Kim, H. and Yamakawa, H. 2012. Multi-objective Optimization for Number of Joints And Lengths of Multi-jointed Robot Arm. *Innovative Engineering Systems,* pp. 196 - 200.

Komura, H., Yamada, H. and Hirose, S., 2015. Development of Snake-like Robot ACM-R8 with Large And Mono-tread Wheel. *Advance Robotics,* **29**(17), pp. 1081-1094.

Koza, J. R. 1992. *Genetic programming: On the Programming of Computers by Means of Natural Selection.* Cambridge: MIT Press.

Koza, J. R. 1994. *Genetic Programming II: Automatic Discovery of Reusable Programs.* Cambridge: MIT Press.

Lee, W. P., Hallam, J. and Lund, H. 1996. A Hybrid GP/GA Approach for Co-evolving Controllers And Robot Bodies to Achieve Fitness-specified Tasks. *Evolutionary Computation,* pp. 384 - 389.

Liljebäck, P., Pettersen, K. Y., Stavdahl, Ø. and Gravdahl, J. T. 2012. A Review on Modelling, Implementation, And Control of Snake Robots. *Robotics and Autonomous Systems,* **60**(1), pp. 29-40.

Lipkin, K. et al. 2007. Differentiable And Piecewise Differentiable Gaits for Snake Robots. *Intelligent Robots and Systems,* pp. 1864 - 1869.

Lipson, H. 2006. Evolutionary Robotics and Open-Ended Design Automation. In: Y. Bar-Cohen, ed. *Biomimetics: Biologically Inspired Technologies.* Boca Raton: CRC Press, pp. 129-156.

Lipson, H. and Pollack, J. B. 2000. Automatic Design And Manufacture of Robotic Lifeforms. *Nature,* Volume 406, pp. 974-978.

Lv, Y. H., Li, L., Wang, M. H. & Guo, X., 2015. Simulation Study on Serpentine Locomotion of Underwater. *International Journal of Control and Automation,* 8(1), pp. 373-384.

Marbach, D. and Ijspeert, A. J. 2004. Co-evolution of Configuration and Control for Homogenous Modular Robots. *Proceedings of 8th International Conference on Intelligent Autonomous Systems*, Amsterdam, pp. 712-719.

Montana, D. J. and Davis, L. 1989. Training Feedforward Neural Networks Using Genetic Algorithms. *Proceedings of the 11th international joint conference on Artificial intelligence,* Volume 1, pp. 762-767.

Mori, M. and Hirose, S. 2001. Development of Active Cord Mechanism ACM-R3 with Agile 3D Mobility. *Intelligent Robots and Systems,* Volume 3, pp. 1552 - 1557.

Mori, M. and Hirose, S. 2002. Three-dimensional Serpentine Motion And Lateral Rolling by Active Cord Mechanism ACM-R3. *Intelligent Robots and Systems,* Volume 1, pp. 829 - 834.

Nolfi, S. and Floreano, D. 2004. *Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines.* Cambridge: A Bradford Book.

O'callaghan, J. 2014. "Would You Let This Terrifying 'Robotic Snake' Slide Down Your Throat to Perform Surgery Inside Your Body?" (online), http://www.dailymail.co.uk/sciencetech/article-2599715/Would-let-terrifying-snake-robot-slide-THROAT-perform-surgery-inside-body.html.

Oliveira, M. et al. 2011. Multi-objective Parameter CPG Optimization For Gait Generation of A Quadruped Robot Considering Behavioral diversity. *Intelligent Robots and Systems,* pp. 2286 - 2291.

Panchal, G., Ganatra, A., Kosta, Y. P. and Panchal, D., 2011. Behaviour Analysis of Multilayer Perceptrons with Multiple Hidden Neurons and Hidden Layers. *International Journal of Computer Theory and Engineering,* **3**(2), pp. 332-337.

Paul, C. and Bongard, J. C. 2001. The Road Less Travelled: Morphology in The Optimization of Biped Robot Locomotion. *Intelligent Robots and Systems,* Volume 1, pp. 226-232.

Pereda, J. C., Lope, J. d. and Rodellar, M. V. 2007. Evolutionary Controllers for Snake Robots Basic Movements. In: E. Corchado, J. M. Corchado and A. Abraham, eds. *Innovations in Hybrid Intelligent Systems.* Berlin: Springer Berlin Heidelberg, pp. 167-174.

Pouya, S., Aydin, E., Möckel, R. and Ijspeert, A. J. 2011. Locomotion Gait Optimization for Modular Robots; Coevolving Morphology and Control. *Procedia Computer Science,* Volume 7, p. 320–322.

Pratihar, D. K. 2003. Evolutionary Robotics—A Review. *Sadhana,* **28**(6), pp. 999-1009.

Shao, L., Guo, B., Wang, Y. and Chen, X., 2015. *An Overview on Theory and Implementation of Snake-like Robots.* Beijing, IEEE, pp. 70-75.

Sims, K. 1994. Evolving 3D Morphology And Behavior by Competition. *Artificial Life,* **1**(4), pp. 353-372.

Tanev, I., Ray, T. and Buller, A. 2005. Automated Evolutionary Design, Robustness, And Adaptation of Sidewinding Locomotion of A Simulated Snake-Like Robot. *IEEE Transactions on Robotics,* **21**(4), pp. 632 - 645.

Teo, J. and Abbass, H. A. 2003. Neuro-Morpho Evolution: What Will Happen If Our Body Is Not Symmetric?. *Australian Conference on Artificial Life,* pp. 261-275.

Toyoda, Y. and Yano, F. 2004. Optimizing Movement of A Multi-Joint Robot Arm. *IEMS,* **3**(1), pp. 78-84.

Turing, A. 1992. In: D. C. Ince, ed. *Collected Works of A.M. Turing: Mechanical Intelligence.* Amsterdam: North-Holland.

Wei, H. X., Li, H. Y. and Wang, T. M. 2010. An Evolutionary Swarm Self-assembly Robot: From Concept to Prototype. *Robotics and Biomimetics,* pp. 104 - 109.

Wright, C. et al. 2007. Design of A Modular Snake Robot. *Intelligent Robots and Systems,* pp. 2609 - 2614.

Yoshida, E. et al. 2003. Evolutionary Synthesis of Dynamic Motion And Reconfiguration Process for A Modular Robot M-TRAN. *Computational Intelligence in Robotics and Automation,* Volume 2, pp. 1004 - 1010 .

Zhang, H., Wang, W., Zong, G. and Zhang, J., 2006. A Novel Reconfigurable Robot for Urban Search and Rescue. International Journal of Advanced Robotic Systems, **3**(4), pp. 359-366.