MULTI-OBJECTIVE OPTIMIZATION FOR EXPLORATION OF UNKNOWN TERRAIN IN COLLABORATIVE SNAKE ROBOT SYSTEM

BY

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ABSTRACT

Exploration of large areas, like borders of a country, forest and areas under collapsed buildings using a team of robots has been the aspiration of the scientists since long. On this context, mapping of unknown terrain is a challenging task, especially when the target area is inaccessible by human, where mobile robot is expected to play a role in performing this task. However, this kind of mapping task is difficult to be accomplished with the traditional robots with active wheels; since they may turn over or get stuck. Moreover, using a single robot to cover a big area is not a good option, since it will take longer time to complete that task. Therefore, this study proposed a multiple snake robot system for mapping task, where the snake features of these robots allow a smooth movement on uneven surface. In this research, a mathematical model of a snake robot has been developed by modifying an existing one. Based on that model, optimal motion control parameters, namely winding angle and acceleration, were obtained using genetic algorithm multi-objective optimization technique to achieve the fastest speed of the snake robot locomotion using minimum energy consumption. On the other hand, collision among moving robots may occur when they share the same area. Therefore, a collision avoidance algorithm was developed in this research to deal with all colliding cases. In this algorithm, an imaginary rectangular safety frame is defined to be surrounding the snake robot. The benefit of this frame is to secure enough space between the robots so that any collision will be will affect to the imaginary frames not the snake robots themselves. Furthermore, multi-coverage of the same area is a common phenomenon in exploration tasks, which leads to increasing the exploration time. Therefore, two methods were proposed in this research to reduce this multi-coverage, first, by optimizing the safety frame size, secondly, by selecting the proper turning angle for collision avoidance. On the experimental side, two identical snake robots have been designed and fabricated based on simulation results. Each snake robot consists of eight links, seven active servomotors and seven free passive joints to facilitate the snake robot movement over uneven surface. One pair of passive wheels is attached to each link to generate anisotropic friction, which allows the snake robot movement along its body curve in semi-sinusoidal pattern. Both snake robots are equipped with microcontrollers, data acquisition sensors and wireless modules to communicate with a central controller. A control algorithm was developed to drive the snake robot smoothly throughout the target area including turning right or left. Simulation results showed that the objectives of minimizing energy consumption and exploration time could be achieved by decreasing the winding angle (30° was found to be the optimal). Furthermore, a trade-off between *travelling speed* and *energy consumption* was obtained using *Pareto* optimality, where the *weighted sum method* could be used to select the best solution. With respect to collaboration, the results showed that using 2.1m as the optimal safety margin besides selecting a random turning angle for collision avoidance, noticeably reduced the exploration time and thus the total energy consumption. Finally, the simulation results were verified by experiments to show the validity of the proposed system in terms of minimizing the total *energy consumption* and the total time needed to complete the mapping task of unknown terrain.

خلاصة البحث

إنّ استكشاف المساحات الكبيرة، مثل حدود بلد ما، أو غابة، أو ما تحت المباني المنهارة، باستخدام فريق من الروبوتات، هو طموح العلماء منذ فترة طويلة. وفي هذا السياق، يُعدّ رسم الخرائط للأماكن ذات التضاريس غير المعروفة مهمة صعبة، خاصةً عندما يتعذر على الإنسان الوصول إلى المنطقة المستهدفة، حيث بالإمكان أن يلعب الروبوت المتحرك دوراً في أداء هذه المهمة. ومع ذلك، يصعب إنجاز هذا النوع من مهام رسم الخرائط باستخدام الروبوتات التقليدية ذات العجلات النشطة؛ لأنها قد تنقلب أو تتعثر. إضافة إلى ذلك، فإن استخدام روبوت واحد لتغطية مساحة كبيرة ليس خياراً جيداً، حيث يستغرق الأمر وقتاً أطول لإكمال هذه المهمة. لذلك، اقترحت هذه الدراسة نظام روبوتات ثعبانية متعددة لرسم الخرائط، حيث تسمح الميزات الثعبانية لهذه الروبوتات بحركة سلسة فوق الأسطح غير المستوية. في هذا البحث، تم تطوير نموذج رياضي للروبوت الثعباني من خلال تعديل نموذج آخر. بناءً على هذا النموذج، تم الحصول على المعاملات المثلى للتحكم في الحركة، وهما زاوية الالتواء، والتسارع الأولي، وذلك باستخدام تقنية التحسين التي تعتمد الخوارزمية الجينية (GA) متعددة الأهداف من أجل تحقيق أعلى سرعة للروبوت الثعباني باستخدام الحد الأدنى من استهلاك الطاقة. من ناحية أخرى، قد يحدث تصادم بين الروبوتات عندما تتحرك في نفس المنطقة. لذلك، تم في هذا البحث تطوير خوارزمية لتجنب الاصطدام للتعامل مع جميع حالات التصادم المتوقعة. في هذه الخوارزمية، تم تعريف إطار أمان مستطيل وهمي يحيط بالروبوت الثعباني، وتتمثل فائدة هذا الإطار في تأمين مسافة كافية بين الروبوتات فيحدث التصادم بين الإطارات الخيالية، وليس بين الروبوتات الثعبانية نفسها. إضافة إلى ذلك، تُعدّ التغطية المتعددة لنفس المنطقة ظاهرة شائعة في مهام الاستكشاف، مما يؤدي إلى زيادة الوقت اللازم لإتمامها. لذلك، اقتُرحَت طريقتان في هذا البحث لتقليل هذه التغطية المتعددة: الأولى، عن طريق الاختيار الأمثل لحجم إطار الأمان، والثانية، عن طريق اختيار زاوية الدوران الأنسب عند تجنب الاصطدام. أمّا من الناحية التطبيقية، فقد تم تصميم روبوتين ثعبانيين متطابقين وتصنيعهما بناءً على نتائج المحاكاة، ويتكون كل روبوت ثعباني من ثمانية أذرع، وسبعة محركات سيرفو نشطة، وسبعة مفاصل حرة لتسهيل حركة الروبوت الثعباني على الأسطح غير المستوية. وفي هذا التصميم، يتم إرفاق زوجين من العجلات حرة الحركة بكل ذراع لتوليد احتكاك متباين، مما يسمح بحركة الثعبان على طول منحنى جسمه في نمط شبه جيبي. وقد تم تجهيز كلا الروبوتين الثعبانيين بوحدات تحكم، وأجهزة استشعار لقراءة البيانات، ووحدات لاسلكية للتواصل مع وحدة التحكم المركزية. كما تم تطوير خوارزمية تحكم لقيادة الروبوت الثعباني بسلاسة في جميع أنحاء المنطقة المستهدفة، بما في ذلك الدوران يميناً ويساراً. وقد أظهرت نتائج المحاكاة أنه يمكن تحقيق هدفي تقليل استهلاك الطاقة وتقليل وقت الاستكشاف عن طريق تصغير زاوية الالتواء (حيث تبيّن أن الزاوية 30 درجة هي الأمثل). إضافة إلى ذلك، تم الحصول على مواءمة بين سرعة الحركة واستهلاك الطاقة باستخدام أمثلية باريتو، حيث يمكن استخدام طريقة المجموع الموزون لاختيار الحل الأفضل. أما فيما يتعلق بالتعاون بين الروبوتات، فقد أظهرت النتائج أن استخدام القيمة 2.1 متر كهامش أمان مثالي إلى جانب اختيار زاوية دوران عشوائية لتجنب الاصطدام، قلل بشكل ملحوظ من وقت الاستكشاف، وبالتالي إجمالي استهلاك الطاقة. أخيراً، تم التحقق من نتائج المحاكاة عن طريق التجارب لإظهار صلاحية النظام المقترح من حيث تقليل إجمالي استهلاك الطاقة، وتقليل الوقت الإجمالي اللازم لإكمال مهمة رسم الخرائط للمنطقة ذات التضاريس غير المعروفة.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigation, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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This thesis is dedicated to

my beloved wife and children

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LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
CAD	Computer-Aided Design
CPG	Central Pattern Generator
DOF	Degree Of Freedom
GA	Genetic Algorithm
GPS	Global Positioning System
ID	Identification
IMU	Inertial Measurement Unit
Lipo	lithium-ion polymer
LL	Lower Left
LR	Lower Right
m	Mass
MRS	Multi-Robot Systems
SAT	Separating Access Theorem
SLAM	Simultaneous Localization And Mapping
U	Utility
UL	Upper Left
UR	Upper Right
w	Weight
(x_H, y_H)	Coordinates of Head
(x_T, y_T)	Coordinates of Tail

LIST OF SYMBOLS

E_T	Total Energy
F_T , F_N	Tangential & Lateral friction force
L	Length of the body Snake robot
L_s	Length of a single link
P	Power
s	body length along the body curve
$\dot{s}$	Velocity along the body curve
$\ddot{s}$	Acceleration along the body curve
t	Time
v_T , v_N	Tangential & Lateral velocity
$\ddot{x}$	Acceleration along x-axis
$\ddot{y}$	Acceleration along y-axis
α	Winding angle
θ	Relative angle
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration
μ_t	Friction coefficient in forward direction
μ_n	Friction coefficient in lateral direction
ρ	Curvature function
τ	Torque
ϕ	Absolute angle

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Efficient exploration and mapping of unknown environments is a fundamental problem in mobile robotics. In many cases, there is a need to use robots instead of human to explore a certain area, like borders of country, forest and under collapsed buildings. To perform this task efficiently, a single robot is not a good option. Instead, the use of a team of robots is a good alternative.

The use of multiple robots is often suggested to have several advantages over single robot systems (Dudek et al., 1996). First, cooperating robots have the potential to accomplish a single task faster than a single robot. Furthermore, multiple robots can localize themselves more efficiently if they exchange information about their position whenever they sense each other (Fox et al., 2006). Finally, using several cheap robots introduces redundancy and expected to be more fault-tolerant than having only one powerful and expensive robot. However, the extension to multiple robots poses several new challenges, including localization of robots and collaboration between robots to exchange information and reduce overlap in mapping task (Tolmidis et al., 2013).

On the other hand, the use of traditional wheeled mobile robots in exploration and mapping of unknown environment is not a good option because of the uneven nature of the explored terrain. Alternatively, autonomous limbless robots, such as snake robot, have and advantage of over the traditional wheeled ones that they are able to move in difficult terrains without entanglement (Cao et al., 1997).

Snake robots are robotic mechanisms designed to move like biological snakes. The advantage of such mechanisms is their long and flexible body, which enables them to move and operate in challenging environments where human presence is unwanted or impossible. Future applications of these mechanisms include search and rescue operations, inspection and maintenance in industrial process plants, and subsea operations (Pettersen et al., 2013).

Moreover, using multi robots may require optimization of multiple conflicting criteria, such as the speed of a system and its energy efficiency. Often, it is tempting to simply consider a scalar combination of these criteria, e.g., to optimize a linear combination of speed and efficiency. However, such combinations limit the solution to a single point based on preferences implied by the aggregate function. In the multi-objective optimization, these multiple objectives are treated as independent unless the user has a clear preference between them (Tesch, et al., 2013).

In this research, a multi-objective optimization will be used to enhance the performance of multi snake robots in terms of time and energy. The main objective is to minimize the energy consumption and the overall time needed for the mapping task.

1.2 PROBLEM STATEMENT

Exploration of an open area like borders of a country or a forest is difficult due to uneven and cluttered terrain. Traditional wheeled robots are unable to maneuver in such environment, thus wheel-less robots like snake robots are better alternative. However, a single robot would require longer time to cover such big areas. There is no collaborative exploration research using snake robots available yet. Snake robots being robots that are capable of executing versatile motion with dynamic change of configuration depending on surrounding environments. However, without optimization of snake robot motion control parameters (winding angle and acceleration), such mapping program may lead to huge unmanageable data.

1.3 RESEARCH PHILOSOPHY

Mapping a large area of unknown environment is difficult using traditional system of robots with active wheels. Snake robots are a good alternative option since they have the advantages of absence of active wheels, flexible motion and multi degrees of freedom. The use of multi collaborative snake robots will minimize the time needed for mapping large areas. At the same time, using an optimization technique will reduce the total time, save energy, and minimize the overlap in mapping.

1.4 RESEARCH OBJECTIVES

The main objective of this research is to create a 3D map of an unknown terrain using multiple collaborative snake robots. To achieve the main objective the following sub-objectives have been set:

1) To optimize the motion control parameters of a snake robot moving in serpentine locomotion to obtain minimum *energy consumption* and minimum *travelling time* for the purpose of collaborative mapping of unknown terrain.
2) To develop control algorithms for multi-snake collaborative mapping of unknown terrain avoiding collision among the robots.
3) To validate the proposed mapping algorithms through simulation and experiments.

1.5 RESEARCH METHODOLOGY

This is an experimental research, which studies the influence of independent variables (such as winding angle and rotation speed) on the dependent variables (such as travelling time and energy consumption). The research methodology in this research starts with literature review of the recent research in collaborative robots, snake robots and optimization in robotics. The next step is the modeling of the snake robot, followed by GA optimization of the motion control parameters that can achieve the objective of minimizing *energy consumption* and the total time needed to complete the mapping task. In this methodology, a control algorithm is developed to guide the snake robots to cover the target area and avoid collision among the team members.

The mapping task starts with definition of the boundary of the target area as a virtual grid of nodes. Then, the motion control parameters of the snake robots are initialization with respect to the starting point, before the deploying the snake robots in the target area. Meanwhile, the equation of motion and collision detection algorithm are used to allow the snake robots to cover the target area. Furthermore, another algorithm is used to minimize the multi-covered area and consequently reducing data overlap.

For data collection, an IMU unit is proposed in this research to obtain the snake robot location and orientation with respect to the starting point. IMU is also used for obtaining the altitude along the z-axis, which is required for building the 3D map. On the other hand, a wireless transceiver is used for data exchange between the snake robots and the main controller.

Finally, the collected data is aggregated in the main controller to build a 3D map of the target area, and the proposed system is evaluated using simulation and experiment. Detail of the methodology is presented in *Chapter Three*. The flowchart of research process for this study is illustrated in Figure 1.1.

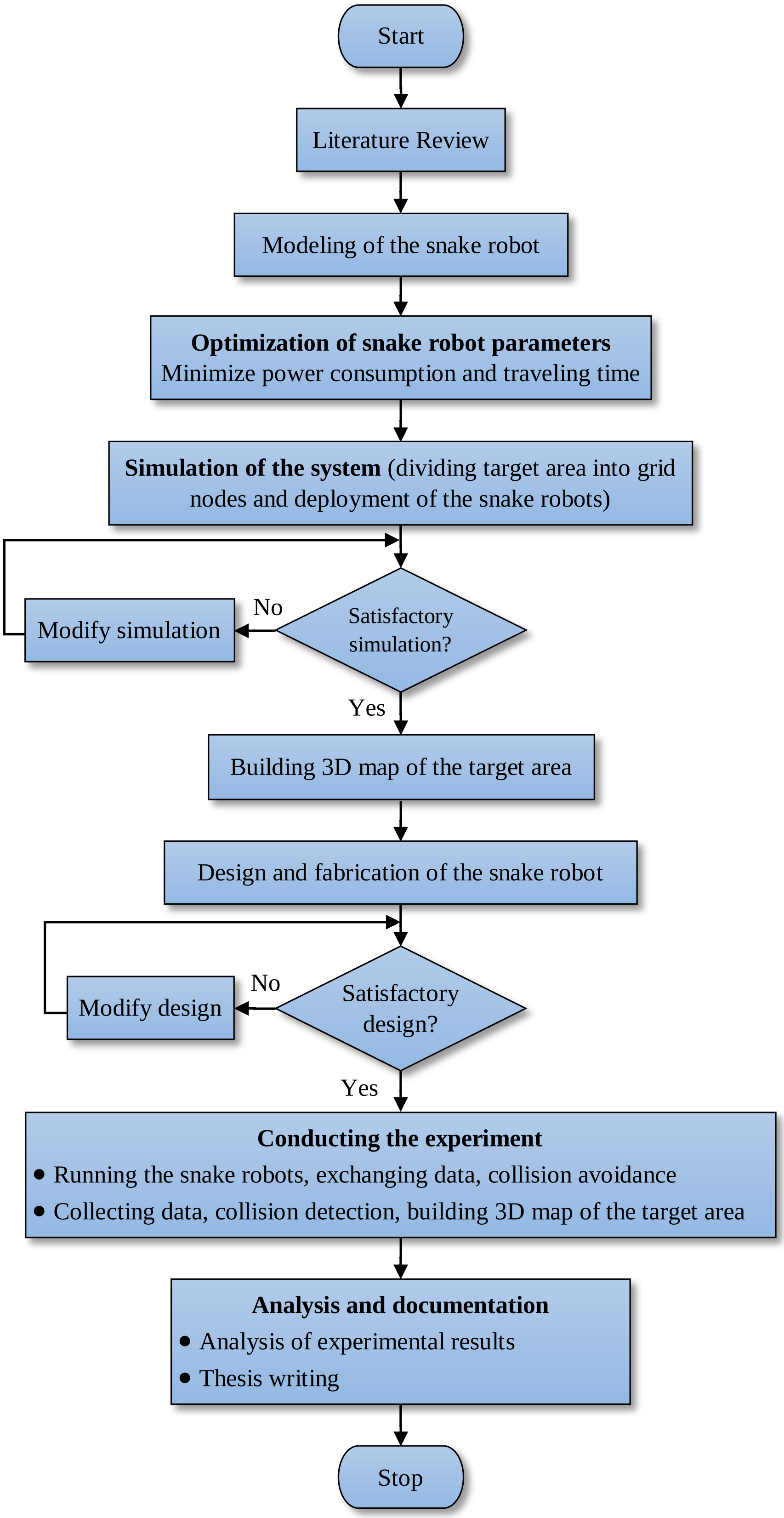

Figure 1.1 Flowchart of research process

1.6 RESEARCH SCOPE

The scope of this research can be described as follows:

The snake robot will use serpentine locomotion in which the joints of the snake robot will be actuated using servomotors, while uncontrolled joints will be used for pitch rotation about Y-axis. For simplicity, the boundary of the mapped area is predefined. In this research, an offline optimization technique is used, so that it is implemented before starting the system. Furthermore, an obstacle-free area is considered in this study except for the snake robots themselves, which represent dynamic obstacles, assuming that no communication disruption during the execution of the collaborative scheme. Finally, the research experiments will be applied to two identical snake robots.

1.7 THESIS ORGANIZATION

The introduction of this research, including problem statement, research objectives and research methodology, is presented in *Chapter One*, while the other chapters are organized as follows: *Chapter Two* contains the literature review of related work in multi-robot systems, snake robots, optimization in robotics and 3d mapping, followed by methodology description in *Chapter Three*. *Chapter Four* illustrates the modeling of the snake robot and optimization of its motion control parameters. Simulation of the proposed system is presented in details in *Chapter Five*, including deployment of the snake robots in the field, collision detection and avoidance, and plotting the 3d map of the target area. The design and fabrication of snake robot besides data collection and motion algorithm are illustrated in *Chapter Six*, followed by experimental validation of snake robot movement control and factors that affect energy consumption in *Chapter Seven*. Finally, the conclusion and recommendations of this research are presented in *Chapter Eight*.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Robotics and its applications represent one of the most interesting and widely studied fields in the last few decades, and it is still an open area of research. The fast and continuous development in the field of robotics led the researchers to study a wide variety of robots, starting from simple arm robot up to complex multi-robot systems. One of these robots that has an increasing interest in the recently studies is the snake robot. The uniqueness and special characteristics of the snake robots and their different applications led them to become a new field of interest. Therefore, this chapter focuses on this specific type of robots as discussed in the literature, starting from modelling reaching to optimization. The chapter also highlights the architecture of multi-robot system and its applications, such as task allocation and mapping collaboration. This chapter paves the way for detailed studying of the snake robot in terms of locomotion, optimization and collaboration in multi-robot system.

2.2 MULTI-ROBOT SYSTEMS (MRS)

Multi-robot systems are considered more useful than single or individual robots, due to the efficiency of task performance of multiple robots as compared to a single robot. Furthermore, multiple robots are more robust to failure, and may achieve tasks that cannot be done using a single robot, besides the advantage of reducing the task completion time. However, multiple robots may help making task achievement become possible, but not necessarily better (Gerkey et al., 2005).