UNIVERSITI PUTRA MALAYSIA

IMPROVED AUTONOMOUS CHARGING OF MOBILE MULTI-ROBOTS USING HONEYBEE-INSPIRED ALGORITHM

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By

FAISUL ARIF BIN AHMAD@MOHD YUSOFF

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

October 2016

DEDICATION

For my loving wife, Haslina Sanusi, mother and father, family who always give me the strength to finish this thesis. May ALLAH, the Almighty God give us all the blessings and strength to continue our work and our lives.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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October 2016

Chairman : Abd Rahman Bin Ramli, PhD
Institute : Advanced Technology

In recent years, the autonomous mobile multi-robot is popular to assist humans in work such as in the high-risk environment and during dangerous explorations. The energy of the mobile robot is supplied using the battery. The battery energy is decreasing during the mobile robot's operation. In order for the mobile robot to work continuously, an autonomous charging system has been developed by the researchers. In the multi-robot environment, various methods have been proposed to avoid the waste of energy when searching for the power station. Application of mobile multi-robot with group and intelligence bio-inspired classified as swarm mobile robot. It is also known as application that applies large number of mobile robot. However, in this thesis, the algorithm based on inspiration of the honeybee's behavior is improved to manage and improve energy utilization of the mobile multi-robot to emulate the working and foraging behavior. To accomplish this aim, the optimum energy for working and foraging based on the knowledge existence was implemented. Two main types of behavior were simulated in the working mobile robot (doing tasks) and foraging mobile robot (searching for the power station). In both types of behavior, the mobile robots move randomly waypoint. The inspired honeybee's behavior was designed based on the integration of knowledge of charging station, remaining energy and environment with static and dynamic obstacles. The knowledge of charging station location own by a mobile robot will be shared to other mobile robots. The dynamic threshold of remaining energy was activated when the mobile robot has knowledge of charging station. The improved honeybee inspired algorithm showed that the mobile robot could increase working time efficiency from 37% to 95%. Hence, the increase of energy utilization in the working behavior can increase the working behavior. This thesis has contributed to the efficiency of multiple mobile robots in energy consumption, increase the time and distance in carrying out the work.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENAMBAHBAIKAN DALAM PENGECASAN ROBOT MUDAH ALIH DENGAN MENGGUNAKAN ALGORITMA BERINSPIRASIKAN LEBAH MADU

Oleh

FAISUL ARIF BIN AHMAD@MOHD YUSOFF

Oktober 2016

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Penyelidikan pelbagai robot mudah alih adalah popular bertujuan bagi membantu manusia di dalam persekitaran pekerjaan yang berisiko tinggi dan semasa pengembaraan yang berbahaya. Tenaga robot mudah alih dibekalkan oleh bateri. Apabia robot mudah alih beroperasi, tenaga daripada bateri akan berkurangan. Aplikasi pengecasan robot mudah alih secara automasi telah dibina oleh penyelidik terdahulu untuk memastikan robot mudah alih sentiasa melakukan tugas tanpa henti. Dalam persekitaran robot mudah alih, system pengecasan telah dibina dan distrukturkan bagi mengelak pembaziran tenaga di dalam pencarian stesen kuasa. Penggunaan pelbagai robot mudah alih secara berkumpulan dengan kecerdikan yang diinspirasikan oleh kumpulan haiwan telah diklasifikasi sebagai “kawanan robot mudah alih”. Ia juga dikenal pasti sebagai aplikasi sistem yang menggunakan bilangan robot yang besar. Walau bagaimanapun, dalam tesis ini, algoritma berdasarkan inspirasi kelakuan lebah madu ini diperbaiki untuk mengurus dan meningkatkan penggunaan tenaga oleh robot mudah alih untuk mencontohi tingkah laku kerja dan mencari makan. Bagi mengawal perlakuan pelbagai robot mudah alih, beberapa kaedah digunakan untuk mengurus penggunaan tenaga kuasa supaya robot mudah alih menggunakannya secara berhemah. Algoritma yang berinspirasikan lebah madu di dalam applikasi ini bukan sahaja dibina bertujuan mengawal kelakuan robot mudah alih, ia juga dibina untuk mengurus dan memperbaiki penggunaan tenaga ketika melakukan pekerjaan dan juga pencarian. Bagi melaksanakan perkara tersebut, peng- gunaan tenaga secara optimum dibina berdasarkan simulasi robot mudah alih terkini. Penggunaan protokol robot bagi kerjasama kawanan robot juga mampu untuk memperbaiki penggunaan tenaga. Dua kelakuan utama robot dibahagikan kepada kerja (robot melakukan pekerjaan yang diamanahkan kepadanya) dan pencari (robot yang mencari stesen kuasa). Bagi kedua-dua perlakuan, robot mudah alih bergerak berdasarkan titik laluan rawak. Algoritma berinspirasi daripada lebah madu dibina berdasarkan intigrasi daripada pengetahuan (stesen kuasa), ambang baki tenaga, persekitaran yang memiliki objek pegun dan juga objek yang beralih. Pengetahuan adalah berdasarkan maklumat berkaitan dengan lokasi stesen

kuasa. Pengalaman robot mudah alih ketika melakukan kerja dan mencari stesen kuasa, mampu membantu robot mudah alih yang lain dengan perkongsian pengetahuan. Ambang mudah suai akan diaktifkan apabila robot mudah alih mengenal pasti unsur-unsur pengetahuan di dalam sistem mereka. Kelakuan ini bukan sahaja mengurangkan masa yang digunakan untuk mencari stesen kuasa, tetapi ia juga meningkatkan kuasa dan tenaga untuk melakukan kerja. Secara tidak langsung, robot mudah alih boleh melakukan kerja dengan lebih lama serta juga dapat menyiapkan dengan lebih cepat dari sistem biasa. Perbandingan antara algoritma yang ditambahbaik berinspirasikan lebah madu menunjukkan peningkatan di dalam kecekapan masa kerja sebanyak 37% hingga 95%. Oleh yang demikian, peningkatan penggunaan tenaga dalam tingkah laku kerja boleh meningkatkan tingkah laku yang bekerja. Tesis ini berjaya menyumbang kecekapan kepada pelbagai robot mudah alih didalam penggunaan tenaga, meningkatkan masa dan jarak didalam melaksanakan pekerjaan.

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I certify that a Thesis Examination Committee has met on 5 October 2016 to conduct the final examination of Faisul Arif bin Ahmad@Mohd Yusoff on his thesis entitled "Improved Autonomous Charging of Mobile Multi-Robots using Honeybee-Inspired Algorithm" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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Signature:	:________________________
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Name of Member of Supervisor Committee:	: Associate Professor Dr. Shaiful Jahari bin Hashim,

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LIST OF SYMBOLS

A	Point of location A
A_n	Point of location A at n-th position
B	Point of location B
D	Searching space
D_f	Foraging distance
D_w	Working distance
E_f	Foraging energy
E_w	Working energy
E^w	Position of end working
fi	Position *i*-th of foraging robot (*i*=0,1,2,…,n)
n_{ij}	Heuristic information from node *i* to node *j*
nw	Weight of the attraction to the previous best location of the particle neighborhood
P	Position/coordinate of power station
p_{ij}^{k}	Probability of ant *k* traverse from node *i* to *j*
$pBest_i$	Best position searched at *i* node
pw	The weight given the attraction to the previous best location
S^W	Position of start working
T_f	Foraging time
T_w	Working time
t_i	Time of *i-th* position
thr	Threshold
thr_S	Threshold static
thr_D	Threshold dynamic
$\kappa(j)$	Knowledge of mobile robot
Wi	Position *i*-th of working mobile robot (*i* = 0,1,…,n)
X_i	Position of the *i*-th particle
x_n	Coordinate-x
y_n	Coordinate-y
v	Velocity of mobile robot
w	Inertia coefficient
α	Corresponding weight

β	Corresponding weight
θ	Orientation angle
τ_{ij}	Intensity of pheromone trail from node i to node j

LIST OF ABBREVIATIONS

ACC	ant colony clustering
ACO	ant colony optimization
AMiR	autonomous miniature robot
ASCII	American Standard Code for Information Interchange
BCO	bee colony optimization
GAA	gradient-ascent algorithm
ID	identification
IHIA	Improved honeybee inspired algorithm
IR	Infrared
PSO	particle swarm optimization
PTZ camera	pan-tilt-zoom camera
TCP/IP	Transmission Control Protocol/Internet Protocol
UDP	User Datagram Protocol
VHS	virtual heading sensor

CHAPTER 1

INTRODUCTION

1.1 Introduction

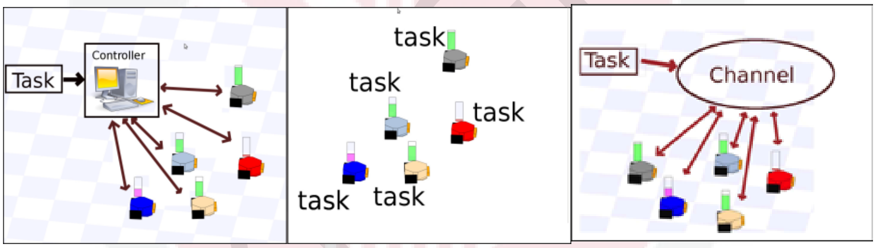
A robot is defined as a mechanical or virtual intelligent agent to do tasks with human guidance remotely and also autonomously [1]. Robots have been developed to assist humans in their work. The mobile robots are normally used for repetitive tasks such as (in factories) to handle large components (e.g. in car productions), and in dangerous or high-risk environments (e.g in nuclear plants). The term robot itself emerges from the word robota which is a word from Slav languages, meaning subordinate labor. It is used in the Czech play called “Rossum’s Universal Robot (R.U.R)” by Carel Capek in 1920 [2]. Previously, robots were designed to be used in the industrial environment. The robots that had been operating in the industries were static robots that were normally large in size, moved fast, and executed repetitive tasks in car manufacturing, electrical product manufacturing, and other industries.

In recent time, mobile multi-robots are becoming popular in the robot world. Small size, cheap, and simple mechanism are the advantages of the mobile multi-robots. The purpose of using mobile multi-robots is to replace the humans in the environment with high risk, hazardous, and repetitive tasks. One example of the application of mobile multi-robots in the logistic environment or warehouse is by using Kiva System [3]. In this system, 3 engineers with hundreds of mobile robots work in one warehouse.

Figure 1.1: Mobile multi-robots in automated warehouse operations [4].

Mobile multi-robots have been used to overcome the limitations of single mobile robots by increasing the performance of the tasks, such as reducing the processing time without reducing the utilization of work. The mobile multi-robot’s system is difficult to control in the dynamic environments. Interference among mobile robots increases when the number of mobile robots increases. The mobile robots should improve their processing time, energy, and distance in the navigation behavior. To control such a complex system that consists of a sub-agent (mobile robot), several control architectures have been used and tested by researchers. Lueth and Laengle [5] classify these control architectures into three groups: centralized system, decentralized system and distributed system.

The centralized system uses a mobile robot or a central command to control other mobile robots in the environment, as illustrated in Figure 1.2(a). Other mobile robots act as agents to receive and identify inputs from the environment and send them to the central commander. The central command then processes and decides on an action by sending back the processed commands to the robot agents. Next, the robots agents execute this action (behavior) based on the information from the central command. This type of system is normally applied in soccer robotics (see Figure 1.3(a)). The limitation of the system is that it can be applied only in the controlled environment and in-house environment because the mobile robots need to have fast processing and good environment in order to communicate with their central commands.



(a) (b) (c)

Figure 1.2: Architecture of mobile multi-robot control system by (a) centralized system (b) decentralized system, and (c) distributed system.

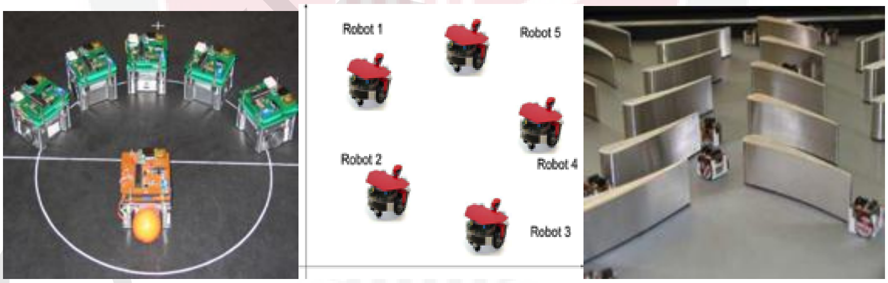
The decentralized system consists of sub-mobile robots (sub-agents) to decide on every decision by them based on inputs given by the agents. All the decisions and executions made by mobile robots are done by the agents (mobile robots) themselves (see Figure 1.2(b) and Figure 1.3(b)). The limitation of the system is that the agents are not able to communicate and share the information frequently as much as centralized system.

On the other hand, for the distributed system, each sub-agent (mobile robot) communicates and shares the information with other agents. The decision is based on the interchange of information through communication (see Figure 1.2(c)). The communication can take place either locally or globally, depending on the environment of operation. One example of the system that has performed is in the research boundary coverage of the blades in a jet turbine mock-up by Corell et al. [6] as shown in Figure 1.3(c).

The word *swarm robotics* refers to mobile multi-robots with a swarm intelligence system. Sometimes this term is used for small sized mobile robots with swarm intelligence. The swarm intelligence has similarities with decentralized and distributed system as a behavior system. This system has the capability to work individually and is also capable to cooperate with other systems without waiting command for their decision.

A swarm robot has been defined to be a group of mobile robots that own the special characteristics which are normally found in the swarm of insects [8]. The characteristics are simple and decentralized control, identical shape and a lack of synchronization. Another characteristic is the small physical size of the mobile robots. The physical size can become a disadvantage to the system, but sometimes the large number can give much advantage. A single mobile robot cannot achieve the target of work without the cooperation of other mobile robots. Currently, the properties of the swarm robotics system for mobile robots are [9]:

1. autonomous
2. large number of robots
3. homogeneous group of robots
4. relatively incapable or inefficient by their own
5. local sensing and communication skills



(a) (b) (c)

Figure 1.3: Environment of architecture system: (a) soccer robotic [7] for centralized system, (b) formation robot for decentralized system, and (c) sensor node [6] for distributed system.

Honeybee algorithm designed by Pham et al. [10] as a tool for complex optimization problems. The algorithm mimics the swarm honeybee in food foraging behavior. The two main types of behavior of the honeybee are working and foraging which have inspired into mobile multi-robots such as performing their task (mimic working behavior) and recharging the battery at power station (mimic foraging for the food). Autonomous mobile multi-robots need to execute and complete the tasks given to them. Meanwhile, the mobile robots also need to find the power stations to recharge their batteries.

1.2 Problem Statements

Applying the biologically inspired algorithm to the mobile multi-robots is one of the solutions to overcome the problems for autonomous mobile multi-robots relating to communication, path finding, and energy management. One of the limitations for mobile multi-robots is the lack of decision mechanism in the energy management system [11,12]. Previous researchers have designed and developed the biologically inspired system to manage the energy consumption of the mobile multi-robots [12,13]. The mobile multi-robots are divided into several groups in order to minimize the redundant tasks of these mobile robots. One of the previous works [12] has three types of mobile robots which are employed forager, unemployed forager onlooker, and unemployed forager scout. This research work applies the unemployed forager onlooker to get food sources. The scout mobile robots only take the information of the food sources. Dividing the group and assigning specific work for the mobile robots can reduce the working capability.

Liu et al. [11] presented a solution by dividing the mobile robots based on three behaviors: mobile robots that find food locations, mobile robots that face other mobile robots during the foraging of food, and the successful team mates for food retrieval. The limitation of this technique is that the mobile robots communicate only in home area, fail to find food after the time is up need to comeback to the resting place and wait for other mobile robots for the information of the locations of the power stations. This behavior definitely consumes and wastes much energy and time. This technique uses a static threshold from their battery energy in order to decide their behaviors. The technique can be improved by modify the threshold for foraging based on the mobile robot that already known the location (knowledge) of power station. This will improve the energy management in the working and foraging because it will reduce unused energy for next iterations.

Kernbach et al [13] used bio-inspired approach to increase the working efficiency in the group of swarm robot. The adoption of bio-inspired algorithms, which are defined as spontaneous and inertial behavior was a strategy to obtain a better collective performance in working time. The results from their experiment show that, the spontaneous behavior (36.88% of efficiency) is better than others (inert behavior with 19.66% and mix with 29.56%) in terms of working time efficiency. The adaptive roles (working, foraging, charging and resting) and the bio-inspired based on the working/recharging distribution were helping the improvement in energetic performances in time efficiency. The limitation of the algorithm is that adaptive decision on the roles (working, foraging, waiting and recharging) is based only the availability of power stations and the priority of the task. If the task is more priority the mobile robot keep performing that task even though its energy level fall to low level. Another disadvantage is the threshold of the foraging is decided based on random decision. The threshold should be designed based on the maximum energy that needed by mobile robot for each required area. For example, if mobile robot forages with random behavior, the distance of all area should be considered. If the mobile robot has the knowledge of the power station, the mobile robot only moves toward power station with straight line. The maximum energy that need by mobile robot for maximum distance in square area is the distance that measuring with diagonal line.

1.3 Objectives

This thesis aims to improve energy management performance of the mobile multi-robots for their working and foraging behavior to minimize unused energy in mobile robot. The behavior is inspired by the honeybee algorithm in order to improve autonomous charging. To achieve this aim, several objectives are formed as follow:

1. To improve the algorithm of honeybee inspired algorithm by modifying the decision to forage power station with two dynamic threshold of battery energy by using the maximum need of energy by mobile robot to move with maximum distance of each foraging area (without knowledge and with knowledge). The result improving the cost function of time, energy and distance in working behavior.
2. To implement the mobile robots with local communication for information sharing about the location of power stations as a knowledge to other mobile robots with simulation environment.
3. To analyze the efficiency of working energy and working time based on the proposed improved algorithm with result on algorithm by Kernbach et al. [13].

1.4 Research Scope

The scope of this thesis is to improve a honeybee inspired algorithm with dynamic decision for foraging behavior in the energy management of mobile multi-robots. The improved algorithm use information of the power station location to increase the performance of mobile robots, that is, the mobile robots can increase their working time before they charge their batteries. The availability of information of position power station (knowledge) is used to determine the foraging threshold, which is based on the mobile robots' remaining energy. The remaining energy is structured base on the maximum distance of running area by mobile robots with knowledge and without knowledge. A total of 10 units of mobile robots which also been used by [11-13] were used in the simulation using Player/Stage software. The number of mobile robots also needs to match the size of the working and foraging area or environment. The mobile robots used in this thesis were autonomous miniature robots (AMiR) [14]. AMiR is used, as it is locally developed and cheaper compared to other miniature mobile robot in order to implement the system in real mobile robots in future plan. The area of working and foraging 140 cm x 115 cm was used in this simulation is based on experiment by Kernbach et al. [13].

1.5 Contributions

The primary contributions of this thesis are as follow;

1. Develop the algorithm inspired by honeybees with improving the mobile robot's decisions by dynamic threshold on foraging behavior for energy management.
2. Dynamic thresholds of the remaining energy are defined by measuring the maximum needs of energy mobile robots to run in maximum distance for the specific distance of area (without knowledge and with knowledge).
3. Provide the information sharing for locations of the power stations through local communication by mimicking honeybees' communication. Information also include with identification of robot sender.

1.6 Organization of the Thesis

This thesis contains of 5 chapters. Chapter 1 introduces the mobile multi-robots, swarm intelligence and biologically inspired systems. It also highlights the research objectives, scope and contributions in this thesis. Next, Chapter 2 reviews the background of the mobile multi-robots and the biologically inspired systems that have been applied and operated in the previous works. Then Chapter 3 discusses the methodology of the proposed algorithms for mobile robots with their platforms. The results and discussions of the experimental algorithms are presented in Chapter 4. Finally, the conclusions and suggestions of the future works are explained in Chapter 5.

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