SENSOR FUSION WITH KALMAN FILTER AND SUPPORT VECTOR MACHINE FOR FAULT DETECTION IN AUTOMATED GUIDED VEHICLE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2023

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards broadening my understanding and thoughts. First and foremost, I wish to express my heartfelt gratitude to my thesis supervisor, Associate Professor Dr. Yeong Che Fai, for his guidance. His continued support and interest made this thesis possible.

I am grateful to the Collaborative Research in Engineering, Science and Technology (CREST) centre for funding my Msc. study. Universiti Teknologi Malaysia (UTM) deserve special thanks for their assistance in supplying the relevant literatures. My appreciation to CAIRO lab for providing me a place to conduct my research and for organizing insightful talks. Special thanks also to DF Automation Sdn. Bhd for the opportunity for collaboration.

To my fellow postgraduate students, colleagues and friends, your sincere support is highly appreciated. I am grateful to all my family members. Their encouragement and support which motivates me immensely throughout the making of this thesis.

ABSTRACT

Industries are moving towards automation and the usage of machines such as Automated Guided Vehicle (AGV) is increasing. Thus, demands for the reliability of AGVs are increasing as they have various complex tasks to carry out. Unfortunately, AGVs are still susceptible to faults and breakdown. Therefore, fault detection is important to provide means of self-diagnosis on AGV. However, fault detections are generally threshold based which are unsatisfying in terms of accuracy and are prone to false triggering. Extended Kalman Filter (EKF) has limitations in handling nonlinear models while Unscented Kalman Filter (UKF) seems promising. Support Vector Machine (SVM) was used as a fault detection method. Thus, this research proposes a sensor fusion enhanced with SVM for fault detection on AGV. The first objective of this research is to develop a test AGV. This AGV is a two-wheeled differential driven mobile robot with multiple sensors and able to make various types of movements to emulate an industrial AGV. Next objective is to develop an enhanced sensor fusion method using EKF and UKF for fault detection with SVM on AGV. The last objective is to evaluate the performance of the developed method. Experiments were carried out where the AGV was used as a test bed for sensor fusion and fault detection. The AGV was tested in different experiment setups such as different track layout, different wheel condition, and different castor conditions. Result shows that UKF handles changes and non-linearity better than EKF. The average residual generated during the test for UKF is 0.0083 meter while for EKF is 0.0129 meter. With sensor fusion, deviations in odometry data can be compensated with the usage of a LiDAR sensor as reference. Using UKF parameters to detect fault, the accuracy achieved with SVM is 64.2% compared to 37.9% without SVM. Fault detection accuracy using EKF parameters with SVM is 82.5% while without SVM is 41.0%. As a conclusion, the results show SVM improves fault detection accuracy regardless of using UKF or EKF.

ABSTRAK

Industri sedang menuju ke arah automasi dan penggunaan mesin seperti kenderaan panduan automatik (AGV) semakin meningkat. Oleh itu, permintaan untuk AGV yang boleh diharap semakin meningkat kerana adanya pelbagai tugas kompleks untuk dijalankan. Malangnya, AGV masih tidak bebas daripada masalah dan kerosakan. Oleh itu, AGV harus mempunyai kemampuan untuk menjalankan pemeriksaan kendiri untuk masalah dan kerosakan. Walaubagaimanapun, kaedah pengesanan kerosakan secara amnya adalah berdasarkan nilai ambang yang tidak memuaskan dari segi ketepatan. Penapis Kalman Berlanjutan (EKF) mempunyai cabaran mengendali model tidak linear sedangkan Penapis Kalman Tidak Berbau (UKF) menunjukkan potensi. Mesin Sokongan Vektor (SVM) telah digunakan untuk kaedah pengesanan kerosakan. Justeru, kajian ini mencadangkan kaedah pelakuran penderia yang dipertingkatkan dengan SVM untuk pengesanan kerosakan pada AGV. Tujuan pertama kajian ini adalah untuk membangunkan sebuah AGV. AGV ini adalah robot pacuan berbeza dua roda dengan pelbagai penderia yang boleh buat pelbagai gerakan untuk menyerupai AGV industri. Tujuan seterusnya adalah untuk menghasilkan kaedah pelakuran penderia yang diperbaiki dengan EKF dan UKF untuk pengesanan kerosakan dengan SVM pada AGV. Tujuan terakhir adalah menguji prestasi kaedah yang telah dihasilkan. AGV telah digunakan dalam kajian untuk menguji pelakuran penderia dan pengesanan kerosakan. AGV tersebut telah diuji dengan keadaan yang berbeza seperti susunan atur trek, keadaan roda dan keadaan kastor yang berlainan. Hasil kajian menunjukan bahawa UKF mengendali perubahan dan model tidak linear lebih baik daripada EKF. Nilai perbezaan antara anggaran dan sebenar yang dijanakan semasa ujian untuk UKF ialah 0.0083 meter dan untuk EKF ialah 0.0129 meter. Penyelewengan dalam data odometri boleh diperbaiki dengan penggunaan peranti pengesanan cahaya dan penjarakan sebagai rujukan. Ketepatan pengesanan kerosakan dengan penggunaan nilai UKF ialah 64.2% dengan SVM dan 37.9% tanpa SVM. Ketepatan pengesanan kerosakan dengan penggunaan nilai EKF ialah 82.5% dengan SVM dan 41.0% tanpa SVM. Kesimpulannya, hasil kajian menunjukan bahawa SVM memperbaiki ketepatan pengesanan kerosakan tanpa mengira samada menggunakan UKF atau EKF.

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LIST OF ABBREVIATIONS

3D CAD	-	3-dimensional computer aided design
4Ds	-	Too Dangerous, too Dull, too Dirty and too Difficult
9-DOF	-	9-degrees of freedom
ADC	-	Analogue to digital conversion
AGV	-	Automated guide vehicle
CCD	-	Charge-coupled device
CMOS	-	Complementary metal-oxide semiconductor
DC	-	Direct current
DMM	-	Digital multimeter
DST	-	Dempster-Shafer theory
EKF	-	Extended Kalman filter
FDI	-	Fault detection and isolation
GPS	-	Global positioning system
IMU	-	Inertial measurement unit
IoT	-	Internet of Things
LiDAR	-	Light detection and ranging
LiPo	-	Lithium polymer
MEMS	-	Microelectromechanical system
MM	-	Multi-model
MSE	-	Mean square error
RFID	-	Radio frequency identification
RMS	-	Root mean square
PC	-	Personal computer
PF	-	Particle filter
SBC	-	Single board computer
SVM	-	Support vector machine
UART	-	Universal asynchronous receiver/transmitter
UAV	-	Unmanned aerial vehicle
UKF	-	Unscented Kalman filter
USB	-	Universal serial bus

QEI	-	Quadrature encoder interface

LIST OF SYMBOLS

d	-	Axial distance between wheels
k	-	Iteration
n	-	Number of pulses
ϕ	-	Heading angle
π	-	Pi constant (3.142)
r	-	Radius of wheel
t	-	Time
v	-	Velocity of AGV
ω	-	Angular velocity of AGV
N	-	Number of pulses per rotation
T	-	Sampling time
x_k^f	-	State prediction
P_k^f	-	Covariance
K_k	-	Kalman gain
x_k^a	-	Updated state
P_k^a	-	Update covariance
$\bar{X}$	-	Predicted state
X	-	Updated state
A	-	State transition matrix
B	-	Coefficient matrix
u	-	Input matrix
$\bar{P}$	-	Predicted state
P	-	Updated state
H	-	Measurement matrix
Q	-	Process noise
R	-	Measurement noise
z	-	Measurement
y	-	Residual
v_e	-	Velocity output based on encoder data

ω_e	-	Steering angle output based on encoder data
r_R	-	Radius of right wheel
r_L	-	Radius of left wheel
ω_R	-	Angular velocity of right wheel
ω_L	-	Angular velocity of left wheel
x_e	-	x-position of AGV based on encoder data
y_e	-	y-position of AGV based on encoder data
ϕ_e	-	Heading angle of AGV based on encoder data
u_e	-	Input matrix based on encoder data
a_x	-	Accelerometer output in x-axis
m_x	-	Magnetometer output in x-axis
m_y	-	Magnetometer output in y-axis
x_i	-	x-position of AGV based on IMU data
y_i	-	y-position of AGV based on IMU data
ϕ_i	-	Heading angle of AGV based on IMU data
u_i	-	Input matrix based on IMU data
v_i	-	Velocity based on IMU output
Δx_l	-	Displacement in x-axis based on LiDAR data
Δx_l	-	Displacement in x-axis based on LiDAR data
$\Delta\phi_l$	-	Heading angle difference based on LiDAR data
x_l	-	x-position of AGV based on LiDAR data
y_l	-	y-position of AGV based on LiDAR data
ϕ_l	-	Heading angle of AGV based on LiDAR data
x	-	x-position of AGV
y	-	y-position of AGV
$\dot{x}$	-	Sigma points
$\dot{y}$	-	Transformed sigma points
ω^m	-	Weight of mean
ω^c	-	Weight of covariance
Z	-	Measurement-transformed sigma points
μ_z	-	Mean of measurement space
P_z	-	Covariance of measurement space
Y	-	Residual

P_{xz}	-	Cross-covariance between state and measurement
$\boldsymbol{F}$	-	Jacobian of state model
$\boldsymbol{H}$	-	Jacobian of measurement model
I	-	Identity matrix

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In this era of Industry 4.0, more solutions are moving towards automation and such automated solutions are automated guided vehicle (AGV). According to the International Federation of Robotics, the population of service mobile robot were 4 million and is increasing to about 31 million in 2014 till 2017 [1]. AGV is a type of self-propelled, mobile robot and is capable of carrying out task. AGVs are deployed in industrial environment to automate industrial operation and to cut down operation cost [2]. In a warehouse, operation cost can be costly with manual labour due to employee salary. The operation is less efficient due to the limitation of human workers where human workers can feel exhausted and are prone to health problems. AGV as machines, work tirelessly and continuously to ensure high productivity. AGV as robot seems suitable for any task which are too Dangerous, too Dull, too Dirty and too Difficult (4Ds) to be done by humans [3]. Modern AGVs are equipped with more different sensors, allowing them to complete complex tasks. Sensors play a vital role on AGVs to acquire information from the environment so AGVs may operate properly in its working environment [4]. By using sensor fusion, the combination of data from more than one sensor enables better robot perception. Uncertainties in sensors can be reduced and the accuracy and reliability of AGVs can be increased with better perception. However, machines can break down and cause business losses and potential harm to the workers. Thus, there is an increase in demands regarding the reliability and maintenance [5]. With fault detection, anomalies in performance of AGV can be detected which could help improve reliability of AGV. Thus, this research aims to design and develop an enhanced sensor fusion algorithm for fault detection in AGV with better accuracy. Hence, sensor fusion method with better estimation accuracy could contribute to better fault detection accuracy.

1.2 Problem Statement

Modern AGVs are equipped with more sensors to collect information on the AGV itself and its surrounding. Data generated from sensors enable AGV functions such as detecting obstacles and performance and status monitoring. Information on the AGV can be utilized to optimize maintenance work on AGV. Efficient maintenance can save time and cost which is beneficial.

The weakness of currently utilized AGV systems are the cost for installation, efficiency of the system, flexibility of the system and the safety of the system [5]. The challenges in fault detection includes robustness, multiple fault diagnosis and real time diagnosis [6]. Failure in mobile robot system may cause robot to be off navigation which will be hazardous to human and degrades service performance [7]. Hence, the AGV should be capable of fault detection with multiple sensors for fault diagnosis and the sensors installed should be reliable so the AGV and its fault detection is robust while dealing with uncertainties in practical operation. The importance of fault detection is that it would bring more advantages not only to the mobile robot itself but also to maintenance planning and safety [8].

Residual generation is vital for most case in fault detection. Model based methods are preferred as data driven based methods are computationally costly. Most previous sensor fusion for fault detection work uses extended Kalman filter (EKF) which has limitation in handling nonlinear model [9]. This limitation causes low accuracy of the generated estimated value. Limited accuracy of the generated estimated value using EKF causes the fault detection to be unsatisfying in terms of accuracy. There are other sensor fusion methods claimed to have better estimation accuracy than EKF when used on other applications such as unscented Kalman filter (UKF). As for fault detection algorithm, previous work mostly relies on thresholding of residual values generated which can be falsely triggered due to inaccuracies of EKF. Classification methods such as support vector machine (SVM) can be used to identify abnormalities in AGV performances.

1.3 Objective of Research

The purpose of this research is to design and develop enhanced sensor fusion for fault detection on AGV. The objectives of this research are:

i. To design and develop an AGV as a test bed for fault detection. Sensors such as current sensor and encoder will be implemented on the test AGV.

ii. To design an enhanced sensor fusion and fault detection method on AGV. Multiple sensor data generated on test AGV will be fused using EKF and UKF. SVM will be used for fault detection.

iii. To evaluate the performance of methods on AGV and compare performance for fault detection on AGV. The performance of methods is measured in terms of estimation accuracy of sensor fusion method and the fault detection accuracy.

1.4 Scope of Research

A prototype AGV will be designed and developed as a test bed to experiment sensor fusion methods and fault detection. A two wheeled differential drive mobile robot will be used as the test AGV. Sensors are to be applied to the AGV. These sensors are vital for an AGV operations as the data outputs from these sensors can be used to measure the performance of the AGV and its fault detection capabilities.

Next, the test AGV uses Arduino Mega microcontroller as controller to govern the operation of the test AGV. Some C programming as prerequisite for coding the program to drive the actuators of the test AGV and to control the sensors. The Raspberry Pi 4 is to collect and analyse data, computing the sensor fusion algorithm. The programming environment to run sensor fusion and fault detection algorithm is mostly in Python programming language.

Lastly, the performance of the fault detection will be evaluated using residual calculation and error evaluation. The generated residual will be evaluated using SVM for fault detection. Based on the residual values calculated, the accuracy of estimation of each sensor fusion method can be measured and abnormality on AGV can be detected using fault detection method.

1.5 Thesis Outline

This report is divided into five chapters with Chapter 1 being the introduction of this report where problem statement, objective and scope of research are discussed. Chapter 2 is the literature review where research and review of AGV, sensor fusion and fault detection are discussed and summarized. Chapter 3 is where the project methodology is explained in detail. Experiment setup and execution to test the AGV test bed, sensor fusion and fault detection methods are mentioned in Chapter 3. Next, Chapter 4 is the result and outcome of the experiment mentioned in Chapter 3. Finally, Chapter 5 is the conclusion and suggestion for future work of this project. This final chapter is to summarize the research based on the findings in previous chapters and to proposed possible improvements for future research work.

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1. **Dares, M.,** Goh, K. W., Koh, Y. S., Yeong, C. F., Su, E., and Tan., P. H. (2020). Development of AGV as Test Bed for Fault Detection. In *2020 6th International Conference on Control, Automation and Robotics (ICCAR)* (pp. 379-383). IEEE. doi: 10.1109/ICCAR49639.2020.9107977. **(Indexed by SCOPUS)**

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