ROBUST AND RELIABLE DUAL TIRE CLASSIFICATION SYSTEM WITH ERROR COMPENSATION MODULE

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ABSTRACT

The toll industry put great emphasis on preventing revenue leakage especially from fraud by toll tellers. An automatic vehicle classification system (AVC) has been developed in order to mitigate the problem based on the classes defined by Malaysian Highway Authority (MHA). The system uses treadle sensors to map tires and count the number of axles while the optical barrier is used to detect the presence of vehicle. However, since the short lifecycle because of wear and tear due to the nature of them being treaded by the vehicles, the treadle breaks quickly and needs frequent replacement. Disruptions during maintenance and replacement causing inconvenience and unreliability that results in a steady demand by worldwide toll collection industries for replacement or at least enhancement of the technology. Two approaches have been made to mitigate this problem. First, the materials in the treadle are improved and second, a system to compensate for small errors is developed. The sensor is changed from fragile contact switch to strain gage that has high fatigue limit. The new sensor housing is made out of stainless steel that has high fatigue limit of 260 MPa. Furthermore, to increase the treadle endurance, the sensors are contained in elastomeric material which possesses hardness of 70 (Shore A scale) that protects the sensors from external impact of vehicles yet still allows force to be transferred to the sensor. The new treadle sensor was tested and can last more than 5 million treading cycles as required by the industry. Moreover, a robust dual tire classification module is installed in the system that can maintain high accuracy even when some sensors have error. Test using simulated data shows that the algorithm can maintain 100% accuracy when two errors are present. The module was also tested on actual data that gives 99.83% accuracy. With these enhancements, the lifecycle of the device is elongated beyond 5 million cycles without compromising the accuracy. Thus, it prevents revenue leakage and avoids traffic disruptions that will contribute positively to the economy.

SISTEM PENGELASAN TAYAR BERGANDA YANG TEGUH DAN BOLEH HARAP DENGAN MODUL PEMBETULAN RALAT

ABSTRAK

Industri tol sangat menekankan kepada pencegahan kebocoran hasil terutamanya daripada pengutipan tol. Sebuah sistem pengelasan kenderaan automatik telah dibangunkan dengan tujuan untuk mengatasi masalah tersebut bersandarkan kepada kelas kenderaan yang ditetapkan oleh Lembaga Lebuhraya Malaysia (LLM). Sistem tersebut menggunakan penderia injak-injak untuk memeta corak tayar dan mengira jumlah gandar manakala penghadang optik digunakan untuk mengesan kehadiran kenderaan. Walaubagaimanapun, memandangkan kitaran hidup yang pendek yang disebabkan haus dan lusuh kerana tabiinya yang sentiasa digelek kenderaan, injak-injak tersebut cepat rosak dan perlu diganti selalu. Gangguan ketika penyenggaraan menyebabkan kesulitan dan ketidakbolehharapan dan ini menuntut industri tol di seluruh dunia untuk menghasilkan kaedah yang lebih efektif untuk mengganti atau menambahbaik teknologi yang sedia ada. Dua pendekatan telah diambil untuk mengatasi masalah ini. Pertama, menambahbaik bahan-bahan untuk membuat injak-injak dan yang kedua, membangunkan sebuah sistem pembetulan bagi ralat kecil. Penderia tersebut telah ditukar daripada suis sentuhan yang mudah rosak kepada jenis tolok terikan yang mempunyai had lusuh yang tinggi. Penutup penderia itu telah dibuat daripada keluli tahan karat yang mempunyai batas lesu tinggi iaitu 260 MPa. Manakala, penderia itu diselaputi oleh bahan elastomerik dengan kekerasan 70 (skala Shore A) yang melindunginya daripada impak luaran oleh kenderaan tetapi masih membenarkan daya untuk dipindahkan kepada penderia itu. Penderia tersebut boleh bertahan lebih daripada 5 juta kitaran injakan seperti yang dikehendaki oleh industri. Tambahan pula, sebuah modul pengelasan tayar berganda yang teguh telah dipasangkan kepada sistem yang boleh mengekalkan kejituan yang tinggi walaupun terdapat beberapa penderia yang mempunyai ralat. Ujian menggunakan data simulasi menunjukkan yang algoritma tersebut dapat mengekalkan kejituan 100% walaupun wujud dua penderia yang mempunyai ralat. Modul tersebut juga telah diuji dengan data sebenar yang mana memberikan kejituan 99.83%. Dengan penambahbaikan-penambahbaikan ini, kitaran hidup peranti tersebut dapat dipanjangkan melebihi 5 juta kitaran tanpa berkompromi dengan kejituan. Justeru, ia mencegah kebocoran hasil dan mengelakkan gangguan trafik yang mana menyumbang secara positif kepada ekonomi.

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LIST OF ABBREVIATIONS

3D	Three dimensions
AVC	Automated Vehicle Classification
BHD	Berhad (Limited)
Co.	Corporation
CPU	Central processing unit
DAQ	Data acquisition
DTC	Dual tire classification
DTD	Dual Tire Detector
ECM	Error compensation module
EDM	Error detection module
exp	Exponential
GmBH	Gesellschaft mit beschränkter Haftung (Limited)
I/O	Input output
L	Low carbon
LED	Light emitting diode
LLM	Lembaga Lebuhraya Malaysia
MHA	Malaysian Highway Authority
MI	Micro Invention
OB	Optical barrier
OpAmp	Operational amplifier
PLUS	Projek Lebuhraya Usahasama Berhad
PU	Polyurethane
RBFNN	Radial Basis Function Neural Network
SDN	Sendirian (Private)
SmEDI	Simultaneous error detection and identification
SqEDI	Sequential error detection and identification
SS	Stainless Steel
SUV	Sports utility vehicle
UKM	Universiti Kebangsaan Malaysia
UTM	Universal Testing Machine

LIST OF SYMBOLS

$2\sigma^2$	Value to determine spread of RBF curve
A	Durometer scale that is commonly used to measure polymer hardness
b	Distance between input and center of RBF
cm	centimeter
c^q	Center of radial basis function at number q
f( )	Network simulation function
GHz	Giga Hertz
h	Hidden layer
Hz	Hertz
kN	Kilo Newton
kPa	Kilo Pascal
K	Gage factor
L	Low carbon
l	The narrowest significant width
m	meter
mm	millimeter
MPa	Mega Pascal
N	Total number of hidden nodes
q	Sequence of weight
R	Resistance
R_G	Strain gage resistance
s	seconds
SG	Strain gage
t	Tire pattern output
T	Matrix form of tire pattern output
V_{EX}	External voltage
V_{in}	Input Voltage
V_{out}	Output Voltage
W	Matrix form of network weight
w_q	Weight at number q
x	Tire pattern input

$\boldsymbol{\alpha}$	Matrix of all possible tire patterns and positions
$\boldsymbol{\beta}$	Matrix of $\boldsymbol{\alpha}$ with column 1 is zeroed
$\boldsymbol{\delta}$	Matrix of error data
ε	strain
$m\varepsilon$	milistrain
$\boldsymbol{\varepsilon}$	Matrix of useful error data
ζ	Matrix of useful error data for all positions
$\boldsymbol{\Phi}$	Matrix form of radial basis function
$\Phi(\ )$	Radial basis function
Ω	Ohm

CHAPTER I

INTRODUCTION

1.1 BACKGROUND

Highway authorities around the world have been using toll collection as a way to fund cost related to highway maintenance and expansion. This method is becoming more popular as they realized that the cost is increasing while tolling is a sustainable, stable and dedicated system for highway development. The revenue from toll is also used by government to develop other infrastructures in other less developed regions. This scheme helps to include more regions in the wealth circulation. Some governments may also use toll as leverage for development of private sector (Lindsey 2009). In Malaysia for example, technology based company such as Micro Invention, Hoptech and Touch n' Go are prospering and bringing positive impact on the economy and technology of this country.

There are three basic methods for toll collection that are practiced worldwide: manual toll, electronic toll and mixed toll. Manual tolling is the earliest method practiced by the toll concessionaire. In this method, toll booths are built on the highway and toll teller is appointed in each booth to collect and record the vehicle classes. The operation is slow but it can be mitigated by operating multiple lanes. Electronic toll is an automated system that either identifies or classifies vehicles, and charges them accordingly. The method is faster than manual toll but requires advance technology to operate successfully. Meanwhile, mixed tolling comprises of both manual toll and electronic toll as practiced in Malaysia (The World Bank Group).

There are mainly two systems that are implemented in toll operation. The first one is Automated Vehicle Classification (AVC) system. This particular system basically classifies vehicles into several classes based on the policies that are enforced by highway authorities. The classes are defined based on various parameters such as number of axle, number of tire, type of services, number of occupancy, weight and vehicle type. Many researches were conducted to automatically identify the classes using apparatus such as microphone, video camera, treadle, laser, infrared camera and metal loop. Usually this particular system integrates multiple apparatus in order to enhance its performance. The AVC system that proven to be reliable and robust was implemented and commercialized.

Another electronic toll system is Automated Vehicle Identification (AVI) system. Tags or transponders that are placed at vehicle windshield contain specific information regarding the vehicle class and its owner. The advancement of radio frequency identification technology made toll charging possible at highway speed. If the vehicle does not possess the transponder, the system will capture the license number image and track the user later (407 Express Toll Route 2010).

Drivers that uses manual toll pay their toll fee by cash or electronic bank card. For electronic toll, the toll fee is either pre-paid or charged monthly based on their usage like electric bill. AVC system is used by both toll collecting methods. In manual toll it is used for auditing while in electronic toll it is used for real-time classification. Toll operators put great emphasis on the accuracy and reliability of the system to ensure that there is no revenue leakage. Therefore, significant investment has been put at toll lane and toll plazas to achieve zero fraud (Monahan 2007).

Accuracy is greatly emphasized and margin of error is difficult to be tolerated in toll system. This is because a small percentage of error can contribute to huge revenue lost due to the high traffic volume. According to Malaysian Highway Authority (MHA), total highway traffic in 2010 is 1.4 billion vehicles (for more detail, refer to Appendix A). Let say if the error rate is 1%, the total vehicle that will be misclassified is 140 million. This shows the magnitude of the value that could have been lost due to poor accuracy.

AVC system usually comprises of sensor called treadle that is embedded in the road surface. However, due to its nature being extensively treaded, especially by the heavy weight vehicles, it wears off quickly and needs frequent replacement. Disruptions during replacement and maintenance are causing inconvenience and unreliability. As a result, there is steady worldwide demand to have replacement of technology or at least enhancement of it (Mirchandani & Head 2001; Mirchandani & Wang 2005).

1.2 PROBLEM STATEMENT

Treadles are sensors that are embedded in the road surface. It could function as axle sensor, dual tire detector (DTD), weigh sensor or speed sensor. When vehicle tire tread on the treadle, the force from vehicle will activate the sensor and produce output that will be used by AVC system to determine the vehicle class. Treadle design usually in the shape of a long bar that would cover the width of a single road pavement. The thickness of the treadle is usually in the range of 1.5 cm to 2 cm but the brute force that it would have to endure from heavy weight vehicles such as trailers and trucks do not match its size.

The treadle developed by Micro Invention (MI) Sdn Bhd functions as dual tire detector. It detects dual tire accurately but the treadle sensor that they manufactured has poor endurance and reliability. This challenge is not only faced by MI but most of treadle manufacturers around the world (Rosakranse & Emirick 1994; Park & Jeong 2001). This occurs mainly because the treadle was made of fragile components that break quickly under the harsh environment. There are multiple layers of components inside the treadle that scrape with one another while moisture and sand grains could creep inside it and damage the treadle. According to MI, their treadle could endure until 3 million treading cycles while their targeted life cycle of a treadle is at least 5 million treading cycle. Other manufacturers such as Sensor Line GmBH has standard warranty of 5 million treading cycle; International Road Dynamic Inc has standard warranty of 1 million treading cycle; and Electronique Contrôle Mesure has standard warranty of 4 million treading cycle (Electronique Contrôle Mesure ; International Road Dynamic Inc 2002; Sensor Line GmbH 2010; Jamaluddin 2011).

Meanwhile, MI system accuracy is 99.67% while the targeted accuracy is 99.95%. These targets are essential to compete internationally in the industry (Jamaluddin 2011). It is noted that over certain period of time, the accuracy rate of the system will drop significantly due to error that were caused by damaged sensors. Unfortunately, even when minor error appears, the whole treadle has to be replaced. The demand for high accuracy cannot be tolerated because huge toll collection loss will occur. Meanwhile, the replacement process would cause traffic congestion because active toll lane had to be closed. The replacement process would not only involve the change of treadle sensor but also involve process such as excavation, wiring, dissembling, assembling, calibration, and testing. The process could take from half day to a full day to finish. Furthermore, this event happens frequently. This frustration demands for a robust and reliable dual tire classification system. Error compensation module development that could maintain the high accuracy even when the treadle has some errors is very much needed. This module is important to elongate the treadle lifecycle hence lessen traffic disruption and lower the maintenance cost of the AVC system.

1.3 OBJECTIVES

This work is actually in collaboration between UKM and Micro Invention Sdn Bhd. These are the main objectives of this thesis:

i. To develop a reliable dual tire detector that can withstand beyond 5 million treading cycles.
ii. To integrate multiple sensor signals used at toll lanes hence increase the accuracy rate of vehicle classification up to 99.95%.
iii. To develop an error compensation module that can extend the treadle lifecycle.

1.4 SCOPE OF WORK

The scope of this thesis comprises of several tasks. The first task is development of reliable dual tire detector for single toll lane. The treadle developed should be an equidistance switch array built using Micro Invention mold. Moreover, the dual tire detector treadle will sample only the right side of vehicle tires. The prototype is expected to withstand at least five million treading cycles. It also should be able to connect to the lane computer systems.

The second task is development of a high accuracy and robust classification algorithm for the prototype. This includes when the sensor has minor errors. The classification is made for auditing toll teller and not electronic toll collection application. This means that classification is not a real-time application. Vehicles that use this service will stop completely before moving onwards. The vehicles also move in a fairly straight manner relative to the road.

1.5 THESIS ORGANIZATION

This thesis has six chapters. Overall, the thesis can be categorized into three main approaches for the technology enhancement. The first approach is finding literature review to assess the state-of-art technology. Secondly, from the assessment, the thesis will focus on developing in regards of the hardware or a reliable dual tire treadle sensor. Meanwhile, the third approach is development of robust dual tire detection software.

In Chapter 1, the background of toll industry is discussed and will be emphasized on AVC system role in toll collection. Then, the current issues of the system are presented. Later, the objectives of this thesis are mentioned.

Chapter 2 discusses at length about the sensors by other researchers in the field. Then, the sensors and methods that were developed by Micro Invention is also presented and compared.

Chapter 3 describes the new treadle design. It will discuss on the topic of the treadle material selection, size specification, spatial resolution determination and sensor selection. Later in the chapter, the method to validate the endurance of the treadle sensor is reviewed.

Chapter 4 regards the development of AVC algorithm according to vehicle class defined by MHA. The chapter emphasized about the dual tire classification system. In the system, there are dual tire classification algorithm, error detection module and error compensation module. Afterwards, methods to measure the performance of the systems are presented.

Chapter 5 contains the results and discussions of the thesis. This chapter displays results from treadle endurance test followed by performance of the dual tire classification system. Next, the results are challenged and refined in in-depth discussions.

Chapter 6 is the conclusions of the thesis. The main findings and contributions are recapitulated. Afterwards, some potential future works is proposed as the closure.

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

Firstly, this chapter defines vehicle class according to Malaysian Highway Authority (MHA) and the parameter associated with vehicle class. Then, the corresponding sensors to detect dual tire were described and discussed particularly the equidistance switch array sensor. Then, the dual tire classification systems that consist of dual tire classification algorithms, error detection module and error compensation module were assessed. Next, Micro Invention technology was described in regards to the topics that were touched earlier.

2.2 MALAYSIA VEHICLE CLASS

MHA was established in accordance to laws of Malaysia Act 231, the Highway Authority of Malaysia (Incorporation) Act 1980. One of the objectives of its establishment is to impose and collect tolls from motorists (Malaysian Highway Authority 2010). Motorists are tolled according to their vehicle class and distance of their travel using the highway. There are six classes of vehicles that were defined as shown in Table 2.1. Class 1, class 2 and class 3 are differentiated by their number of axles and tires. Motorcycles are class 0, taxis are class 4 and busses are class 5. However, motorcycles are exempted from toll fare. Meanwhile, busses and taxis have no difference in term of their number of axle and tires to class 1 and class 2 but they are differentiated by their services.

TABLE 2.1 Vehicle classes in Malaysia

Class	Icon	Description
Class 0		Motorcycles
Class 1		Vehicles with 2 axles and 3 or 4 tires excluding taxis
Class 2		Vehicle with 2 axles and 5 or 6 tires excluding buses
Class 3		Vehicle with 3 or more axles
Class 4		Taxis
Class 5		Buses

Source: PLUS 2012

2.3 DUAL TIRE DETECTOR TECHNOLOGY

Every dual tire detector (DTD) has the ability to indicate tire tread width. An overview of DTDs' categories is shown in Figure 2.1. The DTD can be categorized into two types which are treadle and camera. Meanwhile, the treadle can be divided into switch treadle and pressure sensitive cable treadle. The switch treadle can be further branched out to two parallel diagonal strip switch and equidistance switch array. Therefore, the DTD has four major models as follow:

i. Equidistance switch array
ii. Two parallel diagonal strip switch
iii. Pressure sensitive cable
iv. Camera

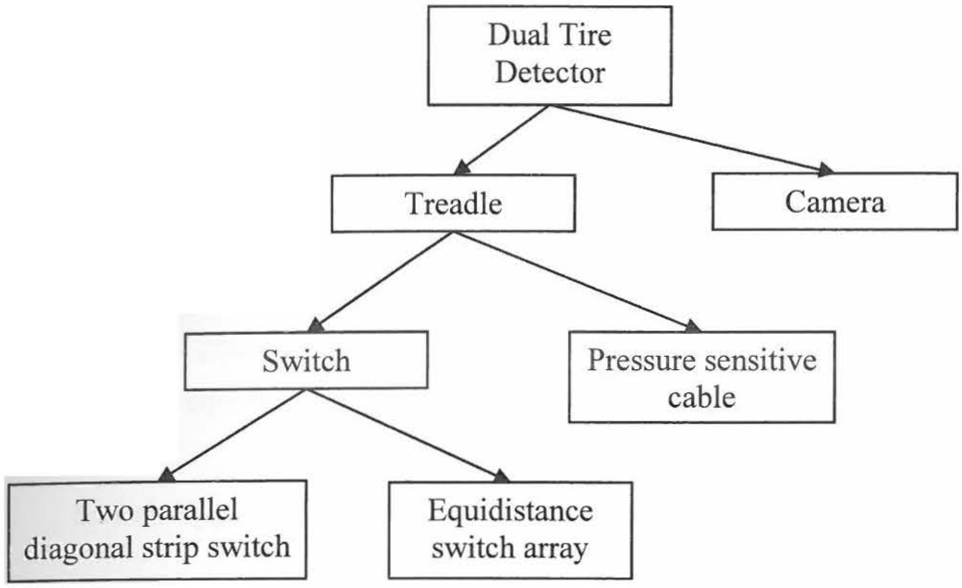

FIGURE 2.1 Dual tire detector categories

2.3.1 Camera

One of the methods to estimate tire width is through image processing. The method is done by firstly photographing the image of the vehicle rear side. Then, a tire region detection unit will scan through the binary coded image to find a half elliptical shape in the lowermost region. The tire shape is verified by template matching algorithm and the vehicle width is determined. Then, tire width is measured with reference to the vehicle width (Lim 2005).

Estimating tire width with image processing acquires complex algorithm and computation. Furthermore, the accuracy is very dependent on weather and lighting condition. In good condition the accuracy achieved for tire detection is only 78 % which is not satisfactory to the toll industry (Achler & Trivedi 2004). However, camera technology is developing rapidly by embracing alternative imaging devices such as infrared camera and scanning laser sensor (Hussain & Moussa 2005). One of the advantage of this DTD is the installation does not disrupt traffic flow. Furthermore, this method is contactless hence no possible damage by wear and tear.

2.3.2 Treadle

Treadles are the sensors that are embedded in the road surface. This type of dual tire technology is one of the most commonly used for automatic vehicle classification since the toll industry started. It can classify vehicle at high accuracy rate but faces the challenge of robustness and durability. There are two types of treadle namely switch type treadle and pressure sensitive treadle. Meanwhile the switch type treadle can be branched out to equidistance switch array and two parallel diagonal strip switches.

a. Switch Type Treadle

There are two types of switch treadle which are equidistance switch array and double parallel diagonal strip switch that will be discussed in the next section. Both DTDs use switch concept to indicate tire width. The treadle switch concept is the same as push-to-make switch concept. The individual switch will be actuated when pressed and go back to its normal form when the treading force has been removed.

Nagel's (1950) switch design is fully made out of metal and steel. However, components that are held together by nuts and bolts are easily damaged by constant vibration and deformation. The treadle packaging later included elastomeric material. This elastomeric material is used not only to protect the switches from direct contact of vehicles but also used as the mechanism to elate the switch after being pressed (Goble 1967). Example of treadle switch contained in elastomeric material is shown in Figure 2.2. In fact, both designs took the advantage of the material rigidity to return switch to its open circuit form after it was depressed.

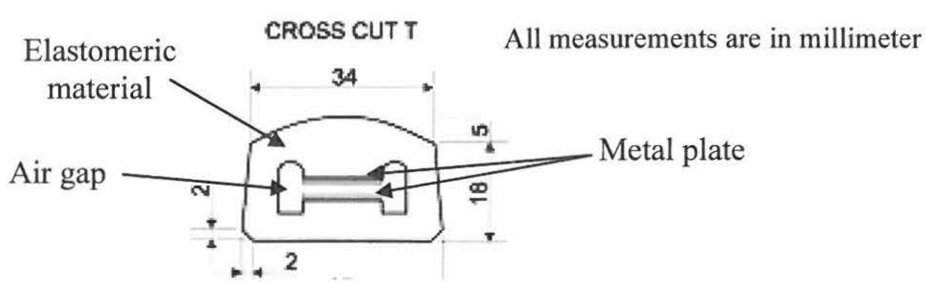

FIGURE 2.2 Example of treadle switch (cross section view)

Source: Intec Inc. undated