# ANALYSIS AND IMPLEMENTATION OF 2D SLAM ALGORITHMS FOR INDOOR MOBILE ROBOTS

BY

IMAAD-UD-DIN MOTAN

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for the degree of Master of Science
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Kulliyah of Engineering
International Islamic University Malaysia

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# ABSTRACT

In this research a comparative analysis and implementation of Simultaneous Localization and Mapping (SLAM) algorithms for indoor mobile robots has been conducted, the purpose of which was to identify a possible area of improvement for future implementations. Robot are widely being used for daily tasks and as such require a technique to be able to easily navigate indoor environments, specifically small maps for helper robots, however simple methods such as dead reckoning and wireless beacons are unreliable. To resolve this problem a new method is being researched upon which is SLAM. SLAM algorithms which are commonly known, accepted by experts in robotics and are compatible with the Robot Operating System (ROS) have been selected for this study. They are GMapping, Hector SLAM and Karto SLAM. Each method is comparatively analysed with various parameters such as computational complexity which is a measure of how complex the algorithm is with respect to the amount of steps and calculations needed, Central Processing Unit (CPU) usage load which measures how much the processor is being used and scenario-based efficiency which takes into account the performance based on different scenarios such as different speeds, map sizes and obstacles. Additionally, the analysis and selection is based on validation techniques such as Corner Detection & Matching, K-Nearest Neighbours and Map Completeness conducted on simulated data. Based on the comparative analysis performed via MATLAB, Hector SLAM was found to be the most appropriate technique for indoor robots in small maps. This technique was implemented on the robot platform and real-world tests conducted. The chosen method i.e. Hector SLAM managed to successfully generate fully visible maps in small indoor locations with numerous features. However, maps with larger sizes or smoother features were not as efficient.

# خلاصة البحث

لقد تم في هذا البحث إجراء تحليل مقارن وتطبيق خوارزميات من التعريب والتخطيط المتزامنين (SLAM) للروبوتات المتنقلة في البيئة الداخلية، وكان الغرض منها هو تحديد مجال محتمل للتحسينات للتطبيقات المستقبلية. يتم استخدام الروبوت على نطاق واسع للأمور اليومية، وعلى هذا النحو يتطلب تقنيات؛ لتكون قادرة على التنقل بسهولة في البيئات الداخلية، وخاصة خرائط صغيرة للروبوتات المساعدة، ولكن أساليب بسيطة مثل أماكن وإشارات لاسلكية لا يمكن الوصول إليها، ولحل هذه المعضلة تم البحث عن طريقة جديدة وهي SLAM (مقبول ومعروف من قبل ابسطه تشغل الروبات، يتم تحليل كل طريقة نسبيا لمتغيرات SLAM وكارتو SLAM ، هيكتور GMapping الدارسة. مثل صعوبة الحسابات وهو مقياس لمدى صعوبة الخوارزمية بالنسبة إلى مقدار الخطوات والحسابات المطلوبة، حمل استخدام وحدة المعالجة المركزية. ويأخذ في الاعتبار الأداء بناءً على سيناريوهات مختلفة مثل السرعات المختلفة وأحجام الخريطة والعقبات. بالإضافة إلى ذلك، يعتمد التحليل والاختيار على تقنيات التحقق من خدمتها مثل كشف الزاوية. استنادًا إلى؛ ليكون أكثر التقنيات SLAM تم العثور على هيكتور MATLAB، التحليل المقارن الذي تم إجراؤه عبر ملاءمة للروبوتات الداخلية في الخرائط الصغيرة. تم تطبيق هذه التقنية على منصة الروبوت واختبارات العالم الحقيقي تمكنت من إنشاء خرائط مرئية بالكامل في مواقع داخلية Hector SLAM التي أجريت الطريقة المختارة، مثل صغيرة مع العديد من الميزات بنجاح. ومع ذلك فإن الخرائط ذات الأحجام الكبيرة أو الميزات الأكثر سلاسة لم تكن فعالة.

# APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a project paper for the degree of Master of Science (Mechatronics Engineering).

……………………………
Muhammad Mahbubur Rashid
Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a project paper for the degree of Master of Science (Mechatronics Engineering)

………………………….
Norsinnira Zainul Azlan
Internal Examiner

………………………….
Nadril Sulaiman
Internal Examiner

This project paper was submitted to the Department of Mechatronics Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechatronics Engineering)

……………………………
Syamsul Bahrin Abdul Hamid
Head, Department of
Mechatronics Engineering

This project paper was submitted to the Kulliyyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechatronics Engineering)

……………………………..
Ahmad Faris Ismail
Dean, Kulliyyah of Engineering

# DECLARATION

I hereby declare that this project paper is the result of my own investigations, 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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# LIST OF ABBREVIATIONS

| | |
|---|---|
| 1D | One Dimensional |
| 2D | Two Dimensioanl |
| 3D | Three Dimensional |
| AI | Artificial Intelligence |
| ARM | Advanced RISC Machines |
| AT | Attention |
| BLE | Bluetooth Low Energy |
| CCD | Charge-Coupled Device |
| CMOS | Complementary Metal-Oxide-Semiconductor |
| CPU | Central Processing Unit |
| DC | Direct Current |
| EC | Exteroceptive |
| EKF | Extended Kalman Filter |
| GN | Gauss-Newton |
| GPIO | General-Purpose Input/Output |
| GPS | Global Positioning System |
| HD | High Definition |
| HDMI | High-Definition Multimedia Interface |
| IDE | Integrated Devlopment Enviroment |
| IMU | Inertial Measurement Unit |
| I/O | Input/Output |
| IP | Internet Protocol |

| | |
|---|---|
| KF | Kalman Filter |
| KNN | K-Nearest Neighbor |
| LIDAR | Light Detection and Ranging |
| LM | Levenberg-Marquard |
| LRF | Laser Range Finder |
| MATLAB | Matrix Laboratory |
| OS | Operating System |
| PC | Proprioceptive |
| PF | Particle Filter |
| PWM | Pulse Width Modulation |
| RBPF | Rao Blackwellised Particle Filter |
| RF | Radio Frequency |
| ROS | Robot Operating System |
| RPM | Rotations per Minute |
| RSSI | Received Signal Strength Indicator |
| RVIZ | ROS visualization |
| RWD | Rear Wheel Drive |
| SD | Secure Digital |
| SIFT | Scale Invariant Feature Transform |
| SSH | Secure Shell |
| SURF | Speeded up Robust Features |
| TCP | Transmission Control Protocol |
| USB | Universal Serial Bus |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $k$ | moment in time | s |
| $X_{(0:t)}$ | robot pose across time | Dimensionless |
| m | map of the environment | Dimensionless |
| $Z_{(1:t)}$ | number of observations across time | Dimensionless |
| $U_{(1:t)}$ | control commands of robot per time | Dimensionless |
| $x_k$ | x axis position | m |
| $y_k$ | y axis position | m |
| $v$ | velocity | m/s |
| $w$ | angular velocity | rad/s |
| $\Theta$ | orientation | degrees (°) |
| $d$ | euclidiean distance | cm |
| $e$ | error deviation | cm |

# CHAPTER ONE

# INTRODUCTION

## 1.1 OVERVIEW

Progress in technological development usually comes about when there is a demand, need or desire to make life simpler and easier than it currently is. One of the most common requirements is a robot which can complete tasks that are menial and time consuming. To cater to these demands mobile robots are developed and equipped with various components and sensors which allow them to work as required.

A mobile robot is an automatic machine that is capable of locomotion. These robots would normally have to move around in indoor environments, and to accomplish this a system is needed which would allow the robot to understand its position/location inside an indoor environment. It is important for a robot to know where it is in any environment so that it can successfully execute its assigned task.

GPS coordinates can easily be used to track the location of a robot while operating in outdoor environments, however within indoor locations GPS signals aren't very accurate, thus a need for indoor localization and mapping techniques. To navigate reliably within indoor environments, a mobile robot must know where it is and where it needs to move. Thus, reliable position estimation is a key problem in mobile robotics, as location information is essential for planning and decision-making processes. Numerous approaches to localization and mapping have been researched; including using laser scanners, vision and wireless strength. These techniques will be discussed next along with their advantages and disadvantages. Additionally, an optimal solution for the SLAM problem will be proposed. Whereby a mobile robot may reliably map its environment and perform accurate localisation and pose estimates. This will take the form of Hector SLAM using ROS where a Laser Distance Scanner will be used to map the environment.

Since indoor mobile robots are now being used in a multitude of tasks, ranging from simple vacuum robots to assistant robots, the problem being faced is to accurately navigate in such environments. A large variety of techniques have been employed for this purpose. Some of the techniques which are being used for indoor localization are RSSI measurements, Odometery, Dead Reckoning, Ultra sonic positioning, Visual tracking etc. These techniques are discussed in a later section.

## 1.2 MOTIVATION

The motivation behind doing this lies in the fact that mobile robots are increasingly becoming an important device in our daily lives. During my undergraduate years I was working on an assistant robot for disabled people described by (Younas, Akbar, Motan, Ali, & Atif, 2017). The biggest problem that I faced was that of localisation and navigation in an indoor unknown environment. The robot that I built, used a line following algorithm and could only follow marked paths and in case of any unknown variables, the robot would not even be able to complete this task. Another problem was that the start and end point of the robot had to be fixed with markers to identify its position and orientation. This became a huge challenge if the robot had to change its route while traversing the path. During this transition period, the robot could not determine how far it was from the goal and at what trajectory would it reach the goal in the shortest time possible. I realised that this was a highly inefficient method for an indoor mobile robot. If a robot was to be used for disabled people as an assistant, then I needed to devise or implement a technique which would reduce the time a robot would take to localise itself and map its environment, so it could efficiently reach its goals effectively. After conducting some further research work and studies it was concluded that SLAM Algorithms are best suited for the desired task. This motivation forms the crux of my postgraduate research, which focuses on analysing SLAM methods and applying various validation techniques to determine a highly effective Algorithm. In addition to the above my research also involves identifying areas of improvement for the selected Algorithm to make it more efficient and reliable.

## 1.3 PROBLEM STATEMENT

This section covers the issues faced with the individual sensor systems in robot localization. Localization and mapping techniques relying on simple sensor systems, face issues such as sensor drift, signal propagation interference, excessive processing power and time delays. Thus, a system or algorithm is required which is free of these issues or at the very least minimizes them as much as possible. Such a system should consist of a number of different sensors, and an algorithm which allows them to complement and support each other. A possible proposed system would be using sensor fusion along with ROS to combine two different sensors to get a reliable and detailed map as well as location and pose estimates by employing a SLAM technique.

## 1.4 OBJECTIVES

- To comparatively analyse the SLAM techniques based on performance parameters.
- To select and implement a SLAM algorithm which meets the following criteria:
    - good performance in small indoor maps with <5% error in measurements
    - low hardware requirements

    - Simple and less CPU intensive.
- To design and build a mobile robot capable of moving in indoor locations.
- To generate indoor maps which can be used for future path planning on any platform.

## 1.5 RESEARCH METHODOLOGY

In this paper the following methodology has been used. First various techniques on the localisation and mapping of robots will be discussed along with their flaws and shortcomings. Next improved techniques based on Sensor Fusion will be explained, these will include a few results from some of the fusion algorithms. The next step is designing a robot to be used for indoor SLAM this section will also include an analysis of difference indoor SLAM algorithms. After analysing each algorithm along with its mathematical model, the hardware and software components are discussed. To determine how the robot will perform, a simulation technique will be discussed, and the simulated results will be validated using two different methods which will provide us with a good estimate of the algorithms efficiency. This step will allow us to select which algorithm is suitable and can be implemented on the robot. The robot will be tested in four ways this will allow us to determine its performance in different scenarios and finally the project will be concluded by defining redefining the objectives and discussing future work for the algorithm improvement. These steps are summarised in the flowchart in Figure 1.1

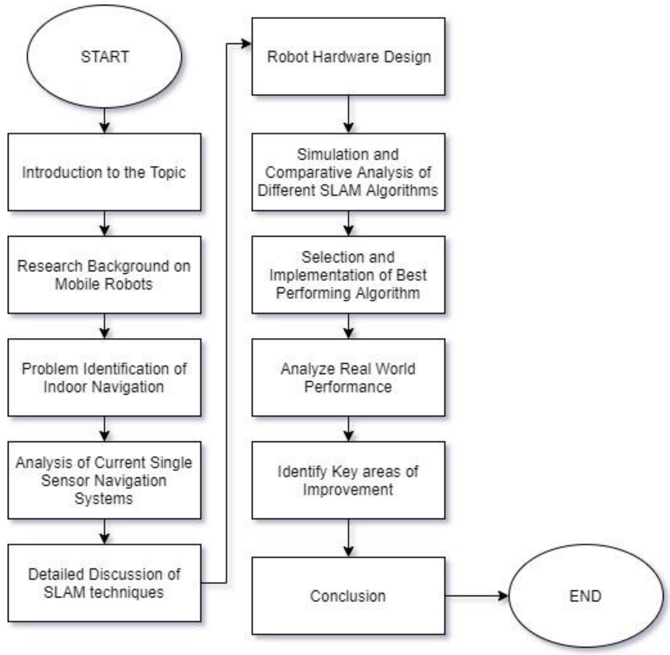

Figure 1.1 Research Methodology Flowchart

## 1.6 STRUCTURE OF THESIS

This study proposes a SLAM algorithm for indoor mobile robot localisation and mapping.

Chapter 1 is an introduction to the work being carried out. Here the need for this work is detailed by describing the issues faced with simple conventional methods. This provides a solid background by describing the problem statement and objectives for this work.

Chapter 2 presents the literature review of Indoor SLAM for mobile robots including sensor fusion techniques as well as SLAM Algorithms. Also, a strong review of current relevant research in recent years is also presented

Chapter 3 focuses on the proposed algorithms with a detailed analysis. Also, a methodology for designing the robot and implementing the proposed algorithm is discussed along with the process flow of data as well as the parameters and hardware.

Chapter 4 gives a detailed method for performing the simulations along with a validation technique with an analysis and discussion on the best suited algorithm

Chapter 5 has an in-depth review of how the real-world experiment is set up. It then shows the results in different scenarios to compare it to the simulation results. After which a short discussion follows where the results are analysed

Chapter 6 concludes this project by highlighting the outcome of this research. This chapter also discusses the limitation of this work by giving recommendation for future work.

## 1.7 SUMMARY

In this chapter the background of the study has been discussed. It explained why localization and mapping are vital to indoor mobile robots, additionally, the problem statement was discussed. This study was conducted to analyse methods by which a robot can simultaneously locate itself and map its environment in the most efficient manner. This chapter also presented the research objectives and the methodology which was followed.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 MOBILE ROBOTS

### 2.1.1 Background

Recent developments in robotics have seen success in industrialised applications for example, the robot arm can perform monotonous tasks in a factory move with high levels of precision and accuracy to. However, these robots face a disadvantage in the mobility aspect. A stationary manipulator has a restricted range and can't perform any action beyond its working area. "In comparison, a mobile robot would be able to navigate all over the factory, adaptably applying its abilities wherever it is most effective." (Siegwart & Nourbakhsh, 2004). Mobile robots can travel everywhere in a physical location. Mobile robots are commonly controlled by software and use sensors and other equipment to detect their surroundings. They make use of Artificial Intelligence along with robotic principles which permits them to traverse their environments.

### 2.1.2 Types of mobile robots

The 2 basic kinds of robots are Legged and Wheeled robots. (Ghassaei, Choi, & Whitaker, 2011) describe walking robots as "those which mimic human or animal motion, as a replacement for wheeled motion." Legged motion makes it possible to negotiate irregular surfaces, steps, and other regions which are beyond the capabilities of wheeled motion. Figure 2.1 shows a four-legged robot as an example.

Figure 2.1 Four Legged Robot

Wheeled robots are those that travel on the ground using a combination of wheels. This design is commonly favoured since it is simpler than legged designs, additionally the manufacturing and programming for such robots is easier. Another plus point of wheeled robots is that they are easier to manoeuvre than other robot types. These robots can be categorised into 2 categories; Holonomic and Non-Holonomic.

**Nonholonomic**

Nonholonomic types as defined by (Lynch & Park, 2017) "are governed by the type of wheels they utilise. Nonholonomic mobile robots employ standard wheels, like those on a car: the wheel rotates about an axis aligned perpendicular to the plane of the robot and it can be steered by rotating it about an axis which is perpendicular to the ground plane." The wheel rolls without being able slip or slide in either side. This restriction is what makes the vehicle Non-Holonomic. Figure 2.2 shows an example of a Nonholonomic robot and Figure 2.3 gives its 2D model.

Figure 2.2: 4 Wheeled Non-Holonomic Robot

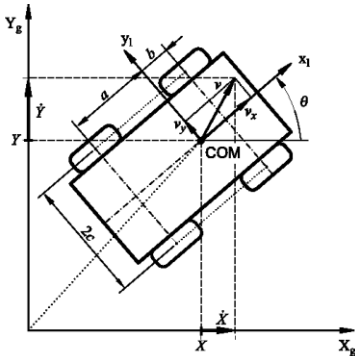

Figure 2.3: 2D Model of a 4 Wheeled Non-Holonomic Robot

**Holonomic**

A robot that is not hindered by these above mentioned restrictions is capable of omnidirectional movement. (Li & Zell, 2009) describes such motion as a vehicle that can travel in any direction under any positioning.” In many cases where mobile robots are put into action, especially in cramped or crowded spaces, omnidirectional movement allows for easier access. It permits the root to move accurately at a faster rate. An example of such a robot with its 2D model are shown in Figures 2.4 and Figure 2.5