PERCEPTION-DRIVEN MODEL FOR HYPER-REDUNDANT MOBILE ROBOT NAVIGATION IN UNSTRUCTURED ENVIRONMENT

AREEJ GHAZI ABDULSHAHEED

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Mechanical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

FEBRUARY 2021

DEDICATION

To the Love of My Life:

My Dear Mother

My Father

Ghazi Abdulshaheed

My Siblings

Bashar, Hyder, Meelad

My Friend

Nada

ACKNOWLEDGEMENT

In preparing this thesis, I owe my deepest appreciation to my parents for all their supporting and love. I wish to express my sincere appreciation to my main thesis supervisor, Assoc. Professor Dr. Mohamed Hussein, for encouragement, guidance, critics and friendship. I am also very thankful to my co-supervisor Dr Mohd Azuwan Mat Dzahir and Dr. Shaharil Mad Saad for their guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here. I also would like to thank Professor Dr Shigeo Hirose for his advices and guidance.

I am also indebted to Universiti Teknologi Malaysia (UTM) for funding my Ph.D study.

My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

ABSTRACT

Navigation in various terrains is considered one of the biggest challenges in the robotics field. Hyper-redundant robots are designed to imitate the feature of biological snakes. Their flexible and multi-degree of freedom body give them an advantage over other traditional mobile robots. Most of the studies that have been done considered wheel snake robots that navigate using horizontal motion in environments with the obstacle. However, irregularity of the surface is challenging for these types of robots. Most of the past works on snake robot locomotion have almost exclusively considered motion across smooth surfaces. However, many real-life environments are not smooth but cluttered with obstacles and irregularities. When the operational scenario is characterized by a surface that is no longer assumed to be flat and obstacles are present, snake robots can move by sensing the surrounding environment. This thesis makes progress towards addressing these issues by developing a perception-driven model for navigation of the hyper robotic system in an unstructured environment. The proposed model should be able to detect the surrounding operational space, identifying the walls, obstacles, and other external objects to create local motion planning. In this thesis, the modeling and design of hyper-redundant mobile robot are presented. The presented model is analyzed using both Newton-Euler and Euler-Lagrange equations. The mathematical model of traveling wave locomotion is verified through simulation and experiment. The simulation shows the relationship between the joint's torque and the position of each joint from the center of gravity. The simulation also describes the effects of the environment, such as the coefficient of friction and initial winding angle on the joint's torque. One of the most challenging of this gait is to stabilize the robot during propulsion. In this research, stability is achieved by controlling the body shape of the robot by controlling the lateral joints of the robot. The main contribution of the thesis is that the development of hyper-redundant mobile robots can navigate in unstructured terrain. A laser range finder sensor (LRF) is used to estimate the distance between the robot and the obstacle. To optimize the sensory signals, undesired detected obstacles points in the scanning zone was eliminated by the established obstacles' filtering. A guidance system is developed to control the navigation of the robot in an unstructured environment. In the system, the robot mode switches between traveling waves, obstacle avoidance, and climbing obstacle locomotion according to the type of the environmental model. The robot system was verified by analyzed the performances in different environments such as narrow path, environment with varying types of obstacles (box, crumple papers, and walls), and steps. Step ascending and descending is achieved by a group of customized designed steps. The perception system could detect and recognize the obstacles' type and achieve successful obstacle avoidance both in narrow and cluttered terrain. The results also showed that the robot could observe and climb the step of 0.1 m height successfully with an average time of 0.9 min.

ABSTRAK

Pemanduan arah di pelbagai rupa bumi dianggap sebagai salah satu cabaran terbesar dalam bidang robotik. Robot lelebih-hiper direka untuk meniru ciri biologi ular. Badan robot ular yang fleksibel dan pelbagai darjah kebebasan memberikan ia kelebihan berbanding robot mudah alih tradisional yang lain. Kebanyakan kajian yang telah dijalankan adalah menggunakan robot ular beroda yang dipandu arah dengan gerakan mendatar di persekitaran berhalangan. Walau bagaimanapun, permukaan tidak sekata amat mencabar bagi robot jenis ini. Sebilangan besar kajian masa lalu yang dijalankan ke atas pergerakan robot ular hampir secara eksklusif menggunakan pergerakan melintasi permukaan licin. Namun, kebanyakan persekitaran sebenar adalah tidak licin tetapi berselerak dengan rintangan dan ketidaksekataan. Apabila senario operasi dicirikan oleh permukaan yang tidak lagi dianggap rata dan terdapat halangan, robot ular akan bergerak dengan menggunakan penderiaan persekitaran. Tesis ini maju kehadapan dalam mengambilkira isu-isu ini dengan membangunkan model dipacu-persepsi untuk sistem navigasi robotik hiper dalam persekitaran yang tidak terstruktur. Model yang dicadangkan harus berupaya mengesan ruang operasi di sekitarnya, mengenal pasti dinding, rintangan, dan objek luaran lainnya untuk membuat perancangan gerakan setempat. Dalam tesis ini, pemodelan dan reka bentuk robot mudah alih lelebih-hiper dibentangkan. Model yang dipersembahkan dianalisa menggunakan kedua-dua persamaan Newton-Euler dan Euler-Lagrange. Model matematik gelombang pergerakan disahkan melalui simulasi dan eksperimen. Simulasi menunjukkan hubungan antara daya kilas sendi dan kedudukan setiap sendi dari pusat graviti. Simulasi juga menunjukkan kesan persekitaran, seperti pekali geseran dan sudut belitan awal pada daya kilas sendi. Salah satu cabaran terbesar dalam menghasilkan pergerakan robot adalah untuk menstabilkan robot semasa pergerakan dorongan. Dalam penyelidikan ini, kestabilan dicapai dengan mengawal bentuk badan robot melalui kawalan sendi lateral robot. Sumbangan utama tesis ini adalah pembangunan robot mudah alih lelebih-hiper yang mampu memandu arah di kawasan tidak berstruktur. Sensor laser pencari jarak (LRF) digunakan untuk menganggarkan jarak antara robot dan halangan. Bagi mengoptimumkan isyarat sensor, titik halangan yang tidak dingini dalam zon imbasan ditapis melalui penapis halangan yang dihasilkan. Sistem panduan dibangunkan untuk mengawal pandu arah robot di persekitaran yang tidak berstruktur. Dalam sistem ini, mod robot bertukar antara pergerakan gelombang perjalanan, penghindaran halangan, dan pergerakan memanjat halangan mengikut jenis model persekitaran. Sistem robot disah melalui analisis prestasi keatas persekitaran yang berbeza seperti jalan sempit, persekitaran dengan pelbagai jenis rintangan (kotak, kertas renyuk serta dinding) dan tangga. Pergerakan menaik dan menurun tangga dicapai menerusi sekumpulan pergerakan yang dirancang khas. Sistem persepsi mampu mengesan dan membeza jenis rintangan serta berjaya mengelak rintangan dalam kedua laluan sempit dan berselerak. Keputusan juga menunjukkan bahawa robot dapat mengenali dan menaiki tangga berkentinggian 0.1 m dengan jayanya dalam purata masa 0.9 min.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	-	2 Dimensions
3D	-	3 Dimensions
ACM	-	Active Core Mechanism
AL	-	Autonomy Level
ALFUS	-	Autonomy Level for Unmanned System
APF	-	Artificial Potential Field
ATRA	-	Autonomy and Technology Readiness Assessment
AUV	-	Autonomous Underwater Vehicle
CAD	-	Computer Aided Design
CM	-	Centre of the Mass
CPG	-	Central Pattern Generator
DoF	-	Degree of Freedom
EC	-	Environmental Complexity
ESI	-	External System Independence
FHS	-	Forward Head Serpentine
GAFNN	-	Genetic Algorithm Fuzzy Neural Network
GNC	-	Guidance, Navigation, and Control
HNR	-	Highly Not Recommended
HR	-	Highly Recommended
IR	-	Infrared sensor
KAIRO3	-	Karlsruhe's Autonomous Inspection Robot 3
LADAR	-	Laser Detection and Ranging
LiDAR	-	Light-Imaging And Ranging
LRF	-	Laser range Finder sensor
LSTM	-	Long Short-Term Memory
MC	-	Mission Complexity
minobs	-	Minimum number of obstacles
NR	-	Not Recommended
ODS	-	Obstacle Detection System
OPF	-	Obstacle Point Filtration

PLA	-	Polylactic Acid
PRBM	-	Pseudo-rigid-body model
R	-	Recommended
RF	-	Radio Frequency
SA	-	Simulated Annealing
RADAR	-	Radio Detection and Ranging
SAR	-	Search and Rescue
SCP	-	Shape Controllable Points
SLAM	-	Simulation Localization and Mapping
SMA	-	Shape Memory Alloy
SONAR	-	Sound Navigation And Ranging
TSD	-	Toroidal Skin Drive
UAV	-	Unmanned Aerial Vehicles
UGV	-	Unmanned Ground Vehicles
USAR	-	Urban Search and Rescue
USV	-	Unmanned Surface Vehicles
UUV	-	Unmanned Underwater Vehicles
UV	-	Unmanned Vehicles
VSOP	-	Virtual Structure for Orientation and Position

LIST OF SYMBOLS

A	-	Sine wave amplitude
Ae	-	Sine wave amplitude of even module
Ao	-	Sine wave amplitude of odd module
A_Φ	-	Sine wave amplitude of the yaw joint angle
d	-	Displacement between two contacting points
F	-	Friction force
f	-	Force acting on the link
F_{obst}	-	Front obstacle
Fx	-	Forces in x- direction
Fz	-	Forces in z- direction
$\bar{F}_\theta$	-	Friction force matrix
$\mathcal{F}_i^{nc}$	-	Non- conservative forces
$\mathcal{F}_{xh}$	-	Supporting force related to x_h
$\mathcal{F}_{zh}$	-	Supporting force related to z_h
$\mathcal{F}_{\theta j}$	-	Generalized force
$\mathcal{F}_\tau$	-	Generalized force related to absolute angle
g	-	Acceleration of gravity
$\bar{G}_\theta$	-	Potential energy matrix
h	-	Height of the step
h_x	-	Constraint force in x- direction
h_z	-	Constraint force in z- direction
I	-	Moment of inertia
K_e	-	Kinetic energy
K_n	-	Number of wave shape
l	-	Unit Length of robot link
L	-	Total length of snake robot
l_{avg}	-	The average body shape length
l_{bi}	-	Projection of l_{b0} on xz plane
l_{b0}	-	Length from the posterior end of the link to the axis of the yaw joint

L_{dis}	-	Linear distance
l_{fi}	-	Projection of l_{f0} on xz plane
l_{f0}	-	Length from the anterior end of the link to the axis of the yaw joint
l_{head}	-	Length of the robot's head
L_m	-	Length of i module
L_{obst}	-	Left obstacle
L_T	-	Total length of the body shape of the robot
m	-	Mass of Link
M	-	Mass matrix
$\bar{\mathcal{M}}$	-	Inertia matrix
n	-	Number of Links
N	-	Normal force
$\bar{N}_\theta$	-	Supporting force
P_c	-	Power consumption
P_{CM}	-	Position of the CM of the robot
P_x	-	Position of the robot's CM in x- direction
P_z	-	Position of the robot's CM in z- direction
q	-	General coordinate of the robot describe absolute joint angle
$\bar{q}$	-	General coordinate of the robot describe relative joint angle
r	-	Distance between the robot and obstacle
R	-	Real number
Rc	-	Critical distance
R_{obst}	-	Right obstacle
$\mathcal{R}$	-	Steering angle
$\mathcal{R}_e$	-	Steering angle of even module
$\mathcal{R}_o$	-	Steering angle of odd module
$\mathcal{R}_\Phi$	-	Steering angle of the yaw joint
s	-	Length along the body curve
t	-	Time
T	-	Time period
v	-	Velocity of each link
Ve	-	Potential energy

V_t	-	Velocity of the robot's CM
W	-	Total weight of robot
$\bar{W}$	-	Coriolis and centrifugal forces
X	-	Global coordinate of the CM robot in x- direction
X_F	-	Front obstacle distance along x- axis
x_h	-	Displacement of head of the robot in x- direction
x_i	-	Displacement of i-link in x- direction
X_L	-	Left obstacle distance along x- axis
X_R	-	Right obstacle distance along x- axis
Y_F	-	Front distance along y- axis
y_h	-	Displacement of head of the robot in y- direction
Y_L	-	Left obstacle distance along y- axis
Y_R	-	Right obstacle distance along y- axis
Z	-	Global coordinate of the CM robot in z- direction
z_h	-	Displacement of head of the robot in z- direction
z_i	-	Displacement of i-link in z- direction
ΔX	-	Transmission distance of the snake robot during one period cycle
α	-	Winding angle
α_d	-	The desired pitch joint angle against the step
β	-	Spatial frequency
β_Φ	-	Spatial frequency of the yaw joint angle
βe	-	Spatial frequency of even module
βo	-	Spatial frequency of odd module
δ	-	Phase shift
θ	-	Absolute joint Angle
$\bar{\theta}$	-	Orientation of the robot head
μ	-	Coefficient of friction
ρ	-	Curvature function
τ	-	Torque applied to robot joint
ψ	-	Pitch joint angle
ψ_h	-	Robot's head pitch joint
Ψ	-	Total absolute pitch joint of the robot

ω	-	Temporal frequency
ϕ	-	Relative joint angle
ϕ_{back}	-	Backward motion
ϕ_{front}	-	Frontward motion
ϕ_{left}	-	Leftward motion
ϕ_{ref}	-	Reference joint angle
ϕ_{right}	-	Rightward motion
Φ	-	Yaw joint angle
Φ_d	-	Desired yaw joint angle

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

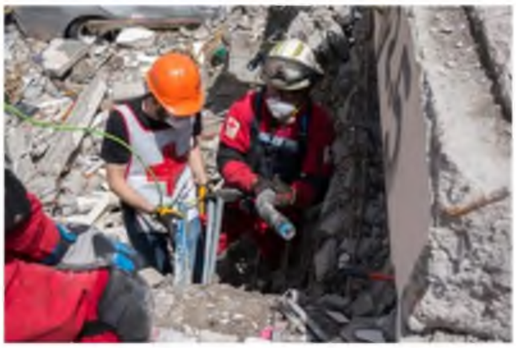
A collapsed building caused by an accident or disaster, such as an earthquake or flood, is considered a hazardous or challenging to access area, where rescuing survivors is considered difficult and dangerous (Tanaka, Kon and Tanaka, 2015; Whitman *et al.*, 2018). Time is crucial in the inspection and searching of the damage zone, especially if there are people buried alive and there is a need to locate them (Labenda, 2013). The mobile robot seems to be a suitable alternative to humans for rescue and search operation (Tanaka, Kon and Tanaka, 2015). However, rough and unregulated terrain is always challenging to the robot's maneuverability (Transeth, Pettersen and Liljeback, 2009). Such terrain may contain a wide range of obstacles, such as gaps, stones, walls, narrow passes, as well as stairs or high steps. Small-size hyper-redundant mobile robots that can adapt to a wide range of terrain are essential for what it can offer compared to traditional mobile robots (Hitaka and Yokomichi, 2013; Hopkins, Spranklin and Gupta, 2009; Manzoor, Khan and Ullah, 2019). This is because their slender, flexible, and slim cross sections enable them to navigate and travel through narrow spaces and tunnels (Liljeback *et al.*, 2010; Nakajima *et al.*, 2018; Qi *et al.*, 2020; Tanaka, Suzuki and Tanaka, 2018; Tanaka and Tanaka, 2016b; Transeth, Pettersen and Liljeback, 2009). The hyper-redundant structure repeated many times reduces joints failure because of its high modularity and redundancy (Hopkins, Spranklin and Gupta, 2009; Transeth, Pettersen and Liljeback, 2009). Hence, the robot continues to move even if one of its joints fails. The discrete and modular design makes the robot more stable due to its constant ground contact at various points, mostly when some parts are lifted during locomotion while the rest of the body is still on the ground (Fu and Li, 2020; Hongyan and Yuanbin, 2017; Hopkins, Spranklin and Gupta, 2009). They also have a low center of gravity. Conventional robots with legs or wheels may slip and ease to tip over (Yu S., 2008). The hyper-redundant mobile robot's large contact surface area helps achieve various postures, outstanding terrain adaption locomotion, and negotiate different types of obstacles (Ariizumi and Matsuno, 2017; Tanaka and Tanaka, 2016a; Tesch *et al.*, 2009).

The hyper-redundant discrete mobile robot is an articulated mobile robot that intends to mimic a biological snake's locomotion, where it moves by bending its body. On the other hand, it is smaller than other mobile robots used in a search detect mission because the joints are the only driving part of the mobile robot requiring the generation of propulsion force (Nakajima *et al.*, 2018). During the task, the robot's crawling motion may be disturbed by obstacles, which may prevent it from moving forward. The robot should have a high degree of perceptions and awareness of their environment to detect the obstacles and react to them by changing motion, either by avoiding or going over them. From this perspective, the environment perception, mapping, and representation are fundamental for the model (Sanfilippo, Stavdahl and Liljebäck, 2017). The snake robot should have a higher level of perception and autonomy with high adaptation to environmental changes. The perception-driven model system is not only capable of comprehending and understanding the current situation, but it can also make an extrapolation or projection of the actual information forward in time to determine how it will affect future states of the operational environment (Sanfilippo *et al.*, 2017). In order to increase the perception and awareness of the robot in the surrounding environment, geometric information should be collected. Starting from sensor data, the robot can represent the environmental model used for motion planning (Sanfilippo *et al.*, 2016b). The environmental model is then simulated and sent to the operator or to the gaudiness system to select the desired path between the ruins structure.

1.2 Possible Application of the Hyper-Redundant Mobile Robot

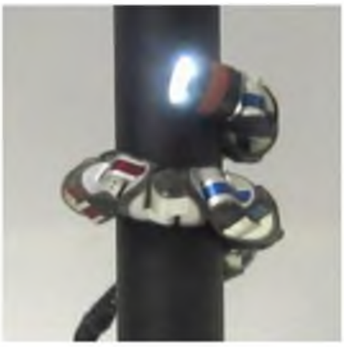
One of the hyper-redundant discrete mobile robot's significant applications is the urban search and rescue (USAR) (Nakajima *et al.*, 2018; Whitman *et al.*, 2018). During an accident or disaster in an urban area, where there are many debris and rubbles, the rescue and searching mission is challenging. In addition, the search environment may become hazardous for human rescuers because of the further collapse possibility of the rest of the building or the presence of toxic gas, radiation, dust, and ash (Tanaka, Suzuki and Tanaka, 2018). In such a situation where survivors may lie under the rubble, each minute is crucial, and the SAR time plays a significant role in saving lives. The rescuers need to collect information about survivors' localization, the disaster area's structure, and flammable gas or fire in the site.

Using a small and flexible mobile robot can offer a lot of help to the rescue crews in many ways. It can be equipped with a camera and other sensors to allow vision and sense of the surroundings and feedback to the rescuer with updated information about the site (Sanfilippo *et al.*, 2017). The hyper-redundant robot can travel in a small tunnel or between remote areas challenging for humans to get in. One example of a rescue mission application is the two snakes made by roboticist Howie Choset's research group at Carnegie Mellon University. They were sent to help in the Mexico earthquake, which struck the city on 19th September 2017, to search for survivors (Whitman *et al.*, 2018). Other robotic usage applications are for firefighting (Liljeback, Stavdahl and Beitnes, 2006), inspection and detecting pipes (Qi *et al.*, 2020), medical application of surgery operation (Zhang *et al.*, 2009), or for marine application underwater inspection (Kelasidi *et al.*, 2017). Figure 1.1 shows the possible application of a hyper-redundant mobile robot.



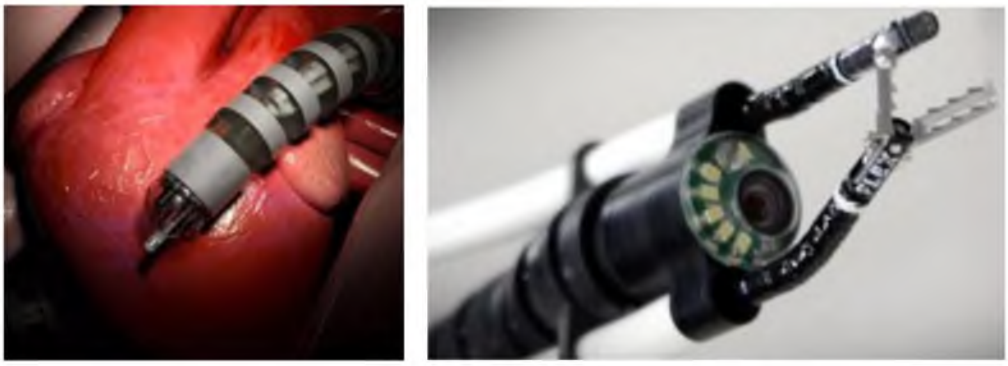
a) Rescue and detection at Mexico earthquake (Whitman *et al.*, 2018)

b) Anna Konda developed at NTNU for firefighting (Liljeback, Stavdahl and Beitnes, 2006)



c) Unified snake robot for pipe inspection which is developed by Howie Choset group at CMU's Biorobotics Lab (Rollinson, Buchan and Choset, 2012)

d) An amphibious snake-like ACM-R5 robot developed by Prof. Hirose (Hirose and Yamada, 2009)



e) Medrobotics developed by Dr. Howie Choset at Carnegie Mellon University (Mitchell, 2018)

Figure 1.1 Possible applications of the hyper-redundant mobile robot (a) Search and detect (b) Firefighting (c) Pipe inspection (d) Marine application (e) Medical application.

1.3 Problem Statement

Navigation in an unstructured terrain (the ground is uneven and contains obstacles of different size and shapes) is always considered a challenge in mobile robotic design and applications because of the size and complexity of this terrain (Labenda, 2013; Nishiwaki, Chestnutt and Kagami, 2012; Schwarz and Behnke, 2014; Zhang *et al.*, 2018). A hyper-redundant discrete mobile robot that resembles a biological snake with a flexible body and multi-degree of freedom seems to be the solution for this problem. However, there are issues in controlling the multi-degrees of freedom and enabling the robot to smoothly navigate different obstacles.

Based on the articles reviewed from the last 10 years (Fu and Li, 2020; Kon, Tanaka and Tanaka, 2015; Liljebäck *et al.*, 2010; Nakajima *et al.*, 2018; Pfotzer *et al.*, 2017; Sanfilippo *et al.*, 2016a, 2017; Tanaka, Kon and Tanaka, 2015; Tanaka, Suzuki and Tanaka, 2018; Tanaka and Tanaka, 2015; Wu and Ma, 2013; Yagnik, Ren and Liscano, 2010), the previous researches divided the problem of locomotion according to the type of obstacle into three sub-problems and tried to solve them separately by several techniques. This is performed either by avoiding (Pfotzer *et al.*, 2017; Tanaka, Kon and Tanaka, 2015; Wu and Ma, 2013; Yagnik, Ren and Liscano, 2010), overcoming (Fu and Li, 2020; Kon, Tanaka and Tanaka, 2015; Nakajima *et al.*, 2018; Tanaka, Suzuki and Tanaka, 2018; Tanaka and Tanaka, 2015), or by using push points by means of propulsion (Liljebäck *et al.*, 2010; Sanfilippo *et al.*, 2016a, 2017). Based on the Autonomy Level for Unmanned System (ALFUS) and Autonomy and Technology Readiness Assessment (ATRA) (Sanfilippo *et al.*, 2017), the current cutting edge technology cannot achieve smart navigation of the hypermobile robot in an unstructured environment without the operator's guidance. All the studies mentioned above used a low to medium level of autonomy with each type of obstacle's locomotion. The robot needs the operator to interfere in order to switch from one type of obstacle locomotion to another.

In real applications, the hyper-redundant discrete mobile robot should be able to negotiate different types of obstacles in the same operational space (Hopkins, Spranklin and Gupta, 2009). For robots to be able to operate autonomously and interact with the environment in any of the ways mentioned (obstacle avoidance, obstacle climbing, or obstacle-aided locomotion), they need to acquire information about the environment that can be used to plan their actions accordingly (Sanfilippo *et al.*, 2017). This task can be divided into three different challenges that need to be solved: sensing, mapping, and localization.

Therefore, the proposed research intends to increase the level of autonomy of the hyper-redundant mobile robot by presenting a perception-driven model constructed by generating local motion planning based on the sensory information. The development of such a robot is motivated by the fact that it can be used in detecting and search missions arising from some disaster in the rubble-strewn habitation environment, e.g., a collapsed building (Whitman *et al.*, 2018). This designed system should enable the robot to maneuver in an operational environment with obstacles by detecting the surrounding environment and using the sensory feedback data to draw the desired path and select the appropriate locomotion type necessary for robot propulsion. The designed system should also enable the robot to switch smoothly from one locomotion to another by using a transition algorithm. Additionally, modeling a hyper-redundant mobile robot with numerous contact points with the environment is a critical step towards enabling effective snake locomotion. Such a simulation model can facilitate the mechanical design of the robot and allow designers to examine the locomotion mechanism's effectiveness. Some works such as (Ariizumi and Matsuno, 2017) and (Chang and Vela, 2020) have proposed a model for snake-like locomotion modeling. However, the dynamical modeling of the snake locomotion capable of simulating the locomotion and studying the joint torque's performance is yet to be fully addressed in more detail.

1.4 Research Objectives

The objectives of the research are:

a) To design and build a hyper-redundant mobile robot that can perform locomotion in two planes: obstacle avoidance and obstacle climbing.

b) To establish a kinematic and dynamical model of traveling wave locomotion of the hyper-redundant mobile robot.

c) To propose an autonomous perception-driven hyper-redundant mobile robot model that enables the robot to navigate through an unstructured environment.

d) To develop a simulation model in verifying the dynamical model of the robot locomotion and validate it experimentally.

1.5 Scope of the Study

The scopes and limitation of this research are:

a) An artificial platform is used to test the navigation system of the hyper-redundant mobile robot.

b) The unstructured environment where the robot navigation system is tested is represented by modeled obstacles made of carton boxes of different sizes, crumpled papers, and imitation wall.

c) The robot has no wheels. Hence the friction force between the robot's body and the supporting plane is very high. To overcome the robot's motion resistance, traveling wave locomotion is chosen as the robot's desired motion pattern to crawl forward.

d) Matlab R2017b is used to operate the coded and simulated the dynamical model of traveling wave locomotion.

e) Low-level control of the servo motor is assumed to be accurate according to the manufacturing specification.

1.6 Contribution of the Study

The experiment research relates to applying a search and detect mission in an irregular and unstructured environment. The contribution of this research is to formulate a perception-driven hyper robotic locomotion model through increasing the mobile robot perception and awareness. This can be done by detecting the surrounding environment, optimizing the sensor feedback data, and selecting the desired path and desired locomotion. The locomotion is determined by the guidance system that can switch smoothly between three locomotions (obstacle avoidance, obstacle climbing, and traveling wave) in enhancing the robot navigation in unstructured terrain. The integrated system is an autonomous system where collision avoidance and climbing are generated automatically by the controller.

1.7 Thesis Outline

This thesis contains six chapters, including this chapter. In Chapter 2, there are two parts of the literature review. The first part presents different types of developed snake robots and their locomotion in an environment with and without obstacles. The second part presents the sensing technology and the scale of the snake robot's level of autonomy. It also identifies what has not yet been done and where the current snake robots' autonomy levels are set on.

Chapter 3 explains the methodology used to conduct the research. In this chapter, the research flowchart is illustrated at the beginning of the chapter, followed by describing the snake robot prototype structure used in the experiment. Modeling and simulation of the traveling wave locomotion along with the control system of the perception-driven model is described.

Chapter 4 presents the design and development of a hyper-redundant mobile robot for locomotion in an unstructured environment. The component used, along with the construction process of the robot modules, is described. This chapter also details the programs used to control the robot's actuation system and design the robot's head.

Chapter 5 presents the kinematic and dynamic model of traveling wave locomotion. The developing mathematical model is validated by simulation using Matlab software. The dynamic effects and detailed model of the friction between the robot and supporting plane are established, and the simulation results are discussed.

Chapter 6 proposes the developed control model of navigation snake robots in an environment with obstacles. In this chapter, the control approach outline, limitation, and procedure are presented in detail. To verify the validity of the control method, experiments were carried out.

Last but not least, Chapter 7 concludes the research findings. Recommendations and suggestions to advance the research work are stated in this chapter.

REFERENCES

Akbarzadeh, A., and Kalani, H. (2012). Design and modeling of a snake robot based on worm-like locomotion. Advanced Robotics, 26(5-6), 537-560.

Arai, M., Tanaka, Y., Hirose, S., Kuwahara, H., and Tsukui, S. (2008). Development of “Souryu-IV” and “Souryu-V:” Serially connected crawler vehicles for in-rubble searching operations. Journal of Field Robotics, 25(1-2), 31-65.

Ariizumi, R., and Matsuno, F. (2017). Dynamic Analysis of Three Snake Robot Gaits. IEEE TRANSACTIONS ON ROBOTICS, 33(5), 1-13.

Astley, H. C., Rieser, J. M., Kaba, A., Paez, V. M., Tomkinson, I., Mendelson, J. R., et al. (2020). Side-Impact Collision: Mechanics of Obstacle Negotiation in Sidewinding Snakes. Bioinspiration & Biomimetics, 15(16), 065005.

Asvadi, A., Premebida, C., Peixoto, P., and Nunes, U. (2016). 3D Lidar-based static and moving obstacle detection in driving environments: An approach based on voxels and multi-region ground planes. Robotics Autonomous Systems, 83, 299-311.

Bai, Y., and Hou, Y. (2017). Research of environmental modeling method of coal mine rescue snake robot based on information fusion. 2017 20th International Conference on Information Fusion (Fusion): IEEE, 1-8.

Barron-Zambrano, J. H., Torres-Huitzil, C., and Girau, B. (2015). Perception-driven adaptive CPG-based locomotion for hexapod robots. Neurocomputing, 170, 63-78.

Bayraktaroglu, Z. Y. (2009). Snake-like locomotion: Experimentations with a biologically inspired wheel-less snake robot. Mechanism Machine Theory, 44(3), 591-602.

Ben-Tzvi, P. Hybrid mobile robot system: Interchanging locomotion and manipulation. PhD Thesis, University of Toronto ,Toronto; 2008.

Borenstein, J., and Borrell, A. (2008). The OmniTread OT-4 serpentine robot. 2008 IEEE International Conference on Robotics and Automation: IEEE, 1766-1767.

Borenstein, J., Granosik, G., and Hansen, M. (2005). The OmniTread serpentine robot: design and field performance. Unmanned Ground Vehicle Technology VII: International Society for Optics and Photonics, 324-332.

Burdick, J. W., Radford, J., and Chirikjian, G. S. (1993). A'sidewinding'locomotion gait for hyper-redundant robots. [1993] Proceedings IEEE International Conference on Robotics and Automation: IEEE, 101-106.

Caglav, E., Erkmen, A. M., and Erkmen, I. (2007). A Snake-like Robot for Variable Friction Unstructured Terrains, Pushing Aside Debris in Clearing Passages .in Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2007), San Diego, CA, USA, 3685–3690.

Chang, A. H., Feng, S., Zhao, Y., Smith, J. S., and Vela, P. A. (2019). Autonomous, Monocular, Vision-Based Snake Robot Navigation and Traversal of Cluttered Environments using Rectilinear Gait Motion. arXiv preprint arXiv, 1-7.

Chang, A. H., and Vela, P. A. (2020). Shape-centric modeling for control of traveling wave rectilinear locomotion on snake-like robots. Robotics Autonomous Systems, 124, 103406.

Chang, K.-H., and Chen, Y.-Y. (2008). Efficiency on snake robot locomotion with constant and variable bending angles. 2008 IEEE Workshop on Advanced robotics and Its Social Impacts: IEEE, 1-5.

Chavan, P., Murugan 2, D., M., EV, V., U., Abhinavkumar Singh, A., Phadatare, P. (2015). Modular Snake Robot with Mapping and Navigation: Urban Search and Rescue (USAR) Robot. 2015 International Conference on Computing Communication Control and Automation, Pune, India, 537 - 541.

Chen, L., Wang, Y., Ma, S., and Li, B. (2003). Analysis of traveling wave locomotion of snake robot. IEEE International Conference on Robotics, Intelligent Systems and Signal Processing, 2003. Proceedings. 2003: IEEE, 365-369.

Chen, L., Wang, Y., Ma, S., and Li, B. (2004). Studies on lateral rolling locomotion of a snake robot. IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004: IEEE, 5070-5074.

Cheng, Z., Ren, G., and Zhang, Y. (2018). Ground Segmentation Algorithm Based on 3D Lidar Point Cloud. 2018 International Conference on Mechanical, Electrical, Electronic Engineering & Science (MEEES 2018): Atlantis Press, 16-21.

Chirikjian, G., and Burdick, J. (1995). The kinematics of hyper-redundant robot locomotion. IEEE Transactions on Robotics and Automation 11(6), 781–793.

Chirikjian, G. S. (2001). Design and analysis of some nonanthropomorphic, biologically inspired robots: An overview. Journal of Robotic Systems, 18(12), 701-713.

Chirikjian, G. S., and Burdick, J. W. (1994). A modal approach to hyper-redundant manipulator kinematics. IEEE Transactions on Robotics Automation, 10(3), 343-354.

Choi, H., and Ryew, S. (2002). Robotic system with active steering capability for internal inspection of urban gas pipelines. Mechatronics, 12(5), 713-736.

Danielsen, S. G. Perception-Driven Obstacle-Aided Locomotion for snake robots, linking virtual to real prototypes. MSc. Thesis, Norwegian University of Science and Technology; 2017.

Daudelin, J., Jing, G., Tosun, T., Yim, M., Kress-Gazit, H., and Campbell, M. (2018). An integrated system for perception-driven autonomy with modular robots. Science Robotics, 3(23), 1-9.

Enner, F., Rollinson, D., and Choset, H. (2013). Motion estimation of snake robots in straight pipes. 2013 IEEE International Conference on Robotics and Automation: IEEE, 5168-5173.

Fritsche, P., Kueppers, S., Briese, G., and Wagner, B. (2016). Radar and LiDAR Sensorfusion in Low Visibility Environments. Proceedings of the 13th International Conference on Informatics in Control, Automation and Robotics, 30-36.

Fu, Q., and Li, C. J. R. S. O. S. (2020). Robotic modelling of snake traversing large, smooth obstacles reveals stability benefits of body compliance. ROYAL SOCIETY OPEN SCIENCE, 7(2), 1-13.

Gawel, A., Lin, Y., Koutros, T., Siegwart, R., and Cadena, C. (2018). Aerial-Ground collaborative sensing: Third-Person view for teleoperation. 2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR): IEEE, 1-7.

Gong, C., Travers, M. J., Astley, H. C., Li, L., Mendelson, J. R., Goldman, D. I., et al. (2016). Kinematic gait synthesis for snake robots. The International Journal of Robotics Research, 35(1-3), 100-113.

Gonzalez-Gomez, J., Gonzalez-Quijano, J., Zhang, H., and Abderrahim, M. (2010). Toward the sense of touch in snake modular robots for search and rescue operations. In Proceedings of the ICRA 2010 Workshop “Modular Robots: State of the Art, Anchorage, AK, USA, 63–68.

Greenfield, A., Rizzi, A. A., and Choset, H. (2005). Dynamic ambiguities in frictional rigid-body systems with application to climbing via bracing. Proceedings of the 2005 IEEE International Conference on Robotics and Automation: IEEE, 1947-1952.

Hasanzadeh, S., and Tootoonchi, A. A. (2008). Obstacle avoidance of snake robot moving with a novel gait using two-level PID controller. 2008 IEEE Conference on Robotics, Automation and Mechatronics: IEEE, 427-432.

Hasnan, K., Bakhsh, Q., Ahmed, A., Das, B., and Ayub, S. (2015). A novel hybrid locomotion mechanism for small mobile robot. Indian Journal of Science and Technology, 8(17), 1-5.

Hirose, S. (1993). Biologically Inspired Robots: Serpentile Locomotors and Manipulators. Oxford university press.

Hirose, S., and Fukushima, E. F. (2002). Development of mobile robots for rescue operations. Advanced Robotics, 16(6), 509-512.

Hirose, S., and Yamada, H. (2009). Snake-like robots [tutorial]. IEEE Robotics Automation Magazine, 16, 88-98.

Hitaka, Y., and Yokomichi, M. (2013). Obstacle avoidance of a non-holonomic snake robot by tracking a desired gliding curve. 2013 IEEE International Conference on Mechatronics and Automation: IEEE, 463-468.

Hitaka, Y., Yoshitake, T., and Yokomichi, M. (2012). Obstacle avoidance of snake robot by switching control constraint. Artificial Life Robotics, 17(2), 180-185.

Hongyan, L., and Yuanbin, H. (2017). A Multi-objective Optimization Behavior Fusion Avoidance Method for Snake-like Rescue Robot. MATEC Web of Conferences: EDP Sciences, 00155.

Hopkins, J. K., Spranklin, B. W., and Gupta, S. K. (2009). A survey of snake-inspired robot designs. Bioinspiration & Biomimetics, 4(2), 1-19.

HOU, X., SHI, Y., LI, L., TIAN, Y., SU, Y., DING, T., et al. (2020). Revealing the Mechanical Characteristics via Kinematic Wave Model for Snake-Like Robot Executing Exploration of Lunar Craters. IEEE Acess, 8, 38368 - 38379.

Hu, J., Peng, A., Ou, Y., and Jiang, G. (2015). On study of a wheel-track transformation robot. 2015 IEEE International Conference on Robotics and Biomimetics (ROBIO): IEEE, 2460-2465.

Huang, H.-M., Pavek, K., Albus, J., and Messina, E. (2005). Autonomy levels for unmanned systems (ALFUS) framework: An update. Unmanned Ground Vehicle Technology VII: International Society for Optics and Photonics, 439-448.

Ito, K., Fukumori, Y., and Takayama, A. (2007). Autonomous control of real snake-like robot using reinforcement learning; abstraction of state-action space using properties of real world. 2007 3rd International Conference on Intelligent Sensors, Sensor Networks and Information: IEEE, 389-394.

Jia, Y., and Ma, S. (2020). A Bayesian-Based Controller for Snake Robot Locomotion in Unstructured Environments. 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Las Vegas, NV, USA.

Kamegawa, T., Akiyama, T., Sakai, S., Fujii, K., Une, K., Ou, E., et al. (2020). Development of a separable search-and-rescue robot composed of a mobile robot and a snake robot. Advanced Robotics, 34(2), 132-139.

Kano, T., Sato, T., Kobayashi, R., and Ishiguro, A. (2012). Local reflexive mechanisms essential for snakes' scaffold-based locomotion. Bioinspiration biomimetics, 7(4), 1-11.

Kawatsuma, S., Fukushima, M., and Okada, T. (2012). Emergency response by robots to Fukushima-Daiichi accident: summary and lessons learned. Industrial Robot: An International Journal, 39(5), 428 - 435.

Kelasidi, E., Liljebäck, P., Pettersen, K. Y., and Gravdahl, J. T. (2017). Integral line-of-sight guidance for path following control of underwater snake robots: Theory and experiments. IEEE Transactions on Robotics, 33(3), 610-628.

Kelasidi, E., Moe, S., Pettersen, K. Y., Kohl, A. M., Liljebäck, P., and Gravdahl, J. T. (2019). Path Following, Obstacle Detection and Obstacle Avoidance for Thrusted Underwater Snake Robots. Frontiers in Robotics and AI, 6(57), 1-15.

Kelasidi, E., and Tzes, A. (2012). Serpentine motion control of snake robots for curvature and heading based trajectory-parameterization. 2012 20th Mediterranean Conference on Control & Automation (MED): IEEE, 536-541.

Khan, M. R., and Billah, M. M. (2014). CPG-based control system for flexible snake robot locomotion. 2014 IEEE International Symposium on Robotics and Manufacturing Automation (ROMA): IEEE, 254-257.

Kim, D., Hong, H., Kim, H. S., and Kim, J. (2012). Optimal design and kinetic analysis of a stair-climbing mobile robot with rocker-bogie mechanism. Mechanism machine theory, 50, 90-108.

Kimura, H., and Hirose, S. (2002). Development of Genbu: Active wheel passive joint articulated mobile robot. IEEE/RSJ International Conference on Intelligent Robots and Systems: IEEE, 823-828.

Klaassen, B., and Paap, K. L. (1999). GMD-SNAKE2: a snake-like robot driven by wheels and a method for motion control. Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C): IEEE, 3014-3019.

Kon, K., Tanaka, M., and Tanaka, K. (2015). Mixed integer programming-based semiautonomous step climbing of a snake robot considering sensing strategy. IEEE Transactions on Control Systems Technology, 24(1), 252-264.

Krausz, N. E., and Hargrove, L. (2019). A survey of teleceptive sensing for wearable assistive robotic devices. Sensors, 19(23), 1-27.

Labenda, P. (2013, 25-28 Feb.). Safeguarding Trafficability of a Wheeled, Snake-like Reconnaissance Robot on Rough Terrain by a Shared Control System based on Fuzzy Logic. 2013 IEEE International Conference on Industrial Technology (ICIT), Cape Town, South Africa, 187 - 192.

Li, D., Pan, Z., and Deng, H. (2020). Two-dimensional obstacle avoidance control algorithm for snake-like robot in water based on immersed boundary-lattice Boltzmann method and improved artificial potential field method. Transactions of the Institute of Measurement Control, 42(10), 1-18.

Li, D., Pan, Z., Deng, H., and Peng, T. (2020). 2D Underwater Obstacle Avoidance Control Algorithm Based on IB-LBM and APF Method for a Multi-Joint Snake-Like Robot. Journal of Intelligent Robotic Systems, 98, 771–790.

Li, P., Sun, Y., Yang, Y., Li, C., Pu, H., Luo, J., et al. (2019). Design and Modeling an Elongatable Robotic Snake towards Augmented Serpentine Gait. 2019 IEEE 4th International Conference on Advanced Robotics and Mechatronics (ICARM): IEEE, 756-762.

Liljeback, P., Pettersen, K. Y., Stavdahl, Ø., and Gravdahl, J. T. (2010). Hybrid modelling and control of obstacle-aided snake robot locomotion. IEEE Transactions on Robotics, 26(5), 781-799.

Liljebäck, P., Pettersen, K. Y., Stavdahl, Ø., and Gravdahl, J. T. (2010). A hybrid model of obstacle-aided snake robot locomotion. 2010 IEEE International Conference on Robotics and Automation: IEEE, 675-682.

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), 29-40.

Liljeback, P., Stavdahl, O., and Beitnes, A. (2006). SnakeFighter-development of a water hydraulic fire fighting snake robot. 2006 9th International Conference on Control, Automation, Robotics and Vision: IEEE, 1-6.

Liljebäck, P., Stavdahl, Ø., and Pettersen, K. Y. (2005). Modular pneumatic snake robot 3D modelling, implementation and control. IFAC Proceedings Volumes, 38(1), 19-24.

Ma, S. (1999). Analysis of snake movement forms for realization of snake-like robots. Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C): IEEE, 3007-3013.

Ma, S., Li, W. J., and Wang, Y. (2001). A simulator to analyze creeping locomotion of a snake-like robot. Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No. 01CH37164): IEEE, 3656-3661.

Malayjerdi, M., and Akbarzadeh, A. (2019). Analytical modeling of a 3-D snake robot based on sidewinding locomotion. International Journal of Dynamics Control, 7(1), 83-93.

Maneewarn, T., and Maneechai, B. (2009). Design of pipe crawling gaits for a snake robot. 2008 IEEE International Conference on Robotics and Biomimetics: IEEE, 1-6.

Manzoor, S., and Choi, Y. (2016). Modular design of snake robot for various motions implementation. 2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI): IEEE, 211-213.

Manzoor, S., Khan, U., and Ullah, I. (2019). Serpentine and Rectilinear Motion Generation in Snake Robot Using Central Pattern Generator with Gait Transition. Iranian Journal of Science Technology, Transactions of Electrical Engineering, 44(3), 1093–1103.

Marvi, H., and Bridges, J. (2013). Snakes mimic earthworms: propulsion using rectilinear travelling waves. Journal of the Royal Society Interface, 10(84), 3067-3079.

Matsuno, F., and Sato, H. (2005). Trajectory tracking control of snake robots based on dynamic model. Proceedings of the 2005 IEEE International Conference on Robotics and Automation: IEEE, 3029-3034.

McKenna, J. C., Anhalt, D. J., Bronson, F. M., Brown, H. B., Schwerin, M., Shammas, E., et al. (2008). Toroidal skin drive for snake robot locomotion. 2008 IEEE International Conference on Robotics and Automation: IEEE, 1150-1155.

Mehta, V., Brennan, S., and Gandhi, F. (2008). Experimentally verified optimal serpentine gait and hyperredundancy of a rigid-link snake robot. IEEE Transactions on Robotics, 24(2), 348-360.

Mitchell, O. (2018). Snake Robots Slither Into Our Hearts, Literally (Publication., from Alley Watch: http://www.alleywatch.com/2017/07/snake-robots-slither-hearts-literally/

Mizutani, M., Maruyama, H., and Ito, K. (2012). Development of autonomous snake-like robot for use in rubble. 2012 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR): IEEE, 1-7.

Moattari, M., and Bagherzadeh, M. A. (2013). Flexible snake robot: Design and implementation. 2013 3rd Joint Conference of AI & Robotics and 5th RoboCup Iran Open International Symposium: IEEE, 1-5.

Mohammed, I. H., Gallardo, N., Benavidez, P., Jamshidi, M., and Champion, B. (2016). Design and control architecture of a 3D printed modular snake robot. 2016 World Automation Congress (WAC): IEEE, 1-6.

Muñoz-Bañón, M. Á., Candelas, F. A., and Torres, F. (2020). Targetless Camera-LiDAR Calibration in Unstructured Environments. IEEE Access, 8, 143692-143705.

Murai, R., Ito, K., and Nakamichi, K. (2008). Proposal of a snake-like rescue robot designed for ease of use-Improvement of operability for non-professional operator. 2008 34th Annual Conference of IEEE Industrial Electronics: IEEE, 1662-1667.

Nakajima, M., Tanaka, M., Tanaka, K., and Matsuno, F. (2018). Motion control of a snake robot moving between two non-parallel planes. Advanced Robotics, 32(10), 1-15.

Ning, M., Ma, Z., Chen, H., Cao, J., Zhu, C., Liu, Y., et al. (2018). Design and analysis for a multifunctional rescue robot with four-bar wheel-legged structure. Advances in Mechanical Engineering, 10(2), 1-14.

Nishiwaki, K., Chestnutt, J., and Kagami, S. J. T. I. J. o. R. R. (2012). Autonomous navigation of a humanoid robot over unknown rough terrain using a laser range sensor. The International Journal of Robotics Research, 31(11), 1251-1262.

Nor, N. M., and Ma, S. (2014a). CPG-based locomotion control of a snake-like robot for obstacle avoidance. 2014 IEEE International Conference on Robotics and Automation (ICRA): IEEE, 347-352.

Nor, N. M., and Ma, S. (2014b). A simplified CPGs network with phase oscillator model for locomotion control of a snake-like robot. Journal of Intelligent Robotic Systems, 75(1), 71-86.

Oliveira, M., Santos, V., Sappa, A. D., and Dias, P. (2016). Scene representations for autonomous driving: an approach based on polygonal primitives. Robot 2015: Second Iberian Robotics Conference: Springer, 503-515.

Ostrowski, J., and Burdick, J. (1996). Gait kinematics for a serpentine robot. Proceedings of IEEE International Conference on Robotics and Automation: IEEE, 1294-1299.

Ouyang, S., and Wei, W. (2020). Flexible Adaptive Control of Snake-Like Robot Based on LSTM and Gait. Journal of Physics: Conference Series, 1487(1), 1-8.

Parubochyi, V., and Shuwar, R. (2018). Fast self-quotient image method for lighting normalization based on modified Gaussian filter kernel. The Imaging Science Journal, 66(8), 471-478.

Patra, A., Patel, M., Chattopadhyay, P., Majumder, A., and Ghoshal, S. K. A Bio-inspired Climbing Robot: Dynamic Modelling and Prototype Development. In Recent Advances in Mechanical Engineering: Springer. 191-209. 2020.

Pendleton, S. D., Andersen, H., Du, X., Shen, X., Meghjani, M., Eng, Y. H., et al. (2017). Perception, planning, control, and coordination for autonomous vehicles. Machines, 5(1), 1-54.

Peng, A., Zhou, Y., Hu, J., and Ou, Y. (2014). Mechanical design for wheel/track transform mobile platform-search and rescue robot. 2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014): IEEE, 1787-1792.

Pettersen, K. Y. (2017). Snake robots. Annual Reviews in Control, 44, 19-44.

Pfotzer, L., Klemm, S., Rönnau, A., Zöllner, J. M., and Dillmann, R. (2017). Autonomous navigation for reconfigurable snake-like robots in challenging, unknown environments. Robotics Autonomous Systems, 89, 123-135.

Pfotzer, L., Staehler, M., Hermann, A., Rönnau, A., and Dillmann, R. (2015). KAIRO 3: Moving over stairs & unknown obstacles with reconfigurable snake-like robots. 2015 European Conference on Mobile Robots (ECMR): IEEE, 1-6.

Poi, G., Scarabeo, C., and Allotta, B. (1998). Traveling wave locomotion hyper-redundant mobile robot. Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No. 98CH36146): IEEE, 418-423.

Prautsch, P., and Mita, T. (1999). Control and analysis of the gait of snake robots. Proceedings of the 1999 IEEE International Conference on Control Applications (Cat. No. 99CH36328): IEEE, 502-507.

Qi, X., Shi, H., Pinto, T., and Tan, X. (2020). A Novel Pneumatic Soft Snake Robot Using Traveling-Wave Locomotion in Constrained Environments. IEEE Robotics Automation Letters, 5(2), 1610-1617.

Qiao, G., Wen, X., Song, G., Liu, D., and Wan, Q. (2016). Effects of the compliant intervertebral discs in the snake-like robots: A simulation study. 2016 IEEE International Conference on Robotics and Biomimetics (ROBIO): IEEE, 813-818.

Reddy, A. H., Kalyan, B., and Murthy, C. S. (2015). Mine Rescue Robot System – A Review. Procedia Earth and Planetary Science, 11, 457-462.

Rezapour, E., Pettersen, K. Y., Gravdahl, J. T., and Liljebäck, P. (2014). Body shape and orientation control for locomotion of biologically-inspired snake robots. 5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics: IEEE, 993-1000.

Riza, N. A., La Torre, J. P., and Amin, M. J. (2016). CAOS-CMOS camera. Optics express, 24(12), 13444-13458.

Rocha, C., Tonetto, C., and Dias, A. (2011). A comparison between the Denavit–Hartenberg and the screw-based methods used in kinematic modeling of robot manipulators. Robotics Computer-Integrated Manufacturing, 27(4), 723-728.

Rollinson, D., Bilgen, Y., Brown, B., Enner, F., Ford, S., Layton, C., et al. (2014). Design and architecture of a series elastic snake robot. 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems: IEEE, 4630-4636.

Rollinson, D., Buchan, A., and Choset, H. (2012). Virtual chassis for snake robots: Definition and applications. Advanced Robotics, 26(17), 2043-2064.

Rönnau, A., Heppner, G., Nowicki, M., and Dillmann, R. (2014). LAURON V: A versatile six-legged walking robot with advanced maneuverability. 2014 IEEE/ASME International Conference on Advanced Intelligent Mechatronics: IEEE, 82-87.

Ruangpayoongsak, N., Roth, H., and Chudoba, J. (2005). Mobile robots for search and rescue. IEEE International Safety, Security and Rescue Rototics, Workshop, 2005.: IEEE, 212-217.

Sack, D., and Burgard, W. (2014). A comparison of methods for line extraction from range data. In Proceedings of the 5th IFAC Symposium on Intelligent Autonomous Vehicles (IAV), Lisbon, Portugal, 5-7.

Sahu, D., Kodi, R., and Singh, S. (2019). Gait Analysis of Multi-Step Climbing Active Wheeled Snake Robot. 2019 4th International Conference on Robotics and Automation Engineering (ICRAE): IEEE, 18-23.

Sanfilippo, F., Azpiazu, J., Marafioti, G., Transeth, A. A., Stavdahl, Ø., and Liljebäck, P. (2016a). A review on perception-driven obstacle-aided locomotion for snake robots. 2016 14th International Conference on Control, Automation, Robotics and Vision (ICARCV): IEEE, 1-7.

Sanfilippo, F., Azpiazu, J., Marafioti, G., Transeth, A. A., Stavdahl, Ø., and Liljebäck, P. (2017). Perception-driven obstacle-aided locomotion for snake robots: the state of the art, challenges and possibilities. Applied Sciences, 7(4), 1-22.

Sanfilippo, F., Stavdahl, Ø., and Liljebäck, P. (2017). SnakeSIM: A ROS-based rapid-prototyping framework for perception-driven obstacle-aided locomotion of snake robots. 2017 IEEE International Conference on Robotics and Biomimetics (ROBIO): IEEE, 1226-1231.

Sanfilippo, F., Stavdahl, Ø., Marafioti, G., Transeth, A. A., and Liljebäck, P. (2016b). Virtual functional segmentation of snake robots for perception-driven obstacle-aided locomotion? 2016 IEEE International Conference on Robotics and Biomimetics (ROBIO): IEEE, 1845-1851.

Sato, M., Fukaya, M., and Iwasaki, T. (2002). Serpentine locomotion with robotic snakes. IEEE Control Systems Magazine, 22(1), 64-81.

Saudabayev, A., Kungozhin, F., Nurseitov, D., and Varol, H. A. (2015). Locomotion strategy selection for a hybrid mobile robot using time of flight depth sensor. Journal of Sensors, 2015, 1-14.

Schwarz, M., and Behnke, S. (2014). Local navigation in rough terrain using omnidirectional height. ISR/Robotik 2014; 41st International Symposium on Robotics: VDE, 1-6.

Selvarajan, A., Kumar, A., Sethu, D., and bin Ramlan, M. A. (2019). Design and Development of a Snake-Robot for Pipeline Inspection. 2019 IEEE Student Conference on Research and Development (SCOReD): IEEE, 237-242.

Shan, S., Gao, W., Cao, B., and Zhao, D. (2003). Illumination normalization for robust face recognition against varying lighting conditions. In Proceedings of the 2003 IEEE International SOI Conference. Proceedings, 157–164.

Shi, P., Shao, Q., and Liang, D. (2016). Design and improved serpentine curve locomotion control of a planar modular snake robot. 2016 IEEE International Conference on Information and Automation (ICIA): IEEE, 1398-1402.

Singh, A., Paigwar, A., Manchukanti, S. T., Saroya, M., Maurya, M., and Chiddarwar, S. (2017). Design and implementation of Omni-directional spherical modular snake robot (OSMOS). 2017 IEEE International Conference on Mechatronics (ICM): IEEE, 79-84.

Sitar, J., Hulmik, T., and Racek, V. (2010). Combined snake robot: Analysis and verification of designed structure. 19th International Workshop on Robotics in Alpe-Adria-Danube Region (RAAD 2010): IEEE, 237-240.

Taal, S., Yamada, H., and Hirose, S. (2009, 12–17 May). 3 axial force sensor for a semi-autonomous snake robot. In Proceedings of the IEEE International Conference on Robotics and Automation, (ICRA '09), Kobe, Japan, 4057–4062.

Tanaka, M., Kon, K., and Tanaka, K. (2015). Range-sensor-based semiautonomous whole-body collision avoidance of a snake robot. IEEE Transactions on Control Systems Technology, 23(5), 1927-1934.

Tanaka, M., and Matsuno, F. (2009). A study on sinus-lifting motion of a snake robot with switching constraints. 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, 2270–2275.

Tanaka, M., Suzuki, Y., and Tanaka, K. (2018). Development and Control of Articulated Mobile Robot for Climbing Steep Stairs. TRANSACTIONS ON MECHATRONICS, 23(2), 531-541.

Tanaka, M., and Tanaka, K. (2015). Control of a Snake Robot for Ascending and Descending Steps. IEEE TRANSACTIONS ON ROBOTICS, 31(2), 511-520.

Tanaka, M., and Tanaka, K. (2016a). Shape control of a snake robot with joint limit and self-collision avoidance. IEEE Transactions on Control Systems Technology, 25(4), 1441-1448.

Tanaka, M., and Tanaka, K. (2016b). Singularity analysis of a snake robot and an articulated mobile robot with unconstrained links. IEEE Transactions on Control Systems Technology, 24(6), 2070-2081.

Tesch, M., Lipkin, K., Brown, I., Hatton, R., Peck, A., Rembisz, J. M., et al. (2009). Parameterized and Scripted Gaits for Modular Snake Robots. Advanced Robotics, 23(9), 1131-1158.

Thrun, S. (2002). Probabilistic robotics. Communications of the ACM, 45(3), 52-57.

Tian, Y., Gomez, V., and Ma, S. (2015). Influence of two SLAM algorithms using serpentine locomotion in a featureless environment. 2015 IEEE International Conference on Robotics and Biomimetics (ROBIO): IEEE, 182-187.

Transeth, A. A., Leine, R. I., Glocker, C., and Pettersen, K. Y. (2006). Non-smooth 3D modeling of a snake robot with external obstacles. 2006 IEEE International Conference on Robotics and Biomimetics: IEEE, 1189-1196.

Transeth, A. A., Leine, R. I., Glocker, C., Pettersen, K. Y., and Liljebäck, P. (2008). Snake robot obstacle-aided locomotion: Modeling, simulations, and experiments. IEEE Transactions on Robotics, 24(1), 88-104.

Transeth, A. A., Liljeback, P., and Pettersen, K. Y. (2007). Snake robot obstacle aided locomotion: An experimental validation of a non-smooth modeling approach. 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems: IEEE, 2582-2589.

Transeth, A. A., Pettersen, K. Y., and Liljeback, P. (2009). A survey on snake robot modeling and locomotion. Robotica, 27, 999-1015.

Varlashin, V., and Shmakov, O. (2019). Comparative analysis of the virtual and physical experiments with a snake robot's rectilinear movement. Journal of Physics: Conference Series: IOP Publishing, 012037.

Wang, H., Liu, T., Xu, W., and Shenzhen, H. W. (2016). A snake-like robot composed of 2-DOFs modularized spherical-shape joints for space application. 2016 14th International Conference on Control, Automation, Robotics and Vision (ICARCV): IEEE, 1-6.

Wang, K., Xiao, C., and Ge, Y. (2014). Motion fusion of rectilinear and serpentine gait in snake robot. 2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014): IEEE, 562-567.

Wang, W., Sakurada, K., and Kawaguchi, N. (2016). Incremental and enhanced scanline-based segmentation method for surface reconstruction of sparse LiDAR data. Remote Sensing, 8(11), 1-22.

Wang, W., Wang, K., and Zhang, H. (2009). Crawling gait realization of the mini-modular climbing caterpillar robot. Progress in Natural Science, 19(12), 1821-1829.

Whitman, J., Zevallos, N., Travers, M., and Choset, H. (2018). Snake robot urban search after the 2017 mexico city earthquake. 2018 IEEE international symposium on safety, security, and rescue robotics (SSRR): IEEE, 1-6.

Wiriyacharoensunthorn, P., and Laowattana, S. (2002). Analysis and design of a multi-link mobile robot (serpentine). 2002 IEEE International Conference on Industrial Technology, 2002. IEEE ICIT'02.: IEEE, 694-699.

Wright, C., Buchan, A., Brown, B., Geist, J., Schwerin, M., Rollinson, D., et al. (2012). Design and architecture of the unified modular snake robot. 2012 IEEE International Conference on Robotics and Automation: IEEE, 4347-4354.

Wright, C., Johnson, A., Peck, A., McCord, Z., Naaktgeboren, A., Gianfortoni, P., et al. (2007). Design of a modular snake robot. 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems: IEEE, 2609-2614.

Wu, Q., Gao, J., Huang, C., Zhao, Z., Wang, C., Su, X., et al. (2012). Obstacle avoidance research of snake-like robot based on multi-sensor information fusion. 2012 IEEE International Conference on Robotics and Biomimetics (ROBIO): IEEE, 1040-1044.

Wu, X., and Ma, S. (2010). Head-navigated locomotion of a snake-like robot for its autonomous obstacle avoidance. 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems: IEEE, 401-406.

Wu, X., and Ma, S. (2011a, 6–8 June). Development of a sensor-driven snake-like robot SR-I. In Proceedings of the 2011 IEEE International Conference on Information and Automation (ICIA), Shenzhen, China, 157–162.

Wu, X., and Ma, S. (2011b). Sensor-driven neural controller for self-adaptive collision-free behavior of a snake-like robot. 2011 IEEE International Conference on Robotics and Automation: IEEE, 191-196.

Wu, X., and Ma, S. (2013). Neurally controlled steering for collision-free behavior of a snake robot. IEEE Transactions on Control Systems Technology, 21(6), 2443-2449.

Yagnik, D., Ren, J., and Liscano, R. (2010). Motion planning for multi-link robots using artificial potential fields and modified simulated annealing. Proceedings of 2010 IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications: IEEE, 421-427.

Yamada, H., and Hirose, S. (2006). Study on the 3D shape of active cord mechanism. Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.: IEEE, 2890-2895.

Yan, L., Yu, Q., Zhou, Z., Jiao, Z., Chen, C.-Y., and Chen, I.-M. (2015). Analysis of kinematics and dynamics of snake-like robot with joints of 4-DOF. 2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA): IEEE, 1899-1903.

Yaqub, S., Ali, A., Usman, M., Zuhaib, K. M., Khan, A. M., An, B., et al. (2019). A Spiral Curve Gait Design for a Modular Snake Robot Moving on a Pipe. International Journal of Control, Automation Systems, 17(10), 2565-2573.

Yu S., M. S., Li B.,Wang Y.,. (2008, Aug. 20-22). Locomotion Control and Gaits' Modality of a 3D Snake-like Robot. SICE Annual Conference 2008, Tokyo, Japan, 3026 - 3030.

Yue, Y., Yang, C., Zhang, J., Wen, M., Wu, Z., Zhang, H., et al. (2020). Day and night collaborative dynamic mapping in unstructured environment based on multimodal sensors. 2020 IEEE international conference on robotics and automation (ICRA): IEEE, 2981-2987.

Zhang, K., Niroui, F., Ficocelli, M., and Nejat, G. (2018). Robot navigation of environments with unknown rough terrain using deep reinforcement learning. 2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR): IEEE, 1-7.

Zhang, Y., Wei, B.-y., Wang, J., and Liu, Y.-f. (2009). Modularization design of a small snake robot for diagnosis and treatment. 2009 IEEE International Symposium on IT in Medicine & Education: IEEE, 1175-1180.

Zhao, X., Liu, C., Dou, L., Qiu, J., and Su, Z. (2019). 3D visual sensing technique based on focal stack for snake robotic applications. Results in Physics, 12, 1520-1528.

Zhen, W., Gong, C., and Choset, H. (2015). Modeling rolling gaits of a snake robot. 2015 IEEE International Conference on Robotics and Automation (ICRA): IEEE, 3741-3746.

Zhong, Y., Wang, S., Xie, S., Cao, Z., Jiang, K., and Yang, D. (2017). 3D scene reconstruction with sparse LiDAR data and monocular image in single frame. SAE International Journal of Passenger Cars-Electronic Electrical Systems, 11(1), 48-56.

LIST OF PUBLICATIONS

Indexed Conference Proceedings

1. **ABDULSHAHEED, A. G.**, HUSSEIN, M. B., DZAHIR, M. A. M. & SAAD, S. M. 2020a. Collision Free Behavior of Snake Robot Moving with Traveling Wave Gait. *International Conference on Researches in Science and Technology (ICRST-20).* Test Engineering and Management. http://www.testmagzine.biz/index.php/testmagzine/article/view/6756.

2. **ABDULSHAHEED, A. G.**, HUSSEIN, M. B., DZAHIR, M. A. M., SAAD, S. M. & OTHMAN, R. 2020b. A Review on Snake Robot Locomotion, Modelling, and Controlling in Challenging Environment. *3rd Asia International Multidisciplinary Conference 2019*. J Journal of Computational Theoretical Nanoscience. https://doi.org/10.1166/jctn.2020.8715.

3. **ABDULSHAHEED, A. G.**, HUSSEIN, M. B., DZAHIR, M. A. M., SAAD, HASHEM ANSAM A., R. 2020. Parameterized Study of Traveling Wave Locomotion of Snake Robot. *Postgraduate Symposium on Industrial Science and Technology 2020*.

4. **ABDULSHAHEED, A. G.**, HUSSEIN, M. B., DZAHIR, M. A. M., SAAD. Modeling and Analyzing of Traveling Wave Gait of Modular Snake Robot. *Innovative Manufacturing, Mechatronics & Materials Forum 2020 (iM3F 2020.*

Indexed Journal

1. Abdulshaheed, A. G., Hussein, M. B., Dzahir, M. A. M., and Saad, S. M. (2020). Obstacle-avoidance Locomotion of wheel-less Snake Robot Navigate in a Complex Environment. *Journal of Advanced Research in Dynamical and Control Systems, 12*(8), 256-267.