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**ENHANCEMENT OF ULTRASONIC SENSOR
SYSTEM FOR INDOOR MOBILE ROBOT
MAPPING AND SELF-LOCALIZATION**

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by

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LIST OF ABBREVIATIONS

USB-5	Ultrasonic Sensor Bank with 5 Pieces Ultrasonic Sensor
USB-8	Ultrasonic Sensor Bank with 8 Pieces Ultrasonic Sensor
USB-16	Ultrasonic Sensor Bank with 16 Pieces Ultrasonic Sensor
NWA	Nominal Wall Angle
HTM	Homogeneous Transformation Matrix
MANOVA	Multivariate Analysis of Variance
KNN	K-Nearest Neighbor
FKNN	Fuzzy K-Nearest Neighbor
LDA	Linear Discriminant Analysis
MLP	Multilayer Perceptron
GUI	Graphical User Interface
ECC	Electronic Compass Correction

Penambahbaikan Sistem Penderia Ultrasonik untuk Pemetaan dan Penyetempatan Kendiri Robot Mudah Alih Dalam

ABSTRAK

Tesis ini adalah mengenai menambahbaik keupayaan penderia ultrasonik untuk pengukuran halangan yang tepat, di mana ianya penting bagi pemetaan dan penyetempatan kendiri robot mudah alih dalaman. Ultrasonik dipilih untuk pemetaan dan penyetempatan kendiri robot mudah alih dalaman disebabkan oleh kawasan pengesanan yang luas, tidak bergantung kepada cahaya, keupayaan untuk mengesan kaca dan dinding bersinar, saiz yang lebih kecil, ringan, menggunakan memori yang sangat rendah, jauh lebih murah daripada Laser Pengesan Jarak (LRF) atau kamera dan penggunaan kuasa yang lebih rendah. Walau bagaimanapun, ia boleh membawa kepada pengukuran yang tidak tepat kerana ciri-cirinya. Menjadi penderia jenis spektrum dan tidak terfokus, ini boleh menyebabkan ukuran penganggaran yang salah selepas pelbagai refleksi halangan. Oleh itu, algoritma yang disertakan perlu dikembangkan untuk menghadapi isu ini, yang membawa kepada penyelidikan ini yang terdiri daripada tiga objektif, berdasarkan kerja teori dan eksperimen. Yang pertama ialah pembangunan teknik pemetaan dinding yang dinamakan sebagai Algoritma Penapisan Sudut Dinding Nominal (NWA), dengan menggunakan gabungan Hukum Sinus dan Kosinus. Yang kedua adalah pembangunan pemetaan 2D masa nyata berdasarkan jarak pengukuran antara pusat bank penderia dan dinding. Matriks Transformasi Homogen (HTM) ditambahbaik dalam kajian ini sebagai algoritma pemetaan dinding. Objektif ketiga ialah untuk menilai prestasi pemetaan dan penyetempatan-kendiri terhadap bentuk dinding asas dan persekitaran dalaman sebenar menggunakan pengelas K-Jiran Terdekat (KNN). Untuk mencapai kesemua objektif, satu bulatan bank penderia terdiri dari enam belas unit 40 kHz penderia ultrasonik dibangunkan. Bank penderia ini dipasang pada platform robot mudah alih beroda dua untuk melaksanakan proses pengimbasan. Platform robot dibina menggunakan sistem pemacu pembezaan kerana ia boleh mengendalikan isu-isu pergerakan di dalam ruang yang sempit dan sesak. Analisis untuk menambahbaik keupayaan ultrasonik mengukur halangan dengan bank penderia ultrasonik dilakukan dengan menetapkan empat set bentuk dinding asas terdiri daripada segiempat tepat, segitiga, lengkung dan segiempat sama dan juga persekitaran makmal yang sebenar. Ujian kenormalan dan Analisis Varian Multivariate (MANOVA) dilakukan untuk memastikan data tersebut adalah sahih. Perlaksanaan algoritma adalah terdiri daripada gabungan beberapa platform perisian seperti BASIC Stamp, BASIC Atom, LabVIEW dan MATLAB. Gabungan algoritma, perkakasan dan perisian ini menghasilkan kemajuan ketepatan di dalam pemetaan, peningkatan daripada purata 90% kepada 97%. Juga pada masa yang sama, pengurangan dimensi data sehingga 75% boleh dicapai di samping mengekalkan kadar prestasi penyetempatan melebihi 90%. Algoritma yang dibangunkan mempunyai keupayaan untuk memadamkan kesilapan ilusi untuk meningkatkan ketepatan pengukuran semasa proses imbasan.

Enhancement of Ultrasonic Sensor System for Indoor Mobile Robot Mapping and Self-Localization

ABSTRACT

This thesis is about enhancing the ability of ultrasonic sensor for accurate measurement of obstacles, which is important in indoor mobile robot mapping and self-localization application. Ultrasonic is preferred for indoor mobile robot mapping and self-localization due to its wide detection area, does not depends on light, the ability to detect glass and shining wall, smaller in size, lightweight, use a very low memory, much cheaper than Laser Range Finder (LRF) or camera and lower power consumption. However, it can lead towards inaccurate measurement due to its characteristics. Being a specular type of sensor and not narrowly focused, this can causes wrong measurement of estimation after multiple obstacle reflection. Therefore, necessary accompanying algorithms should be developed to encounter this issue, which lead towards this research that consists of three objectives, based on theoretical and experimental work. The first is the development of an enhanced wall mapping technique named as the Nominal Wall Angle (NWA) filtering algorithm, using the combination of Sine and Cosine Law. The second is the development of real time 2D mapping based on the measurement distance between the centre of sensor bank and the wall. Homogeneous Transformation Matrix (HTM) is enhanced in this research as the wall mapping algorithm. The third objective is to evaluate the performance of mapping and self-localization of basic wall shape and real indoor environment using K-Nearest Neighbour (KNN) classifier. To achieve these objectives, a ring of sixteen pieces 40 kHz ultrasonic sensor bank is developed. This sensor bank is mounted on a two-wheeled mobile robot platform to perform the scanning process. The robot platform was built using a differential drive system as it can handle issues of maneuvering in crowded and narrow spaces. Analysis for enhancing ultrasonic capability in obstacle measurement with ultrasonic sensor bank is carried out by fixing four set of basic walls shape of rectangular, triangular, curve and square and also in a real laboratory environment. Normality and Multivariate analysis of variance (MANOVA) test was performed to ensure that the data is valid. The algorithm has the combined implementation of several software platforms such as BASIC Stamp, BASIC Atom, LabVIEW and MATLAB. The combination of these algorithms, hardware and software results in an improvement in accuracy of mapping, increased from an average of 90% to 97%. Also at the same time, data dimension reduction of up to 75% can be achieved while maintaining localization performance rate beyond 90%. The developed algorithm has the capability to suppress phantom error for improving the accuracy of measurements during the scanning process.

CHAPTER 1

INTRODUCTION

1.1 Background and Research Motivation

Mapping and self-localization is a major problem for mobile robots application. Utilization of proprioceptive sensors like odometer or inertial (Siegwart & Nourbakhsh, 2004; Everett, 1995) only provides information about the internal state of the mobile robot. Unfortunately, sensor does not free from noise, so noise is also integrated, therefore making the estimation in the mapping and self-localization is inaccurate. To improve the accuracy of mapping and self-localization, external exteroceptive sensors such as laser, ultrasonic and camera were used. External exteroceptive sensor provides a measurement of the environment around the robot and performs geometric assumptions about the environment when the robot moves. This measurement will change when the mobile robot moves and the problem of mapping and self-localization can be formulated in terms of the correlation between consecutive sensor readings. External exteroceptive sensor reading is very useful because it can be matched with priori map directly after going through several filtering process and it is called scan matching algorithm (Krajnik, 2011; Andersone, 2017). But, an autonomous mobile robot does not need to rely on a priori map since it prevents the mobile robot to be useful in the exploration tasks.

There are many types of external exteroceptive sensors that often used in mobile robot applications such as ultrasonic, Light Detection and Ranging (LIDAR), infrared

and vision that able to provide range / distance measurement. The vision sensor are better in providing image data but there are still drawback as the usage of one camera is monoscopic, thus making it difficult to get the exact accuracy of range / distance data as needed, unless there are two vision systems (stereoscopic). Vision system also requires a high speed computer to analyze huge data before getting the distance measurement (Jung, Kim & Kim, 2009). At the same time, vision system is not selected in this research due to the privacy concerns. Based on Khoshgozaran & Shahabi (2010), Damiani, Silvestri & Bertino (2011) and Sooyeon Jeong et al (2015), revealing private information such as image or personal information to potentially untrusted service providers poses significant privacy concerns.

The angular resolution of Laser Range Finder (LRF) or Light Detection and Ranging (LIDAR) such as SICK laser scanner is 0.25 to 1 degree angular resolution and the depth resolution is approximately $\pm 0.01\text{m}$ (SICK Sensor Intelligent, 2016; Abdul Shukor, Young & Rushforth, 2011). This far exceeds the resolutions of ultrasonic sensors. However, it uses directional type of sensors; that is only capable to detect the obstacle in the front of the sensor and is not capable to detect obstacles that are near to the path or when the obstacle is in a vertical position. It is also similar to infrared sensors. Furthermore, LRF has errors to be studied involving mixed pixels and loss of synchronization at its highest data transfer rate. The sensor itself is quite heavy and requires high power consumption. Also, the cost for LRF is higher than other type of sensors. LRF is also inadvisable to be used because it may endanger the human eye if contact occurs (Ye & Borenstein, 2002).

The ultrasonic sensor does not rely on light, surface brightness, smoke, dust, dirt, transparent surfaces, mirror or light-absorbing obstacles in which LIDAR often fails, yet it is able to detect small objects located within its cone of reflection ($\pm 15^\circ$) (Andy,

2005; Dobrev, Flores & Vossiek, 2016; Li, Du & Zhao, 2016; Adarsh, Mohamed Kaleemuddin, Bose & Ramachandran, 2016). It is also resistant to vibration, infrared radiation, ambient noise and Electromagnetic Interference (EMI) radiation. Apart from that, the sensor also consumes low power, very light in weight and is easier to calibrate compared to a vision system or LIDAR (Ciarcia, 1980; Moravec & Elfes, 1985; Valentin, 1994; Corion, et al., 1996; Borenstein, et al., 1996; Cao & Borenstein, 2002; Baharuddin, et al., 2013. Another example of an environment with significant transparent obstacle is the museum, with its heavy use of glass (Siegwart & Nourbakhsh, 2004; Giannoccaro & Spedicato, 2013). Table 1.1 shows the comparison review between each type of the related sensor.

Table 1.1: Summary of Sensor Review

	Ultrasonic	LIDAR	Infrared	Vision
Model	Parallax PING Ultrasonic	Hokuyo URG-04LX-UG01	Sharp GP2Y0A21YK 0F	Kinect Sensor
Cost	Low (US\$1-30)	Very High (>US\$1140)	Low (US\$5-10)	High (>US\$160)
Computation Overhead	Low	High	Low	Very High
Horizontal Field of View	$\pm 15^\circ$	240°	Single Point	640 pixel
Vertical Field of View	$\pm 15^\circ$	N/A	N/A	480 pixel
Data Processing with	Yes	No	Yes	No

Microcontroller				
Range	Up to 3m	Up to 5.6m	Up to 0.8m	Line of sight
Indoor Operating Conditions Requirement	All condition	Clear as human eyes visibility	Clear as human eyes visibility	Clear as human eyes visibility
Commercially available	Yes	Yes	Yes	Yes
Accuracy	±0.01m	±0.03m	±0.01m	NA
Update Frequency	40kHz	38.4kHz - 400kHz	40kHz	38.4kHz
Power Supply	5V	5V	5V	12V
Power Consumption	Low	Very High	Low	Medium
Weight	9g	160g	3.6g	300g

Although there are many types of external exteroceptive sensors used in this mapping and self-localization application of mobile robot, till the use of ultrasonic sensors almost ceased (Krajnik, 2011), but it is preferred choice in this research because it is superior while maneuvering as well as in obstacle avoidance applications compared to other sensors available (Corion, Desodt & Jolly, 1996; Borenstein, Everett & Feng, 1996; Cao & Borenstein, 2002; Kim, Seo & Jang, 2007; Sonali, Dharmesh & Nishant, 2011; Santiago, Anzueto, Feijoo & Grajales, 2014; Patil & Agiwal, 2015; Sindhuja & Lavanya, 2016; Fathan, Jati, & Saputra, 2017).

Therefore, this research focuses on ultrasonic sensor and the signal from an electronic compass for indoor mapping of basic wall shape and real laboratory

environment. The research work started at detecting four basic wall shape of obstacle before tested in real laboratory environment in real time which has not been reported except in image processing research group. This is important because the basic wall shape is the fundamental shapes with unique characteristics that can be differentiate. Many researches especially in vision system used it to evaluate the performance of the developed system before applying it in the real environment (Sanket, et al., 2013; Shaline, et al., 2013). This research establishes a new mathematical computation to perform accurate mapping and self-localization algorithm for both situations (Basic wall shapes and real environment). Statistical analysis such as data normality test, mean value of class using Multivariate Analysis of Variance (MANOVA), and classification/localization test are conducted to validate the experiment results. The mapping and self-localization algorithm used BASIC Stamp, Basic ATOM, MATLAB and LabVIEW programming software.

1.2 Problem Statements

Mapping and self-localization is a well-known topic in the mobile robot community over the past three decades. Most of the time, LRF and vision system were utilized by the robot to solve mapping and self-localization issues. Only few researches used ultrasonic sensor in mapping and self-localization system even though it is a very superior sensor (Corion, Desodt & Jolly, 1996; Borenstein, Everett & Feng, 1996; Cao & Borenstein, 2002; Omron Adept Mobilerobots, 2016; Mojaev & Vorst, 2016) in the maneuvering and scanning application in various fields and environment condition. However, in mapping the surrounding wall, ultrasonic has limitation especially towards mapping complicated shapes such as square because the sensor is working based on

specular basis, which mean it scanning angle is not narrowly focused. Since the sensor reads time of flight, the reflected energy from different angle of the wall can gives a wrong estimation after striking multiple wall surfaces. This reflection situation is called phantom error. The error causes incorrect range measurement, particularly for indoor applications where objects like tables, walls or flat surfaces are not always perpendicular to the acoustic axis of the ultrasonic sensor beam (Borenstein & Koren, 1991; Leonard & Durrant-Whyte, 1992; Burguera, 2009; Wang, Su, Shi, Liu & Miro, 2017; Andersone, 2017).

Moreover, in order to evaluate the performance of ultrasonic sensor, it is best to test on basic wall shape such as square, rectangle, triangle and curve. However, based from the survey, to the best of author's knowledge, there are no reports of actual ultrasonic sensor capabilities evaluated on basic wall shape before the test is performed on the real environment. Only tests on one or two simple basic shapes such as square or curve were done by some researchers (Yuan, Mao & Guo, 2016). The reason of using four basic wall shapes is because these four basic wall shapes have their own unique characteristics that can be differentiate. A square has 4 edges with same length, while rectangular shape has 4 edges but different pair of side length. For triangular shape, there will be 3 edges and same side length, while there is no edge for curve. With the entire unique characteristic, the basic wall shape will give different situation of wall angle that can help to evaluate the real performance of ultrasonic sensor. The best performance of ultrasonic measurement can only be achieved by suppressing the phantom error and in the meantime, generating an acceptable mapping accuracy for self-localization and maneuvering application.

Self-localization is another critical issue in indoor mobile robotics application. Previously, artificial markers were placed on the wall to enable the robot to identify

location in solving localization issue. However, for the operation in an office environment or in domestic application, it might not be acceptable to place artificial markers throughout the environment for the purpose of localization. This is because the number of artificial markers is dependent on the size of the area, so the larger the area, the more the number of artificial maker will be installed, and this could be messy. Furthermore, it is in general impossible to assume that a map of the environment can be provided. Therefore, it is of interest to investigate suitable methods that allow automatic acquisition of maps of the environment based on existing features and subsequent use of such maps for self-localization.

1.3 Research Aims and Objectives

The aim of this research is to develop a mapping and self-localization system using ultrasonic sensor for an appropriate indoor mobile robot. This thesis is concerned with the accuracy issues for a practical differential drive robot for mapping and self-localization applications for easier maneuvering and avoiding obstacle in small and medium scale indoor environments. The principal objectives of this thesis are as follows:

- To develop an enhanced algorithm for suppressing phantom error in mapping
- To modify kinematic algorithm for generating a 2D mapping of basic wall shape and real indoor environment.
- To evaluate the performance of the developed algorithm and the accompanying robot in mapping and self-localization of basic wall shape and real indoor environment.

1.4 Scope of the Thesis

The scope on this research is to develop a mapping algorithm using the USB-16 sensor bank placed on a differential drive mobile robot. This mapping system uses ultrasonic sensor with a scanning range of three meters and coverage area of detection within ± 15 degree as defined in the specification. Since there are not that many researchers are researching the true ultrasonic capability in basic wall shape mapping, due to its importance, this research work is focused on static environment without dynamic obstacle for obtaining real data accuracy. This mapping algorithm is tested in five types of environments namely: rectangular wall, triangular wall, curve wall, square wall and real laboratory environment. The 2D mapping is generated by Homogeneous Transformation Matrix algorithm with the z-axis height is fixed according to the actual height of the sensor mounted on a mobile robot platform which is equivalent to 25 cm. Classification algorithm will be used in recognizing the type of wall shape and self-localization due to its advantages proven while conducting this study, and shown in Chapter 6.

1.5 Thesis Outline

In this chapter, the objectives of this research have been described with an introduction to mapping and self-localization with ultrasonic sensor.

In Chapter 2, the advantages of ultrasonic sensor for mapping and self-localization application are explained. The detailed study on the history of mapping and self-localization are also discussed in this chapter.

Chapter 3 explains the aspects of mapping and self-localization hardware development conducted in this research. The hardware includes the robot platform, the sensors, the microcontroller, the dc motor selection, electronic compass and the wireless communication link.

Chapter 4 explains software development for related mapping and self-localization application such as the development of an enhanced real time 2D wall mapping technique named as the Nominal Wall Angle (NWA) filtering algorithm and Homogeneous Transformation Matrix (HTM). Next, the development of localization algorithm with K-Nearest Neighbour (KNN), Fuzzy K-Nearest Neighbour (FKNN), Linear Discriminant Analysis (LDA) and Multilayer Perceptron (MLP) classifier and finally, the development of Graphical User Interface (GUI) for mapping and self-localization using LabVIEW software are also covered.

In Chapter 5, the methodology on carrying out the experiment is described. The experiment was carried in two types of the indoor environment which is basic wall shape and real laboratory environment. Firstly, validation of ultrasonic and electronic compass sensor measurement and selection of dc motor for mobile robot platform is covered. Next is data collection with USB-16 sensor bank and data filtering with NWA algorithm. Then, validation of the data collected using normality and MANOVA statistical analysis tools is conducted. The data will be plotted in the form of 2D map using the HTM algorithms developed in LabVIEW software. The KNN, FKNN, LDA and MLP classifier to evaluate the performance of localization was applied in this research. Finally, real time 2D mapping with self-localization algorithm are displayed in the developed GUI.

Chapter 6 explains the result and performance study of mapping and self-localization robot that is carried out in both off-line and on-line method to evaluate the