DESIGN, OPTIMISATION AND FABRICATION OF A CLIMBING SIX ARTICULATED-WHEELED ROBOT USING THE ARTIFICIAL EVOLUTION AND 3D PRINTING

LIM SHUN HOE

THESIS SUBMITTED IN THE FULFILLMENT FOR THE DEGREE OF MASTER OF ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITI MALAYSIA SABAH
2016

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS

JUDUL: DESIGN, OPTIMISATION AND FABRICATION OF A CLIMBING SIX ARTICULATED-WHEELED ROBOT USING THE ARTIFICITAL EVOLUTION AND 3D PRINTING

IJAZAH: SARJANA KERJURUTERAAN

Saya LIM SHUN HOE, Sesi Pengajian 2013-2015, mengaku membenarkan tesis Sarjana 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 pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. Sila tandakan (/)

☐ SULIT (Mengandungi maklumat yang berdajah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

☐ TERHAD (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

☑ TIDAK TERHAD

Disahkan oleh,

(Tandatangan Penulis)

(Tandatangan Pustakawan)

Alamat Tetap: 90, Tiang Dua
75460 Melaka.

Tarikh: 30 Januari 2016

(ASSOC. PROF. DR. JASON TEO TZE WI)
Penyelia Utama

DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, excerpts, equation, summaries and references, which have been duly acknowledged.

29 November 2015

Lim Shun Hoe
MK1221024T

CERTIFICATION

NAME : **LIM SHUN HOE**

MATRIC NO. : **MK1221024T**

TITLE : **DESIGN, OPTIMISATION AND FABRICATION OF A CLIMBING SIX ARTICULATED-WHEELED ROBOT USING THE ARTIFICIAL EVOLUTION AND 3D PRINTING**

DEGREE : **MASTER OF ENGINEERING (COMPUTER ENGINEERING)**

DATE OF VIVA : **25 September 2015**

CERTIFIED BY

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

   Signature

2. **CO-SUPERVISOR**
   Assoc. Prof. Dr. Jamal Ahmad Dargham

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to Vice-Chancellor of Universiti Malaysia Sabah, Prof. Datuk. Dr. Mohd Harun Abdullah for his permission to carry out this research in Universiti Malaysia Sabah.

I would like to express my thanks to the Dean of Faculty of Engineering, Prof. Ir. Dr. Rosalam Hj. Sarbatly for providing support during my research work.

I would like to take this opportunity to thank my supervisor Assoc. Prof. Dr. Jason Teo Tze Wi for his constant encouragement and guidance. Without his presence, I would not be able to go this far.

I would like to acknowledge the help and guidance that I received from my co-supervisor, Assoc. Prof. Dr. Jamal Ahmad Dargham.

I would like to show my appreciation to the Ministry of Higher Education, Malaysian for supporting this Master's program through its MyBrain-MyMaster program.

Last but not least, I would like to thank to my parents and family members who had been providing great support during my research work and also to everyone who helped me from the beginning until the final phase of my thesis work.

Lim Shun Hoe
November 2015

ABSTRACT

Over the last decade, various mobile robots have been developed and widely used in myriad sectors. However, the vast majority of mobile robots are manually designed where the designers must have the preliminary knowledge of the interaction between the robots and the environment. Additionally, the high complexity involved in the design of the kinematics and controllers of a mobile robot has always been the biggest challenge for researchers and practitioners alike. Thus, the task of designing a robot can be considered very demanding and extremely challenging. In this research, an artificial evolution approach utilizing Single-Objective Evolutionary Algorithm (SOEA) and Multi-Objective Evolutionary Algorithm (MOEA) respectively are investigated in the automatic design and optimization of the morphology of a Six Articulated-Wheeled Robot (SAWR) with climbing ability. Simulations are carried out in Webots, a high fidelity physical-based robot simulator. Simulations results show that the SOEA is able to produce optimized SAWR with climbing ability while the MOEA is able to produce a set of Pareto optimal solutions which provide users with a choice of solutions for trade-off between the objectives of morphology size and climbing performance. The Pareto optimal set of solutions are the smallest SAWR with the least climbing ability to the biggest SAWR with the best climbing ability. The research continues by transferring the evolved solutions from simulation to the real world using 3D printing. The body, legs and wheels of the evolved robots are printed by a 3D printer and assembled with sensors, servos and motors for real world testing. Results show that the fabricated real world SAWRs were able to perform the climbing motion with an average accuracy of 80.9% compared to the performance in simulation.

ABSTRAK

PEREKAAN, PENGOPTIMUMAN DAN PEMASANGAN ROBOT MENDAKI YANG TERATUR BERODA ENAM MENGGUNAKAN EVOLUSI DAN PENCETAKAN 3D

Lebih sedekad yang lalu, pelbagai robot bergerak telah dibangunkan dan digunakan secara meluas dalam pelbagai sektor. Walau bagaimanapun, sebahagian besar robot bergerak direka bentuk secara manual di mana pereka mesti mempunyai pengetahuan awal interaksi antara robot dengan persekitarannya. Selain itu, kompleksiti yang tinggi yang terlibat dalam reka bentuk kinematik dan pengawal robot bergerak sentiasa menjadi cabaran terbesar bagi para penyelidik dan pengamal sama. Oleh itu, kerja merekabentuk robot yang boleh dianggap sebagai amat mencabar. Dalam kajian ini, pendekatan pengkomputeran evolusi menggunakan "Single-Objektive Evolutionary Algorithm" (SOEA) dan "Multi-Objektive Evolutionary Algorithm" (MOEA) masing-masing disiasat dalam reka bentuk automatik dan pengoptimuman morfologi robot enam kaki beroda (SAWR) dengan keupayaan mendaki. Proses simulasi dijalankan dengan menggunakan Webots, iaitu simulator robot berasaskan bentuk fizikal fideliti tinggi. Keputusan menunjukkan bahawa SOEA mampu menghasilkan SAWR yang dioptimumkan dengan keupayaan mendaki manakala MOEA mampu menghasilkan satu set penyelesaian yang optimum Pareto yang memberi pengguna pilihan penyelesaian untuk keseimbangan antara objektif saiz morfologi dan prestasi memanjat. Set optimum Pareto penyelesaian adalah SAWR yang paling kecil dengan keupayaan mendaki yang terkurang kepada SAWR terbesar dengan keupayaan mendaki yang paling tinggi. Kajian ini diteruskan dengan memindahkan penyelesaian yang dievolusi daripada simulasi kepada dunia sebenar dengan menggunakan percetakan 3D. Badan, kaki dan roda robot dievolusi dicetak oleh pencetak 3D dan dipasang dengan alat pengesan, servos dan motor untuk ujian dunia sebenar. Keputusan menunjukkan bahawa SAWRs dunia sebenar yang difabrikasi dapat melaksanakan gerakan pendakian dalam persekitarannya dengan ketepatan skor keseluruhan 80.9% berbanding dengan prestasi dalam simulasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AM	Addictive Manufacturing
API	Application Programming Interface
ATR	All-Terrain-Rover
CAD	Computer-Aided Design
DOF	Degree-of-Freedom
EA	Evolutionary Algorithm
EP	Evolution Programming
ES	Evolution Strategies
FSM	Finite State Machine
GA	Genetic Algorithm
GP	Genetic Programming
MOEA	Multi-Objective Evolutionary Algorithm
PAW	Platform for Ambulating Wheels
PWM	Pulse Width Modulation
SAR	Synthetic Aperture Radar
SAWR	Six Articulated-Wheeled Robot
SOEA	Single-Objective Evolutionary Algorithm
VLSI	Very Large Scale Integration

CHAPTER 1

INTRODUCTION

1.1 Introduction

Mobile robotics has become an extremely popular research topic since the first implementation of mobile robots in World War II. By definition, a mobile robot is a machine with the capability to move in a given environment. In other words, mobile robots are able to move around in a specified environment and are not just fixed to one physical location. Mobile robotics is a field of great interest in robotics as it has a close interaction with the environment. Mobile robotics can be utilized in a wide range of applications. For example, in the service industry, military deployments, manufacturing, cleaning, entertainment and remote exploration, especially in search and rescue operations where human lives can be endangered.

1.2 Mobile Robots

Mobile robots have been showing a great success in the real-world implementation. For the first time, robots were assisting in an actual urban search and rescue mission of the World Trade Center tragedy on 11 September 2001. The team assisted by search and rescue robots had succeeded to discover more than ten victims, which are more than two percent of total victims discovered (Angela, 2002). The successful involvement of mobile robots in real life rescue missions has garnered much attention from researchers.

For ground mobile robots' locomotion, wheels and legs are the two common adopted methodologies. From a biological perspective, land animals with their sturdy legs are able to move over uneven terrains smoothly and rapidly after a long evolutionary process. On the other hand, during pre-historic times, humans invented wheels that were specialized in rolling to assist in ground locomotion. The excellent performance of wheels in both power efficiency and traveling speed can scarcely be achieved by legged mechanism. A hybrid platform with the combination of leg and wheel has excellent maneuverability on flat ground and uneven terrain.

Therefore, a hybrid platform is highly recommended for general indoor and outdoor environment operations as it is the trend for "future" mobile platforms (Shen, Li, Cheng, Lu, Wang, and Lin, 2009). The characteristics of each locomotion methodology are explained in detailed in Chapter Two.

1.3 Hybrid Mobile Robots

A hybrid mobile robot is a platform that combines both the legged and wheeled locomotion mechanisms. In recent years, hybrid mobile robots have been designed for various functionality and purposes. For example, there are hybrid mobile robots that were designed for stairs climbing purposes, performing jumping behavior, in-situ reconfiguring robots posture and adapting to uneven terrain, among others. In general, hybrid mobile robots can carry out their mission better in rough terrains compared to the traditional wheeled or legged mobile robots. Hybrid mobile robots utilize the advantages of both wheeled and legged mechanisms while compensating the downside of each other.

There are many successful examples of hybrid mobile robots, which are built and designed for a wide range of operations. A group of researchers from a few universities in Japan had developed a hybrid wheeled-legged platform through a retracting mechanism inspired by the armadillo (Tadakuma, Tadakuma, Maruyama, Rohmer, Nagatani, Yoshina, Ming, Makoto, Higashimori and Kaneko, 2009). The idea of a retractable wheeled-legged module is that the specially-designed wheels can be transformed into a legs-like mechanism. Smith, Sharf and Trentini (2006a) from the McGill University proposed PAW, a four legs robot with wheels equipped at the end of each leg. PAW is the first to combine wheeled mode locomotion with dynamically stable legged locomotion.

University Lübeck in Germany developed WheeHy, which is capable of doing in-situ reconfiguration of its posture (Bojan, Martin, Michael, and Erik, 2010). One of the key features of WheeHy is that the robot can perform adaptation of its posture during its traversal over uneven terrain. National Taiwan University proposed a Quattroped platform with hybrid legged-wheeled locomotion (Shen, Li, Cheng, Lu, Wang, and Lin, 2009). The proposed system utilizes a transformation method where the morphology of its wheels can be directly transformed into legs.

Sojourner and Rocky 7 Rover by the NASA (Volpe, Balaram, Ohm, and Ivlev, 1997) and Shrimp by the Swiss Federal Institute of Technology Lausanne (Siegwart, Lamon, Estier, Lauria, and Piguet, 2002) are some other examples of hybrid mobile robots.

1.4 Artificial Evolution

The use of artificial evolution for the automatic generation and synthesis of controllers and/or morphologies for robots is one of the more recent methods in developing robots (Wang, Tan and Chew, 2006). By implementing evolutionary algorithms in designing a robot, an optimized controller and/or morphologies can be obtained where at times, these evolved solutions might be beyond the designers' design capability.

Successful examples of designing robots with artificial evolutionary approaches include walking robots designed with evolutionary computation in optimizing the morphology and controller (Rommerman, Kuhn, and Kirchner, 2009) and swarm robotics with their controllers designed using evolutionary algorithms with artificial neural networks (Kadota, Yasuda, Matsumura, and Ohkura, 2012).

1.5 Problem Statement

As been discussed earlier, there are numerous type of hybrid mobile robots that have been proposed and developed. However, as far as we aware, hybrid mobile robots are manually designed where the designers must have the preliminary knowledge of the interaction between the robots and the environment. Besides that, the extremely complexity in the kinematic and controller designing of a hybrid mobile robot has always been the biggest challenge for the researchers. Planning is an important aspect of the effort to design robots that perform their task with some degree of flexibility and responsiveness to the environment (Akerka, 2005). According to Akerka (2005), planning is a difficult problem for a number of reasons, not the least of which is the size of the space of possible sequences of moves. Even a simple robot, which can only move forward, backward, right or left has so many different ways that the robot can possibly move around in an environment. On the other hand, manually designed morphology on trial-and-error basis is not guaranteed to be optimal from the large design space (Endo, Yamasaki, Maeno, and Kitano, 2003). Thus, the task of designing a robot can be considered demanding (Lee, 1998), especially in designing a hybrid mobile robot. Here, it raises the research question on the possibility of obtaining an optimized morphology of a climbing SAWR using an artificial evolution approach.

On the other hand, one of the biggest challenges in evolutionary robotics is to crawl out from simulation to the real-world implementation. Researches on evolutionary robotics usually stop at the simulation level where the results are not tested in the real-world environments. This might be due to the high cost in fabricating the robots as the cost of manufacturing a robot must be absorbed in mass production (Lipson and Pollack, 2000). With the invention of 3D printers, it provides a solution for rapid prototyping at a relatively low cost with almost immediate physical availability as soon as it is 3D printed. Therefore, evolved solutions in this research are to be fabricated with the aid of 3D printer and the performance of the fabricated real-world SAWRs is to be investigated.

1.6 Objectives

The objectives of this research are to obtain the fittest climbing hybrid mobile robots with evolutionary algorithms where the evolved solutions are transferred into real-world robots. The objectives are summarized as below:

i. To propose an artificial evolution method in designing and optimizing the morphology of a six articulated-wheeled robot (SAWR) with climbing ability.
ii. To integrate single-objective and multi-objective optimization into the evolutionary algorithm for evolving SAWRs.
iii. To transfer the evolved robots from simulation to real world with 3D printing fabrication.

1.7 Project Scope

The scopes of the research are listed below:

i. The controller of the SAWR is manually designed and not involved in the evolution. The objective of this research is to obtain an optimized morphology of a SAWR with climbing ability, therefore the controller is designed to be as simple as possible for each evolved individual to perform climbing motion. Thus, SAWR with the designed controller is expected to be able to move forward only and perform a series of reconfiguration method to perform climbing motion when approaching obstacles.

ii. The morphology design of the SAWR consists of three main parts which are the robot main body, legs and wheels. Thus, in order to obtain an optimized morphology, the parameter of these three main parts have to be minimized which are the body length, leg length and wheel radius.

iii. Flat terrain with flat step/steps as the obstacles is designed as the task environment for the SAWR. In this research, two environments have been selected, which are single-step environment and multi-steps environment. In single-step environment, there is only a single step of 55mm in height which is to be stridden by each individual SAWR in reaching the goal. While for multi-steps environment, there are three steps in the task environment. First, a single step of 50mm in height, the second is stairs-like step of 55mm in height and the last is a single step of 80mm in height.

iv. Evolved solutions from simulations are transferred into real-world SAWRs with 3D printing with the material of Acrylonitrile Butadiene Styrene (ABS) plastic which has the limitation of only being able to print out geometries without any overhangs.

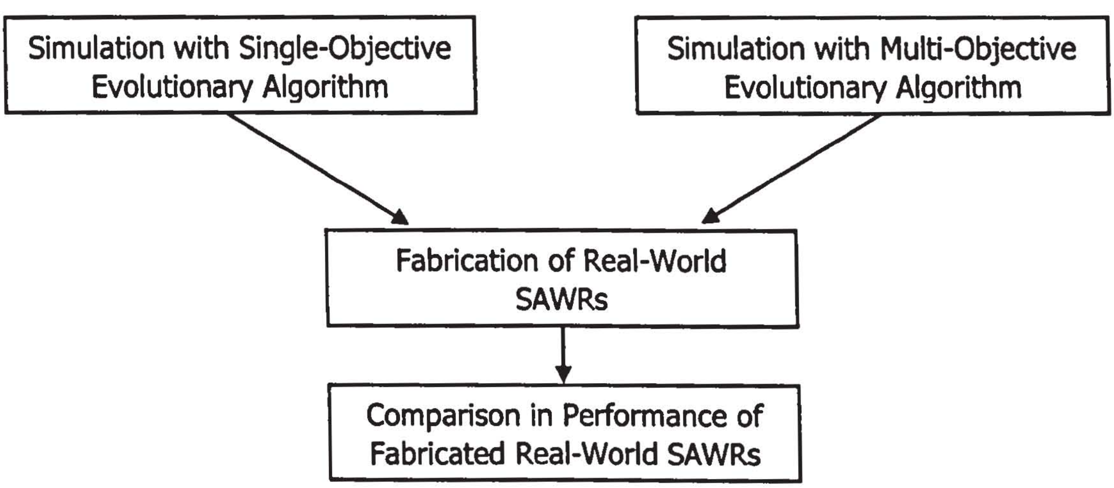

Figure 1.1: Research Overview Block Diagram.

Figure 1.1 shows the research overview block diagram. The experiment of this research was started with the simulation using the single-objective evolutionary algorithm. This was followed by the simulation with the multi-objective evolutionary

REFERENCES

3dprinting. 2015, January 13. *What is 3D printing?* Retrieved from http://3dprinting.com: http://3dprinting.com/what-is-3d-printing

Akerka, R. 2005. *Introduction to Artificial Intelligence.* PHI Learning Pvt. Ltd.

Angela, D. 2002. Urban Search and Rescue Robots: From Tragedy to Technology. *IEEE Intelligent Systems,* **7**(2):81-83.

Arduino. 2015, February 4. *Arduino Mega 2560.* Retrieved from Arduino: http://www.arduino.cc

Arkin, R. C. 1998. *Behavior-Based Robotics.* MIT Press.

Beielstein, T., Ewald, C., & Markon, S. 2003. Optimal Elevator Group Control by Evolution Strategies. *Proceedings of the Genetic and Evolutionary Computation Conference,* 1963-1974.

Bits From Bytes. 2011. *3D Touch.*

Bojan, J., Martin, H., Michael, K., & Erik, M. 2010. Design of a Hybrid Wheeled-Legged Robot-Wheehy. *Robotics (ISR), 2010 41st International Symposium on and 2010 6th German Conference on Robotics (ROBOTIK),* 1-6.

Bruzzone, L., & Fanghella, P. 2014. Mantis Hybrid Leg-Wheel Robot: Stability Analysis and Motion Law Synthesis for Step Climbing. *10th International Conference on Mechatronic and Embedded Systems and Applications,* 10-12.

Catania, V., Malgeri, M., & Russo, M. 1997. Applying Fuzzy Logic to Codesign Partitioning. *IEEE Micro,* **17**(3):62-70.

Chandrasekharam, R., Subhramanian, S., & Chaudhury, S. 1993. Genetic Algorithm for Node Partitioning Problem and Application in VLSI Design. *IEEE Proceedings Series E: Computers and Digital Techniques,* **140**(5):255-260.

Chin, K. O., & Teo, J. 2010. Evolution and Analysis of Self-Synthesized Minimalist Neural Controllers for Collective Robotics Using Pareto Multi-Objective Optimization. *IEEE Congress on Evolutionary Computation,* 1-7.

Cytron. 2015, March 2. *RC Servo Motor (Metal Gear).* Retrieved from Cytron Technologies: http://cytron.com.my

Deb, K. 2001. *Multi-Objective Optimization Using Evolutionary Algorithms.* New York: Wiley.

Endo, G., & Hirose, S. 1999. Study on Roller-Walker. *IEEE International Conference on Robotics and Automation (system integration and basic experiments),* **3**: 2032-2037.

Endo, K., Yamasaki, F., Maeno, T., & Kitano, H. 2003. Co-evolution of Morphology and Controller for Biped Humanoid Robot. In Kaminka, A. Gal, Lima, U. Pedro, & R. Rojas, *RoboCup 2002: Robot Soccer World Cup VI.* Springer.

Enrique, A., & Carlos, C. 2004. Evolutionary Algorithms, *Handbook of Bioinspired Algorithms and Applications,* 3-19.

Floreano, D., Zufferey, J.-C., & Nicoud, J.-D. 2005. From Wheels to Wings with Evolutionary Spiking Circuits. *Artificial Life,* **11**(1-2):121-138.

Fogel, D. B. 1998. *Evolutionary Computation: The Fossil Record.* Wiley IEEE-Press.

Fogel, L. J., Angeline, P. J., & Fogel, D. B. 1995. An Evolutionary Programming Approach to Self-Adaptation on Finite State Machines. *In Proceedings of the 4th Annual Conference on Evolutionary Programming,* 355-365.

Fogel, L. J., Owens, A. J., & Walsh, M. J. 1966. *Artificial Intelligence Through Simulated Evolution.* John Wiley & Sons.

Gianni, C., & Erika, O. 2009. Design and Simulation of a New Hybrid Mobile Robot for Overpassing Obstacle. *Proceedings of EUCOMES,* 101-108.

Grand, C., Benamar, F., Plumet, F., & Bidaud, P. 2004. Stability and Traction Optimization of a Reconfigurable Wheel-Legged Robot. *The International Journal of Robotics Research,* **23**(10-11):1041-1058.

Guo, Y., Zhang, S., Ritter, A., & Man, H. 2014. A Case Study on a Capsule Robot in the Gastrointestinal Tract to Teach Robot Programming and Navigation. *IEEE Transaction on Education,* **57**(2):112-121.

Hansen, N., Arnold, D., & Auger, A. 2013. Evolution Strategies. In K. Janusz, & P. Witold, *Handbook of Computational Intelligence.* Springer.

Hayati, S., Volpe, R., Backes, P., Balaram, J., Welch, R., Ivlev, R., Tharp, G., Peters, S., Ohm, T., Petras, R., Laubach, S. 1997. The Rocky 7 Rover: A Mars Sciencecraft Prototype. *Proceedings of the IEEE International Conference on Robotics and Automation,* **3**:2458-2464.

Horward, D., Roberts, S., & Brankin, R. 1999. Target detection in SAR imagery by genetic programming. *Advances in Engineering Software,* **30**(5):303-311.

Iba, H. 2008. *Frontiers in Evolutionary Robotics.* I-Tech Education and Publishing.

Jakobi, N., Husbands, P., & Harvey, I. 1995. Noise and the Reality Gap: The Use of Simulation in Evolutionary Robotics. *Advances in artificial life, Springer,* 704-720.

Kadota, T., Yasuda, T., Matsumara, Y., & Ohkura, K. 2012. An Incremental Approach to an Evolutionary Robotic Swarm. *IEEE/SICE International Symposium on System Integration (SII),* 458-463.

Karr, C. 1991. Genetic Algorithms for Fuzzy Controllers. *AI Experts,* **6**(2):26-33.

Kim, I., Lee, J., Jeong, W., Kim, J., & Yang, H. 2013. Design of Morphological Changing All-Terrain-Rover for Enhancing Mobility. *16th International Conference on Advanced Robotics,* 1-6.

Koos, S., Mouret, B., & Doncieux, S. 2013. The Transferability Approach: Crossing the Realigy Gap in Evolutionary Robotics. *IEEE Transactions on Evolutionary Computation,* **17**(1):122-145.

Koza, J. 1990. Evolution and Co-Evolution of Computer Programs to Control Independently-Acting Agents. *Proceedings of the International Conference on Simulation of Adaptive Behavior on From Animals To Animats,* 366-375.

Lacagnina, M., Muscato, G., & Sinatra, R. 2003. Kinematics, Dynamics and Control of a Hybrid Robot Wheeleg. *Robotics and Autonomous Systems,* **45**(3):161-180.

Lee, M. A., & Takagi, H. 1993. Integrating Design Stages of Fuzzy Systems Using Genetic Algorithms. *Proceedings of the IEEE International Conference on Fuzzy Systems*, 612-617.

Lee, W. P. 1998. An Evolutionary System for Automatic Robot Design. *IEEE Internatonal Conference on Systems, Man, and Cybernatics*, **4**:3477-3482.

Lipson, H., & Pollack, J. B. 2000. Automatic Design and Manufacture of Robotic Lifeforms. *Nature*, **406**(6799):974-978.

Lu, J. L., & Bu, C. G. 2009. Study on the Mobile Robot Reconfiguration Control Methods. *IEEE International Conference on Automation and Logistics*, 2045-2049.

Marocco, D., Floreano, D. 2002. Active Vision and Feature Selection in Evolutionary Behavioral Systems. *Proceedings of the Seventh International Conference on Simulation of Adaptive Behavioral*, **7**:247-255.

Mazzapioda, M., Cangelosi, A., & Nolfi, S. 2009. Evolving Morphology and Controller: A Distributed Approach. *IEEE Congress on Evolutionary Computation*, 2217-2224.

Mohammad, S. H., Jeffril, M. A., & Shariff, N. 2013. Mobile Robot Obstacle Avoidance by Using Fuzzy Logic Technique. *IEEE International Conference on System Engineering and Technology*, 331-335.

Nakajima, S., Nakano, E., & Takahashi, T. 2004. Motion Control Technique For Practical Use of a Leg-Wheel Robot on Unknown Outdoor Rough. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, **2**:1353-1358.

Nelson, A. L., Barlow, G. J., Doitsidis, L. 2009. Fitness Functions in Evolutionary Robotics: A Survey and Analysis. *Robotics and Autonomous Systems*, **57**(4): 345-370.

Nolfi, S., & Floreano, D. 2000. *Evolutionary Robotics: The biology, intelligence, and technology of self-organizing machines*, MIT Press.

Okan, A., & Levent, A. H. 2014. A Visual Compass for Robot Soccer. *Signal Processing and Communication Applications Conference*, 2003-2006.

Ong, C. H., Shamsudin, H. M., & Amin. 2002. A Biologically Inspired Hybrid Three Legged Mobile Robot. *Student Conference on Research and Development*, 181-183.

Parker, G. B., Georgescu, R. A. 2005. Using cyclic genetic algorithms to evolve multiloop control programs. *Proceedings of the 2005 IEEE International Conference on Mechatronics and Automation, ICMA 2005* **1**:131-118.

PP3DP. 2015, January 13. *UP Plus 2*. Retrieved from PP3DP: http://www.pp3dp.com

Rechenberg, I. 1965. *Cybernetic Solution Path of an Experiment Problem*. Royal Aircraft Establishment Library Translation, No.1122 .

Rommerman, M., Kuhn, D., & Kirchner, F. 2009. Robot Design for Space Missions Using Evolutionary Computation. *IEEE Congress on Evolutionary Computation (CEC)*, 2098-2015.

Ryan, C., Collins, J., & Neil, M. 1998. *Genetic Programming*. Springer.

Schenk, O., & Hillmann, M. 2004. Optimal Design of Metal Forming Die Surfaces with Evolution Strategies. *Journal Computers and Structures*, **82**(20):1695-1705.

Shen, S. Y., Li, C. H., Cheng, C. C., Lu, J. C., Wang, S. F., & Lin, P. C. 2009. Design of a Leg-Wheel Hybrid Mobile Platform. *IEEE International Conference on Intelligent Robots and Systems*, 4682-4687.

Siegwart, R., Lamon, P., Estier, T., Lauria, M., & Piguet, R. 2002. Innovative Design for Wheeled Locomotion in Rough Terrain. *Robotics and Autonomous Systems*, **40**(2):151-162.

Smith, J. A., Sharf, I., & Terntini, M. 2006. PAW: A Hybrid Wheeled-Leg Robot. *Proceedings of the IEEE International Conference on Robotics and Automation*, 4043-4048.

Smith, J. A., Sharf, I., & Trentini, M. 2006. Bounding Gait in a Hybrid Wheeled-Leg Robot. *IEEE / RSJ International Conference on Intelligent Robots and Systems*, 5750-5755.

Suwannasit, K., & Laksanachawen, S. 2004. A Bio-Inspired Hybrid Leg-Wheel Robot. *TENCON 2004 IEEE Region 10 Conference*, **500**:495-497.

Tadakuma, K., Tadakuma, R., Maruyama, A., Rohmer, E., Nagatani, K., Yoshida, K., Ming, A., Makoto, S., Higashimori, M., Kaneko, M. 2009. Armadillo-Inspired Wheel-Leg Retractable Module. *IEEE International Conference on Robotics and Biomimetics*, 610-615.

Tan, T. G., Teo, J., & Chin, K. O. 2013. Single-Versus Multiobjective Optimization for Evolution of Neural Controllers in Ms. Pac-Man. *Internatinal Journal of Computer Games Technology*.

Taylor, T., & Massey, C. 2001. Recent Developments in the Evolution of Morhpologies and Controllers for Physically Simulated Creatures. *Artificial LIfe*, **7**(1):77-87.

Thuerr, T., & Siegwart, R. 2010. Mobility Evaluation of Wheeled All-Terrain Robots. *Robotics and Autonomous System*, **58**(5):508-519.

Trianni, V., Dorigo, M. 2006. Self-organisation and communication in groups of simulated and physical robots, *Biological Cybernetics*, **95**(3):213-231.

Volpe, R., Balaram, J., Ohm, T., & Ivlev , R. 1997. Rocky 7: A Next Generation Mars Rover Prototype. *Advaned Robotics*, **11**(4):341-358.

Wang, L., Tan, K. C., & Chew, C. M. 2006. *Evolutionary Robotics: From Algorithms to Implementations*. World Scientific Publishing.

Wang, W. C., Yang, S. X., Shi, W. R., & Meng, M. Q. 2004. A Co-Evolution Approach to Sensor Placement and Controller Design for Robot Obstacle Avoidance. *Procceding of 2004 International Conference on Information Acquisition*, 107-112.

Webots. 2015, January 11. *Webots User Guide*. Retrieved from Cyberbotics: http://www.cyberbotics.com/dvd/common/doc/webots/guide/section2.7.html

Whitley, D. 1994. A Genetic Algorithm Tutorial. *Statistics and Computing*, **4**(2):65-85.

Wong, K. P., & Yuryevich, J. 1998. Optimal Power Flow Method Using Evolutionary Programming. *Lecture Notes in Artificial Intelligence*, 405-412.

Yuan, J., & Hirose, S. 2004. Research on Leg-Wheel Hybrid Stairclimbing Robot, Zero Carrier. *IEEE International Conference on Robotics and Biomimetics*, 654-659.