UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DESIGN AND DEVELOPMENT OF COOPERATIVE SIMULTANEOUS LOCALIZATION AND MAPPING INTEGRATED WITH NEURAL NETWORK FOR MOBILE ROBOT

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A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled “Design and Development of Cooperative Simultaneous Localization and Mapping Integrated with Neural Network for Mobile Robot” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Amirul Bin Jamaludin

Date: : 27 May 2024

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electronics Engineering.

Signature	:	....
Supervisor Name	:	Dr. Norhidayah Binti Mohamad Yatim
Date:	:	27 May 2024

DEDICATION

This thesis is dedicated to:

My beloved parents, Saripah Kassim and Jamaludin Sulaiman

My beloved siblings

and to all my family.

ABSTRACT

Autonomous cooperating mobile robots is one of technological advancement in enabling autonomy in search and rescue task (SaR). While, simultaneous localization and mapping (SLAM) algorithm is one of a key element to enable autonomous navigation. Many researchers chose to adopt high-end sensors to solve Cooperative SLAM or CSLAM. But this will cause staggering cost for multiple robot system. Thus, the alternative is to implement low-cost sensors with limited sensing to perform CSLAM. However, this approach introduces challenges such as inaccurate robots' sensors measurements and low accuracy cooperative mapping were reported. In this research, an Artificial Neural Network (ANN) is proposed to improve the accuracy of the CSLAM algorithm with low-cost sensors and is evaluated using real robots. Here, the selected methodologies are divided into three important stages to support three objectives defined to solve the stated problem statement. Firstly, the ANN configurations is established to reduce the nonlinearity error of the low-cost sensor measurements for building high accuracy environmental map. By training the ANN using sensor measurements, it learns to model the data and reduce the error or uncertainties present in the measurements obtained from the low-cost sensors. Secondly, a framework of CSLAM algorithm integrated with ANN using Rao-Blackwellized particle filter (RBPF) algorithm for single SLAM robot, and the map merging using random sample consensus (RANSAC) algorithm, is designed and developed. Lastly, the performance of the CSLAM algorithm with ANN is evaluated and validated using measurements from real robot platforms, and compared to that without ANN. From the real-world experiment, CSLAM with ANN has increased the performance of resulting maps by 61.09% compared to without ANN. It shows that, CSLAM integrated with ANN have improved the performance of CSLAM significantly. Moreover, CSLAM integrated with ANN have achieved 3 closed loop condition out of 10 trials for 600 particles compared to without ANN that does not achieve closed loop map out of 10 trials even though, the number of particles is increased. From the results, it can be concluded that the development of CSLAM algorithm integrated with ANN able to improve the performance of CSLAM for mobile robot using low-cost sensor.

REKABENTUK DAN PEMBANGUNAN KOPERATIF PENYETEMPATAN DAN PEMETAAN SERENTAK BERSEPADU DENGAN RANGKAIAN NEURAL BAGI ROBOT MUDAH ALIH

ABSTRAK

Robot-robot bergerak secara autonomi yang bekerjasama merupakan salah satu kemajuan teknologi dalam membolehkan autonomi dalam tugas mencari dan menyelamat (SaR). Sementara itu, algoritma penyetempatan dan pemetaan (SLAM) merupakan salah satu elemen utama untuk membolehkan navigasi autonomi. Banyak penyelidik memilih untuk mengadopsi sensor-sensor berkualiti tinggi untuk menyelesaikan Cooperative SLAM atau CSLAM. Namun, ini akan menyebabkan kos yang tinggi untuk sistem robot yang banyak. Oleh itu, alternatifnya adalah mengimplementasikan sensor-sensor berkos rendah dengan penerimaan yang terhad untuk melaksanakan CSLAM. Walau bagaimanapun, pendekatan ini membawa cabaran seperti pengukuran sensor robot yang tidak tepat dan pemetaan koperatif yang kurang tepat dilaporkan. Dalam penyelidikan ini, Jaringan Neural Tiruan (ANN) dicadangkan untuk meningkatkan ketepatan algoritma CSLAM dengan sensor berkos rendah dan dinilai menggunakan robot sebenar. Di sini, metodologi yang dipilih dibahagikan kepada tiga peringkat penting untuk menyokong tiga objektif yang ditakrifkan untuk menyelesaikan kenyataan masalah. Pertama, konfigurasi ANN dibina untuk mengurangkan ralat bukan linear pengukuran sensor berkos rendah untuk membina peta alam sekitar dengan ketepatan tinggi. Dengan melatih ANN pada data sensor, ia mempelajari untuk memodelkan dan mengurangkan ketidaklinearan yang hadir dalam pengukuran yang diperoleh daripada sensor berkos rendah. Kedua, rangkaian algoritma CSLAM yang terintegrasi dengan ANN menggunakan algoritma Rao-Blackwellized particle filter (RBPF) untuk robot SLAM tunggal, dan penggabungan peta menggunakan algoritma random sample consensus (RANSAC), direka dan dibangunkan. Akhirnya, prestasi algoritma CSLAM dengan ANN dinilai dan disahkan menggunakan pengukuran dari platfrom robot sebenar, dan dibandingkan dengan yang tanpa ANN. Dari eksperimen dunia nyata, CSLAM dengan ANN telah meningkatkan prestasi peta hasil sebanyak 61.09% berbanding tanpa ANN. Ini menunjukkan bahawa CSLAM yang terintegrasi dengan ANN telah meningkatkan prestasi CSLAM secara signifikan. Selain itu, CSLAM yang terintegrasi dengan ANN telah mencapai 3 keadaan litar tertutup daripada 10 percubaan untuk 600 partikel berbanding tanpa ANN yang tidak mencapai peta litar tertutup daripada 10 percubaan walaupun bilangan partikel telah ditingkatkan. Dari hasil ini, dapat disimpulkan bahawa pembangunan algoritma CSLAM yang terintegrasi dengan ANN dapat meningkatkan prestasi CSLAM untuk robot bergerak menggunakan sensor berkos rendah.

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LIST OF ABBREVIATIONS

SLAM	-	Simultaneous Localization and Mapping
CSLAM	-	Cooperative SLAM
MRSLAM	-	Multi-Robot SLAM
MRS	-	Multi-Robot System
SaR	-	Search and Rescue
RBPF	-	Rao-Blackwellized Particle Filter
OGM	-	Occupancy Grid Map
GPS	-	Global Positioning System
LiDAR	-	Light Detection and Ranging
LDS	-	Laser Distance Sensor
AGV	-	Automated Guided Vehicle
ANN	-	Artificial Neural Network
LM	-	Levenberg Marquardt
PF	-	Particle Filter
EIF	-	Extended Information Filter
SEIF	-	Sparse Extended Information Filter
KF	-	Kalman Filter
EKF	-	Extended Kalman filter
VSF	-	Variable Structure Filter
SVSF	-	Smooth Variable Structure Filter
HMM	-	Hidden Markov model
RFS	-	Random Finite Set
FBM	-	Feature Based Mapping
SIFT	-	Scale Invariant Feature Transform
SURF	-	Speeded Up Robust Features
MP-CSLAM	-	Median Of Local Posterior Probability CSLAM
TMP-CSLAM	-	Time-MP-CSLAM
RANSAC	-	Random Sample Consensus
MTM	-	Map Transformation Matrix
PGVD	-	Probabilistic Generalized Voronoi Diagram

ROS	-	Robot Operating System
WFD	-	Wave-front Frontier Detector
CTS	-	Cellular Transport System
Radish	-	Data Set Repository
MSE	-	Mean Squared Error
RMSE	-	Root Mean Squared Error
CHOPIN	-	Human and Robotoc Teams in Catastrophic Incidents
LRS	-	Laser Range Scanner
LRF	-	Laser Range Finder
ICC	-	Instantaneous Center of Curvature
SIR	-	Sampling Importance Filter
ORB	-	Oriented FAST and Rotated BRIEF
Rviz	-	ROS Visualizer
URDF	-	Unified Robot Description Format
GPU	-	Graphic Processing Unit
CPU	-	Central Processing Unit
FAST	-	Feature from Accelerated Segment Test
BRIEF	-	Binary Robust Independant Elementary Features

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis:

Jamaludin, A., Mohamad Yatim, N., Mohd Noh, Z., Buniyamin, N., 2023. Rao-Blackwellized Particle Filter Algorithm Integrated with Neural Network Sensor Model Using Laser Distance Sensor. *Micromachines*, 14(3), 560. Available at: https://doi.org/10.3390/mi14030560.

Jamaludin, A., Mohamad Yatim, N., Mohd Noh, 2023. The Effect of Artificial Neural Network Towards the Number of Particles of Rao-Blackwellized Particle Filter using Laser Distance Sensor. *International Journal of Advanced Computer Science and Applications(IJACSA)*, 14(1). Available at: http://doi.org/10.14569/IJACSA.2023.0140176.

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CHAPTER 1

INTRODUCTION

1.1 Background

These days the necessity to respond successfully to catastrophic and unanticipated incidents has increased, which include natural and civil crises, industrial accidents and acts of terrorism and crime. Present defense agencies face a lack of specialist dedicated resources, leading to the vulnerability of search and rescue (SaR) teams to the risk of human lives and less than ideal successful casualty aid within the civilian community (Couceiro, Portugal and Rocha, 2013). From this cause, robotics are designed and developed to enhance the safety of human rescue workers and potential victims, and to achieve faster, more accurate, and cost-effective responses in SaR applications in cooperation with human rescue teams (Kruijff et al., 2012). By taking advantage of the expendability of robotics, a team of mobile robots operating cooperatively will reduce human capital and increase productivity from human exhaustion during crisis operations. To survive and operate within its environments, an autonomous robot has to solve two crucial problems: mapping an unknown environment and locating its relative position within the map. These two common problems in robotics are known as simultaneous localization and mapping (SLAM).

SLAM plays an important role in robotics, and particularly in mobile robot systems. SLAM's primary objective is to jointly measure the robot's position as well as the surrounding map model (Alexandre, 2013; Saeedi et al., 2016; Wen et al., 2019; Ullah et al., 2020). For this purpose, Rao-Blackwellized particle filter (RBPF) algorithm and occupancy grid map (OGM) algorithm are proposed in this study for individual robot framework. However, in this study, the main purpose is to design and develop cooperative simultaneous localization and mapping (CSLAM) for mobile robot. While it is difficult enough to build single SLAM robot, moving to multiple robots adds another layer of difficulty. For CSLAM, the crucial part is the ability to collaborate in order to merge the maps produced by individual robots and it is the benchmark of the performance of the CSLAM. Robots must include all of the data available to build a coherent world map in a multiple robot environment while locating themselves within the global map. CSLAM has many advantages, including the ability to complete missions quicker and being resilient to the malfunction of any one of the robots. However, these advantages come at the expense of a complex system that necessarily involves robot teamwork and cooperation. Hence, the methods and algorithms to solve the cooperative robot's problem which is merging the map is studied and included in this work. Random Sample Consensus (RANSAC) algorithm for map merging is employed in this study to solve the crucial part of the CSLAM problem. This is due to the algorithm can be implemented in real-time applications and suitable for SaR applications since SaR need to achieve faster and real-time responses.

To achieve high accuracy of the mapping, many researchers chose to go for high-cost sensors to solve CSLAM (Bautin et al., 2013; Andre, Neuhold and Bettstetter, 2014; Li et al., 2014; Saeedi et al., 2014b; B et al., 2017; Demim, Nemra, et al., 2017; Seong, Lee and Kim, 2019; Martins, Portugal and Rocha, 2021). High-cost sensors typically require a greater financial investment as they possess advanced features, higher precision, and enhanced capabilities, but they also come with a higher price tag. Hence, this will cause staggering cost for multiple robot system. Thus, the alternative is to implement low-cost sensors with limited sensing to perform CSLAM. Low-cost sensors refer to sensors that are economically affordable and suitable for applications where cost is a significant consideration. These sensors are characterized by their relatively lower price point compared to high-end alternatives. However, this approach introduces challenges such as low accuracy of the sensors measurements and unstable cooperative mapping were reported (Waniek, Ieee and Biedermann, 2015). In addition, although RANSAC algorithm is reported to have fast computation time but the accuracy is lower than other method like Hough Transform and direct optimization method (Nasir, Hille and Roth, 2012; Iv, 2014; Bultmann et al., 2017). However, the other methods are not as fast as RANSAC to have real-time application, hence, RANSAC is chosen.

In this research, a CSLAM algorithm integrated with artificial neural network (ANN) is proposed and evaluated using both simulation and real robots. Within this framework, a sensor model is developed to interpret measurements and generate corrected readings using ANN. The aim is to improve sensor measurements, enhance map estimation accuracy and optimize the RANSAC algorithm for the map merging process. This finding will be beneficial in overcoming low-cost sensors limitation in order to enhance the capability of multi-robots' system with low-cost sensors.

1.2 Motivation

Robotics can contribute to enhance the safety of human rescue workers and potential victims, by achieving achieve faster, more accurate, and cost-effective responses in SaR applications. It is achieved through the use of mobile robotic agent teams in cooperation with human rescue teams (Kruijff et al., 2012). Through taking advantage of the expendability of robotics, a team of mobile robots operating cooperatively will reduce