PROBABILISTIC VOXELATED THREE DIMENSIONAL GRID MAP FOR SIMULTANEOUS LOCALIZATION AND MAPPING

BY

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ABSTRACT

With the increase of robot chassis mobility and the abundant solution for simultaneous localization and map-building, an autonomous robot has unprecedented opportunity to explore an environment in situ. However, the mobility of the robot is hindered by the limited availability of three dimensional probabilistic model of the environment. In so doing, this research proposed and investigated the potential of using probabilistic voxelated three dimensional grid map that can produce three dimensional map probabilistically by incorporating stochastic nature of sensor reading and robot movements. The map is modelled to give direct probability of an occupied space. The grid cells are voxelized and embedded with relax logit function to emanate probability value of an occupied space. The performance of the probabilistic voxelated three dimensional grid map was tested by using scans collected *a priori*. These scans act as a kernel to the registration technique. Two separate sets of map were reconstructed using pose estimate obtained from Bayesian filters. The result was compared between maps produced under recursive Bayesian filter and Bayes' rule filtering with referenced to the geometric information of the controlled environment. The probabilistic voxelated three dimensional grid map restored the geometric information of the environment with accuracy of 0.87. The runtime of the method converged to 0.23 s after the fifth map registration. The method also compressed the metrical data from Hokuyo UTM-30LX by two decades in logarithmic scale. By using continuous probability value to represent occlusion, the map has the potential to be used with any Bayesian filtering family. The potential of the probabilistic voxelated grid map to be used as path planning method was also observed since the probability value in each grid cell of the map behaves similarly to vector field.

ملخص البحث

إن للربوط المستقلي فرصة بديعة في اكتشاف البيئة المعينة في مواقع شتى، بسبب زيادة الشاسه التحركية للربوط والحلول الكثيرة لدوام التمكين وبناء الخريطة. ولكن توجد ثلاثة من نماذج البعد الاحتمالي تمنع هذه التحركية. لذلك، قدم البحث إمكانية خريطة الشبكة للأبعاد الثلاثية في استخدام البوءسلاشون الاحتمالي (Probabilistic Voxelation) للحصول على خريطة الأبعاد الثلاثي الاحتمالي من خلال المشاركة بين قراءة المكشاف وحركات الربوط عبر الطبيعة العشوائية. وتتمثل الخريطة لأخذ الاحتمال المباشري في مكان ممتلئ. ثم رسمت (voxelized) حلية الشبكة بالبوءسلاشون وضمّنتها بدالة لوجيت الأمنية لتحديد قيمة المكان الاحتمالية. وامتحنت الخريطة الاحتمالية بجمع البداهة الممسوحة لمعرفة آداءها. وبعد ذلك، سجلت البداهة كلها كمفتاح قواعد البوءسلاشون. ومن خلال البحث، أقيمت خريطتان مختلفتان محصولتان من مرشحات البايزية. ثم قورنت الخريطتان تحت ظل المرشحات المذكورة وعامل بايز، التي راجعت نتيجتهما من المعلومات الهندسية للبيئة المخططة. ومن النتيجة، عوضت الخريطة الاحتمالية عن المعلومات الهندسية للبيئة في دقة 0,87. وتركز وقت التشغيل للقواعد إلى 0,23س بعد تسجيل الخريطة الخامسة. وضغطت القواعد أيضا البيانات المترية بعقدين اثنين تحت المقياس الوغاريتمي من هوكويو UTM-30LX. لذلك، تمكن استخدام الخريطة مع مجموعة من المرشحات البايزية. وتمكن أيضا الاحتمال من استخدام الخريطة كطريقة تخطيط المسار بسبب مشابهة القيمة الاحتمالية عند حلية الخريطة ومجال الناقلات بعد الملاحظة بها.

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 thesis for the degree of Master of Science in Mechatronics Engineering.

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DECLARATION

I hereby declare that this thesis 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.

Hafiz bin Iman

Signature: ………………………………. Date: ……………………

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LIST OF ABBREVIATIONS

3D	Three dimension
AUV	Autonomous underwater vehicle
BRF	Bayes' rule filtering
CSV	Comma separated value file
DOF	Degree of freedom
GVG	Generalized Voronoi graph
ICP	Iterative closest point
IMU	Inertial measurement unit
VFH	Vector field histogram
LIDAR	Laser radar or laser range finder
RBF	Recursive Bayes' rule filtering
RGB-D	visual-depth sensor unit
SARS	Search and rescue missions
SLAM	Simultaneous localization and map-building
UAV	Unmanned aerial vehicle
USARS	Urban search and rescue missions

LIST OF SYMBOLS

μ_1	Mean of prior estimate
μ_2	Mean of measurement
μ_{new}	Mean of posterior estimate
σ_1	Standard deviation of prior estimate
σ_2	Standard deviation of measurement
σ_{new}	Standard deviation of posterior estimate
σ'	Standard deviation of posterior estimate after filtering
$p(x)$	Prior estimate function
$p(y \mid x)$	Measurement Probability function
$p(x \mid y)$	Posterior estimate function
$p(y)$	Measurement state space function
$\bar{U}$	Command vector
ε	Error coefficient
$pcl(x, y, z)$	Euclidean position of point clould
V_n	Voxelated grid cell
$\delta(\bar{\mathrm{x}})$	Dirac delta function
$\bar{x}_n$	Position vector of voxelated grid cell
t'	Time between starting point and mid- point of planar sweep scanning
$t'_{initial}$	Time at the mid position of planar sweep scanning
$t_{initial}$	Time at the beginning of planar sweep scanning
t_{final}	Time at the end of planar sweep scanning

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In the most optimistic definition, robots are autonomous. They are devised to perform impossible amount of calculation, trained to learn patterns, and concordantly, designed to help in mortally task. We shaped the history of robotics with an aim to replace us, from tasks or activities deemed too complex, too haphazard, and too dangerous. This history of modern robotics, specifically on autonomous robots, spans for almost four decades starting in the early 1970's to this day.

In 1970's, troops of fixed robots were introduced, for their efficiency, in the heavy industry instrumented to boost the economic stagnation at the time (Crafts & Toniolo, 1996). These industrial robots were programmed based on fixed model, characterized as open-loop system (Georgeff & Lansky, 1987), without using any sensors as a feedback mechanism. Sensors were only introduced in robotics in the early 1980's, investigated to help naive approach to robotics navigations (Georgeff & Lansky, 1987) and path planning (Firby, 1987), to retrofit robots that can react with the environment. To plan its motion, these robots follow specific behavior determined by the sensors (Brooks, 1986) as a series of differential equations. Early 1990's saw the integration of fixed-model and reactive-model robots (Arkin, 1990). These hybrid system models the robot behavior and its environment which defined the characteristic of autonomous robotics. However, the models were analytical and thus, depended on accurate sensing regime.

In an unknown environment, a robot should be able to identify its location and deduce action based on the accurate reading of its sensors. Without accurate sensing regime, hybrid-model robots fail to address simple autonomous task. This was regarded as a major problem, since the span of autonomous robotics at the time relied on readily available sensors such as ultrasonic transducers or sonar (Elfes, 1987). The requirement of accurate sensing by hybrid-model was impractical because these sensors are prone to error and noise. Thus a solution was stumble upon in mid-1990's where the model of the environment and the robot based on sensor reading was revamp to incorporate probabilistic approach. The method was coined simultaneous localization and map-building (SLAM) which model robot system based on its pose (localization) and the environment (map) probabilistically and concurrently with each cogent to the other (Thrun et al., 1998). Probabilistic models of the robot and the environment, were seen to cope with the complexity of navigation problem in unknown environment (Dellaert et al., 1999), lest, limited to two dimensional space.

The model of an environment that represents a three dimensional space, allowed a more practical use of autonomous robotics and thus opening a new opportunity of research in mid-1990's. This model, known as map, is bisected into two major taxonomies, namely, topological map and metrical map. Topological maps are spatial model in a form of graph consist of nodes that establish relationships between semantic information, such as relationships between chairs, trees, lines in a wall, observed in an environment (Thrun & Bücken, 1996). Metrical maps define an environment in a form of measurement clusters obtained from sensor readings. Metrical maps are often gestate into grid cell to better represent an occupancy of space (Martin & Moravec, 1996). Put differently, extending metrical maps into three dimension could describe an environment logically since topological maps, in the contexts of graph theory, only defines their nodes in multidimensional space implicitly. Three dimensional extension is significant because with the reliance on three dimensional map, an autonomous robot will have a complete solution to SLAM.

The extension of map into three dimensional space, particularly for metrical map, is important because this type of map represent geometrical information that will be assessed by a person after an autonomous robot completes a map-building operation. Without three dimensional image, a person would have a limited geometrical information to identify and assess an environment. As human, our binocular vision perceives an environment as a three dimensional space due to stereopsis, a superimposition of two retinal images (Mayhew & Frisby, 1981). Human has the ability to identify three dimensional object in two dimensional image due to mental rotation ability as a result of stereopsis experience (Shepard & Metzler, 1971). Indeed, representing an environment as a three dimensional map is less contriving and can give a complete geometrical information of an environment and better suits our nature to view the world in stereo vision.

Maps with three dimensional metrical data also resolve uncertainty in exploration. With only two dimension, the decision to move and to strategize path planning is limited and can be deceiving. With three dimensional map, the path planning and strategic decision for exploration can be assess fully and with proper alternatives because the spatial information in three dimensional map is complete.

Laser range finder has recently increase in number and selection (Pomerleau et al., 2012). Since the introduction laser range finder such as Hokuyo UTM 30-LX, the research on SLAM continues to grow and has recently shifting from two dimensional map-building to three dimensional map-building. Although most of laser range finders give reading for two dimensional plane, the response rate and the accuracy of the sensors are high enough to enable researchers to physically move the laser in a controlled fashion to provide three dimensional image (Thrun et al., 2000; Bosse & Zlot, 2009; (Nüchter et al., 2007). In retrospect, the use of transducer ranger or sonar inhibits such map-building approach because the acquired noise and incomplete reading, inherent in these sensors, would result in a diverging map. Accordingly, with the availability of sensor such as laser range finder, and domestically available RGB-D sensors such as Kinect, three dimensional map-building should be a staple for SLAM solution.

Robot chassis has increased in mobility particularly for autonomous robotics. The increase of the robot's degree of freedom from two to six acclimate a three dimensional representation of the environment. Quadrotors and micro-helicopters have been used widely to perform SLAM in indoors and outdoors environments (Weiss et al., 2011; Grzonka et al., 2012; Meyer et al., 2012; Gupte et al., 2012). These type of robot chassis can be described by six degree of freedom pose and thus requires a higher dimensional representation of the environment. With only planar map, the motion that describes this six degree of motion contrived to two or three degree of freedom because planar map can only describe the pose of the robot up to three degree of freedom. This hinders the true potential of these robots to navigate and explore an environment proving that three dimensional maps are more superior for use in SLAM.

The four factors described above reason that three dimensional map is favourable for SLAM. The map, however, has limitation that will be addressed in this research.

1.2 PROBLEM STATEMENT

It has been discussed that three dimensional map is superior choice for SLAM. However, most of the solutions for three dimensional map-building are in the form of point clouds. Point clouds could not effectively represent geometrical data for autonomous robotics, meant for SLAM solutions, due to large memory footprint (Borrmann et al., 2008; Cole & Newman, 2006; Engelhard et al., 2011; Weingarten & Siegwart, 2005). It is also important to note that these point clouds are discrete series of metrical data, which introduce gaps in three dimensional map, which would result in inefficient path planning and exploration strategy.

To plan a path efficiently under strategic exploration steps, a three dimensional map should clearly emphasize the geometrical data of an environment with little memory usage, specifying particularly occupancy of space in a continuous series of metrical data, for autonomous robot. To address the problem of discretized map in point clouds, a method called tessellation can be used to represent the environment (Okabe, 2000). One example of tessellation in map-building is grid map. Hornung et al. (2013) suggested a three dimensional grid map that represents occupied space as grid cells which has been stack continuously in series of cubic primitives. Each grid cells is embedded with binary value which represent the occurrence of an occlusion. The binary value, however, does not reflect the nature of the probabilistic model of the sensors. Therefore, a solution of three dimensional map that can incorporate both the probabilistic nature of sensors reading and also the uncertainty in locomotion is needed to produce, not just a three dimensional map, but a map that has probabilistic information of spatial geometry for path planning and exploration.

1.3 OBJECTIVE

This research addresses the problem of map-building for three dimensional spatial representation by taking regard the probabilistic model of the sensors and also the uncertainty of the robot's locomotion under small computational footprint. The objectives of this thesis are tailored to reflect such requirements by attempting:

1. to develop probabilistic voxelated three dimensional grid map algorithm based on grid map model for simultaneous localization and mapping
2. to evaluate the performance of the algorithm and its ability to efficiently serialized and manipulate metrical data into grid map under Bayes' rule

1.4 METHODOLOGY

Item one in the objective section guides this research into developing probabilistic voxelated three dimensional grid map algorithm. This algorithm is build based on probabilistic paradigm significant in understanding random signals coming from sensor readings, which explain the structure of the environment and also estimate the state or pose of a robot. Probabilistic paradigm is essential to SLAM solution (Thrun, 2000; Thrun et al., 2005). Thus this current research follows the theory that comes with probability concept applied in robotics particularly concerning SLAM solution. This research follows these steps to achieve the objectives:

1. *Literature review*

Accepted dogma was investigated via literature review, to establish acceptable solution for three dimensional mapping using probabilistic voxelation. Works and papers on developments of point clouds map-building, graph map-building, two dimensional occupancy grid map-building and three dimensional occupancy grid map-building were ruminated by addressing the contribution of these methods into SLAM particularly on three dimensional map-building. The papers were also used to note philosophy and flaws of each map-building method. Works on point clouds map-building, a method that use raw range data to represent a point in space, formulated the definition of three dimensional image. Research on graph maps explained the use of point clouds as mean to extract features. Graphs are used to relate the correspondence of each feature and utilize this correspondence to align local maps into a global map.

The works on two dimensional map-building was assessed to show the basic guidelines of constructing map based on occupancy of an area in space and. The works on two dimensional mapping also exemplified simplification of complex and isolated problem in SLAM. Endeavours that investigated the method and use of three dimensional grid map-building were addressed simply because they reflect aims of this research. Thus, papers by Hornung et al., (2013) and Wurm et al., (2010) on three dimensional grid map were used critically to establish the concept of the algorithm in this research project. This paper, however, extend the definition of three dimensional grid map by using continuous probability value as a direct notion of occupancy in space contrary to the use of binary value suggested by the former and the latter.

2. *Mathematical model*

To achieve item two of the objective, the mathematical concept of probabilistic voxelated grid map was constructed. The mathematical model of the sensor was addressed based on the sensitivity of the sensor per se. The map, that modelled the environment, was designed based on the nature of locomotion of wheeled autonomous robot and the sensitivity of the laser. The mathematical concept for the map, in turn, was used to develop algorithm for probabilistic voxelated three dimensional grid map, which incorporates the use of continuous probability value, agreeing to the guidelines of the item two in the objective of this research.

3. *Experiment*

The performance of the voxelation algorithm has to be tested under Bayes' Rule. Bayes' Rule is in accordance to the probabilistic paradigm of this research. In order to achieve this research objectives, an experimental hypothesis was constructed. The objective of this experiment was simply trying to prove the hypothesis which states that:

Probabilistic voxelated three dimensional grid map will be able to represent the nature of geometric information of an unknown environment by using recursive Bayesian filtering to construct the map with Bayes' rule filtering as a control method to evaluate the performance of the algorithm.

The experimental objective guides the design of the algorithm to perform the probabilistic voxelated three dimensional occupancy grid map and programmatically coded into series of functions. This hypothesis also addressed item four of the objectives implicitly because it will be shown that voxelation method in the algorithm decreases the number of point clouds in the grid map.

An experimental set up was designed and constructed. The experiment consist of a controlled environment and a laser ranger. The controlled environment consist of cardboard boxes stacked together to emulate an unknown enclosed environment. The laser interacts with that environment by collecting data in a form of scans and by moving in the environment at a predetermined positions. The scans collected were in metrical form and were combined incrementally under a process called registration after being voxelized. The registration used recursive Bayesian filtering (RBF) technique, reiterated separately using Bayes' rule filtering (BRF) for comparison.

4. *Qualitative and quantitative evaluation*

The qualitative and quantitative assessment of the result from a complete scan registrations are comparative, instating the controlled environment as the reference for geometric consistency. Qualitatively the geometric information in both maps produced under RBF and BRF should represent closely the structure of the controlled environment. The quantitative aspect of the result assessment take note the inconsistent geometry in the map from the qualitative evaluation, formerly mentioned.

5. *Evaluation of algorithm*

The success of the algorithm in showing geometric information of the controlled environment was evaluated according to the objectives. If there was a contingency that suggest the algorithm fails, re-evaluation ensues.

To better describe the chronology of the methodology of this research, Figure 1.2 summarizes each step.

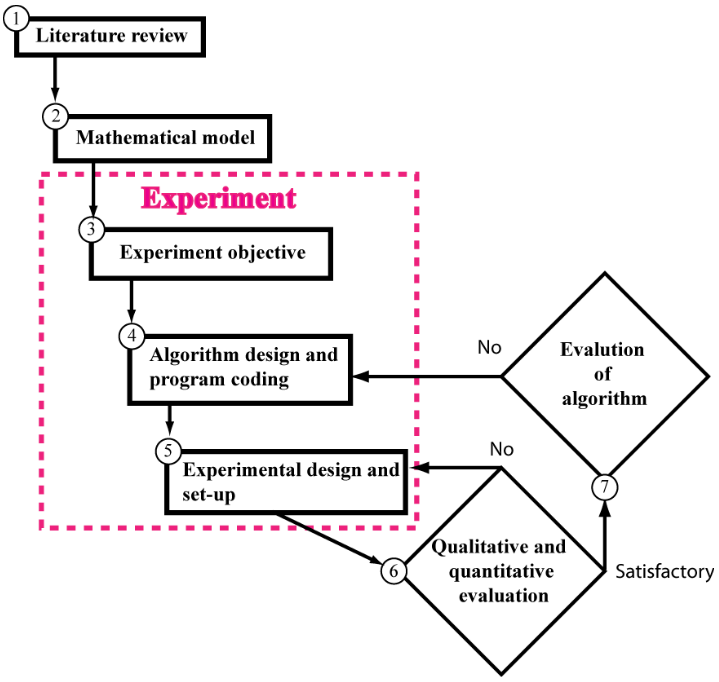

Figure 1.1 Methodology conforming to objectives

1.5 RESEARCH SCOPE

The scope of this research was based on the methodology of the research where this research used probability as the paradigm of the mathematical model and the experimental design. However, the algorithm used probabilistic parameter that can only be modelled by Gaussian curve. The model of the laser (LIDAR), map model, and