DIESEL ENGINE CONTROL AND IN-CYLINDER PEAK PRESSURE MONITORING SYSTEM USING RASPBERRY PI

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF NOTATIONS AND ABBREVIATIONS

ADC	Analog to digital converter
ATDC	After top dead center
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CA	Crank angle
CO	Carbon monoxide
CO_2	Carbon dioxide
DME	Dimethyl ether
ECU	Engine control unit
EGR	Exhaust gas recirculation
GPIO	General purpose input output
GUI	Graphical user interface
HC	Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
ICE	Internal combustion engine
IMEP	Indicated mean effective pressure
IRQ	Interrupt request
ksps	Kilo samples per second
LPG	Liquid Petroleum Gas
LTC	Low Temperature Combustion

Mbpd	Thousand barrels per day
Msps	Mega samples per second
NO_x	Nitrogen oxide
PCCI	Premixed Charge Compression Ignition
PID	Proportional integral and differential
PODE	Polyoxymethylene dimethyl ether
PWM	Pulse width modulation
RAM	Random access memory
RCCI	Reactivity Controlled Combustion Ignition
ROHR	Rate of heat release
SD	Secure digital
SOI	Start of injection timing
TDC	Top dead center

ABSTRAK

Enjin diesel merupakan salah satu enjin pembakaran dalaman yang memberi efisiensi yang lebih tinggi berbanding enjin petrol. Walau bagaimanapun, variasi dalam kitaran pembakaran enjin diesel menyebabkan kenurunan efisiensi dan peningkatan dalam gas pencemar alam. Untuk menyelesaikan masalah ini, kaedah yang berbeza telah dikaji dalam penyelidikan sejak beberapa dekad yang lalu. Dalam projek ini, unit kawalan enjin diesel telah dibangunkan menggunakan Raspberry Pi 3 B. Unit kawalan engin tersebut mempunyai keupayaan untuk melakukan pengiraan yang memerlukan kuasa pengiraan yang tinggi. Ia boleh mengubah masa suntikan dalam waktu sebenar berdasarkan pengiraan yang dilakukan pada data sensor. Algoritma gelung tertutup yang mudah dibangunkan untuk mengawal permulaan masa suntikan enjin diesel silinder tunggal menggunakan unit kawalan engin tersebut. Tujuan utama sistem gelung tertutup adalah untuk menilai keupayaan unit kawalan engin dalam melaksanakan algoritma gelung tertutup dalam jangka masa kurang daripada satu kitaran pembakaran. Unit kawalan engin yang dibangunkan mampu melaksanakan sistem gelung tertutup tanpa mengalami kegagalan. Puncak tekanan boleh dikekalkan pada nilai yang berdekatan dengan nilai yang dikehendaki. Unit kawalan engin juga dapat melaksanakan sistem gelung tertutup dalam jangka masa kurang daripada satu kitaran pembakaran. Namun begitu, keupayaan sistem gelung tertutup untuk mengawal variasi dalam kitaran pembakaran tidak cukup berkesan. Sisihan piawai puncak tekanan meningkat semasa sistem gelung tertutup diaktifkan apabila perubahan masa suntikan setiap kitaran pembakaran lebih besar daripada 0.5 ° selepas pusat mati atas.

ABSTRACT

Diesel engine is one of the internal combustion engines (ICE) which provides a higher efficiency compare to gasoline engine. However, the cycle to cycle variation of diesel engine causes a decrease in efficiency and increase in pollutant emission. To solve the problem, different methods have been investigated by the researches over the past decades. In this project, an engine control unit (ECU) of diesel engine has been developed using Raspberry Pi 3 B. The ECU has the capability to perform calculation which requires considerable computational power. It has the function of real time injection timing alteration based on the calculation it performs on sensors data. A simple closed loop algorithm is developed to control the start of injection timing (SOI) of a single cylinder diesel engine using the ECU. The main purpose of the closed loop system is to evaluate the capability of ECU in executing the closed loop algorithm within the time span of less than one combustion cycle. It is found that the ECU developed is able to execute the closed loop system without failure. The mean peak pressure can be maintained at a value close to the setpoint. The closed loop algorithm can be performed in the time span of less than one combustion cycle. The only drawback is that the cycle to cycle reduction ability of closed loop system is not effective enough. The standard deviation of peak pressure increases as the closed loop system is activated when the change in SOI during each combustion cycle is larger than 0.5 ° after top dead center (ATDC).

CHAPTER 1 : INTRODUCTION

1.1 Background

The increasing human population is accelerating the depletion of fossil fuel. Anne Goujon [1] performed predictive analysis which showed that the population is likely to increase from the present 7.6 billion to 11.2 billion in 2100. The increment of human population has caused a rapid growth in industrialization. This in turn results in elevated energy demand. Energy demand is anticipated to increase by 50 % to 80 % in 2020 compared to 1990 and in 2035, increased again by more than one-third [2]. Fossil fuel is one of the main energy sources. Survey of world energy resources by World Council Energy showed that 86.0 % of energy sources originated from fossil fuel in 2015 [2]. According to Florinda Martins et. al. [3], in 24 nations out of 29 European nations investigated, more than 60 % of the energy was generated from fossil fuel. Review on oil demand by N. Abas et. al. [4] showed that the peak oil production occurred in 2009 at a rate of 86 thousand barrels per day (Mbpd) and will decline to 40 Mbpd by 2050. In order to slow down the exhaustion of fossil fuel, a more efficient energy conversion system can be developed. In transportation, this can be achieved by creating an engine system which consumes less fuel per distance. Diesel engine is one of the ICE which offers a higher fuel efficiency compared to petrol engine due to its higher compression ratio. Compression ignition allows diesel engine to function at full air intake while petrol engine is only able to operate with air intake amount adjusted to generate the wheel rotational speed required. The throttle can be removed in diesel engine which improves the efficiency by reducing the head loss at throttle. On the other hand, extra energy is required to account for the loss due to presence of throttle in petrol engine. Hence, diesel engine can be one of the solutions to mitigate the depletion of fossil fuel.

Diesel engine efficiency can be improved in many ways to save more resources. One of the methods is by reducing the cycle to cycle variation in diesel engine. Cycle to cycle variation can cause a decrement in diesel engine efficiency [5]. The cycle to cycle variation pattern can be observed in the in-cylinder pressure profile. The problem is due to factors such as instabilities present in fuel injection system and the prolonged ignition delay. This can reduce the efficiency of diesel engine by causing unstable combustion process and misfire. The variation occurs more prevalently in diesel engine which applies combustion processes including Low Temperature Combustion (LTC), Homogeneous Charge Compression Ignition (HCCI) and Premixed Charge Compression Ignition (PCCI) [6]. Cycle to cycle variation becomes more obvious when parameters such as fuel properties are altered to improve diesel engine performance. The problem has also become one of the issues which hamper the effort to avoid the depletion of fossil fuel.

One of the methods to improvise the cycle to cycle stability of diesel engine is by introducing an engine control strategy which aims to mitigate the cycle to cycle variation. Diesel engine fuel injection system can be modified to carry out fuel injection at the right moment to induce a more stable combustion. For example, by retarding or advancing the SOI, the start of combustion will be different which results in different engine performance. By applying SOI in a correct way, the cyclic to cyclic variation can be avoided. The suggested solution posts another problem regarding conventional diesel engine. Conventional diesel engine applies mechanical fuel injection system. The fuel injection system is cam-driven. The injection timing is dependent on the engine rotational speed and inflexible. To overcome this limitation, common rail injection system can be implemented. The system operates electronically and hence the SOI timing can be adjusted freely by programming the injector controller. Most of the diesel engine with electronical fuel injection system determines the injection parameters from maps and tables. The maps and tables provide mapping from parameters such as vehicle speed and vehicle acceleration to the injection parameters to be used during each fuel injection. The mapping does not take the cycle to cycle variation into consideration. Thus, improvement has to be done on the injection control strategy.

There are some ongoing researches which investigate the methods to determine suitable injection parameters to be applied to reduce the cycle to cycle variation. These methods include closed loop system, physical model-based method, statistical method and others. Some of these methods are computationally expansive to be conducted on the current ECU. The methods may require the ECU to obtain readings from various sensors to perform decision making in injection. In order to employ the methods, the conventional ECU has to be modified. The ECU should have the capability to receive signals from sensors and sufficient computational power to compute the injection parameters to be applied in a short time span of a combustion cycle. In this way, the efficiency of diesel engine can be improved and in turn promoting diesel engine as a tool to slow down the depletion of fossil fuels.

1.2 Problem Statement

The cycle to cycle variation of diesel engine performance which occurs during fuel combustion has caused decrease in fuel efficiency and increase in pollutant emission. Current engine control system makes use of performance maps to determine injections parameter to be applied. This method is not tailored to reduce the cycle to cycle variation in diesel engine. Closed loop system has to be developed to minimize the cyclic variation. The conventional ECU does not provide the flexibility and sufficient computational power to conduct the closed loop algorithm in time.

1.3 Objective

The objectives of the project are shown below:

1. To develop a diesel engine ECU which is capable of executing a closed loop system.
2. To evaluate the performance of ECU in implementing the closed loop system.

1.4 Scope of Work

The scope of project is discussed in this section. The diesel engine used in this project is a single cylinder diesel engine. Single cylinder diesel engine is used due to its simplicity. Only a signal is required to activate the injection compared to more signals in multiple cylinder diesel engine. The engine operating range is around 1200 rpm with low load below 3 Nm. A low engine rotational speed of 1200 rpm is used to avoid the freezing of ECU due to the high rate of interrupts being activated. A low load below 3 Nm is used to avoid the stalling of engine. When ECU is still in the development stage, there will be problems encountered which cause the engine to be stalled or cannot be activated. To reduce the sources of problem, one of the methods is to apply a low load to ensure that engine does not stall due to load.

An ECU will be developed using Raspberry Pi 3 B. Raspberry Pi 3 B is selected as the hardware due to its specification and cost. The detailed information of Raspberry Pi 3 B is shown in section 3.3. A Linux real time operating system will be developed using Xenomai 3.0.8. Real time operating system is the operating system which process data which it receives in real time, usually without buffer delays. The term 'real time' means that the system will complete its task within the time required. Real time system is important in ECU development as the data has to be processed fast enough so that the system can response by injecting fuel on time. Xenomai is one of the real time development framework which can be used to program the control system of diesel engine. Detailed information about Xenomai can be found in section 3.6.

An injector driver will be set up. Injection driver is the hardware which initializes the fuel injection. It sends signal to injector and causes the opening of injector. The ECU developed from Raspberry Pi 3 B does not have enough potential difference and current output to cause opening in injector. Hence, injection driver has to be set up and integrated with ECU developed. Besides, a simple closed loop system is established using the ECU. Closed loop system is one of the method to reduce the cycle to cycle variation in engine performance. In this project, the closed loop system aims to reduce the cycle to cycle variation of peak pressure.

Finally, diesel engine performance based on peak pressure is investigated. The work aims to determine whether Raspberry Pi 3 B can successfully run closed loop system without failure. The effectiveness of closed loop system in reducing the cycle to cycle variation is not that important based on the objectives stated in section 1.3.

1.5 Chapter Outline

This thesis contains five chapters. The chapters are described as follow:

- Chapter 1 provides explanations about the energy consumption which involves the use of fossil fuels. Diesel engine is suggested as one of the solutions to slow down the fossil fuel depletion. The disadvantage and limitation of diesel engine is described in problem statement. The objective and scope of work of the project are explained too.
- Chapter 2 provides the literature review about research background of diesel engine and various methods implemented to improve its efficiency. The application of closed loop system in diesel engine ECU which will be conducted in this project is discussed.
- Chapter 3 describes the methodology to develop diesel engine ECU with closed loop system. The hardware and software required are explained in detail.
- Chapter 4 shows the diesel engine performance in term of peak pressure when the ECU equipped with closed loop algorithm is run. Discussion on the results is carried out.
- Chapter 5 contains the conclusion of the project. Future work recommendation is suggested in this chapter too.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

The literature review consists of three sections. Section 2.2 presents one of the problems faced in improving diesel engine efficiency, which is cycle to cycle variation of engine performance. In section 2.3, the methods which can be applied to overcome cycle to cycle variation in diesel engine are discussed. Effect of SOI timing towards diesel engine performance is explained in section 2.4. On the other hand, the alternatives to replace conventional diesel engine ECU so that the methods to minimize cycle to cycle variation can be implemented are investigated in section 2.5. In section 2.6, the current diesel engine technology which can contribute in the commercialization of diesel engine closed loop system is described.

2.2 Cycle to Cycle Variation

Cycle to cycle variation in diesel engine performance has been studied in a few past researches. The variation can be observed in various engine characteristics such as pressure, temperature, emission and others. The engine characteristics mentioned will fluctuate to a different value during the next combustion cycle compared to the current combustion cycle. According to Yang et. al. [7] and Murayama et. al. [8], cycle to cycle variation has caused a decrease in fuel efficiency and increase in pollutant emission. When the peak pressure becomes the limiting factor of power output, cycle to cycle variation of peak pressure will limit the engine power density [5]. On the other hand, Xu Min et. al. [9] discovered that cycle to cycle variation in combustion characteristics have caused large amount of pollutant emission as a minor change in combustion characteristic can affect the emission profoundly. Cyclic variation in diesel engine performance have become increasingly disruptive nowadays. This is due to the fact that the problem become more obvious when the parameters such as fuel properties are changed to enhance some aspects of diesel engine. According to Alexandru Cernat et. al. [10], when diesel fuel was substituted partially with Liquid Petroleum Gas (LPG), the cycle to cycle variation at the beginning of combustion process increased. Obed M. Ali et. al. [11] found that cyclic variation increased with higher concentration of diethyl ether additive added into biodiesel to reduce the Nitrogen oxide (NO_x) emission. In the attempt to partially substitute diesel fuel with dimethyl ether (DME) which is renewable, Ying Wang et. al. [12] found that the cycle to cycle variation of pressure and temperature increased with rising DME amount. Hence, solutions have to be implemented to reduce the cycle to cycle variation in diesel engine.

The root causes of cycle to cycle variation have been studied to mitigate the problem. Some researches [7, 13] found that cycle to cycle variation effect increased when intake temperature, intake pressure and injection timing were altered to increase ignition delay. Sczomak et. al [14] showed that ignition delay is the cause of cyclic variation of in-cylinder pressure. It has been shown that fuel with lower cetane number will result in greater cycle to cycle variation [7, 8]. Yang et. al. [7] and Musculus et. al. [15] observed that the cycle to cycle variation pattern were random or stochastic where short term prediction was not possible. Kyrtatos et. al. [5] studied the relationship between pressure fluctuation intensity of consecutive cycles using a return map. The results showed no correlation between the parameters. However, according to Vaughan et. al. [16], there is relationship between engine performance of consecutive cycle which lead to cycle to cycle variation, which can be described with bifurcation model. This relationship can signify that the cycle to cycle variation is actually deterministic and a suitable engine control system can be developed to predict the variation.

2.3 Methods to Reduce Cycle to Cycle Variation

By reducing the cycle to cycle variation and maintain the operating condition at the optimum condition, the efficiency of diesel engine can be improved. One of the methods to achieve this goal is by developing a better control strategy. The control strategy employed in conventional ECU of diesel engine is unable to mitigate the cycle to cycle variation effectively. In conventional compression ignition, the start of injection crank angle is determined by referring to the map and table. Accurate calibration has to be done to obtain the suitable values in the map. The calibration is done at steady state. When there are changes in engine operating point occurs, especially during acceleration and deceleration, the start of injection crank angle obtained from the map will not be able to produce optimum performance. The transient state occurs frequently at city where travelling will involve many starts and stops. Engine operation out of optimum point can cause a reduction in efficiency and increase in pollutant emission. The power output can be affected too. The fuel injection parameters extracted from maps and tables are not accurate enough to produce stable engine performance as described by Grahn et. al. [17], especially in reducing cycle to cycle variation. In addition, engine characteristics such as in-cylinder pressure and temperature are not taken into consideration when the map and table are calibrated. The map and table will not be able to be used to reduce the cycle to cycle variation of the engine characteristics when the data is not fed into the map and table.

Over the past few decades, a variety of more advanced diesel engine control systems have been developed to improve its fuel efficiency. One of the methods is by applying closed loop in engine control system. Closed loop system is able to control heat release rate and improve the engine combustion stability. This can reduce the pollutant emission and fuel consumption. Z. Yang et. al. [18] have developed indicated mean effective pressure (IMEP) closed loop control system which injected different amount of fuel based on the IMEP of previous combustion cycle. The Closed loop system which consisted of inner loop which served to reject the disturbances and the outer loop which was used for speed control purpose successfully reduce the cycle to cycle variation. However, closed loop system is unable to predict the best start of injection crank angle and injection timing to be applied to produce the most optimum engine operating point during the next instance. The efforts to fully optimize diesel engine performance leads to the development of method to predict the next instance of engine performance and implement decision which can result in the best performance.

Physical modelling of engine operating system has been carried out where the physical connections between parameters such as torque, rotational speed and others with engine performance are identified [19]. A very accurate physical modelling will involve the application of knowledge such as computational fluid dynamics and chemical kinetics of combustion which occurs in engine cylinders [20-22]. The drawback of the detailed physical modeling is the large computational power required to run the simulation. The large amount of time required to predict the system behavior causes the methods to be difficult to be implemented in real time with low computational power ECU. To overcome this shortcoming, Enzhe Song et. al. [23] have employed multi-zone modelling method which was the combination between single zone zero-dimensional model and computational fluid dynamics in creating the real time modelling of diesel engine combustion. They successfully achieved error of less than 5 % between simulation and experimental results by using hardware with only 2.2 GHz clock speed. With the advent of real time diesel engine combustion modelling, the better injection parameters can be determined based on the results to obtain a more stable combustion during the next cycle.

There is another method which can be conducted to optimize diesel engine performance. Mathematical modelling based on the engine parameter applied and the resulted engine performance can be developed. Over the past decade, machine learning which is developed based on mathematical modelling has emerged as an effective tool in prediction model. There have been many types of machine learning algorithm being established, for example neural network [24], support vector machine [25] and genetic programming [26]. Some researchers have developed ECU based on neural network. Neural network is basically a statistically deep learning method which is used to find the mathematical relationship between input and output without the needs to model the physical system. By applying the input predicted from neural network, the best injection parameter can be determined to produce the most optimum engine performance during each cycle. According to Gurgen et. al. [27], the artificial neural network developed can predict the experiment data up to correlation coefficient of cycle to cycle variation ranging from 0.858 to 0.983. Vaughana et. al. [16] showed that the cycle to cycle variation can be reduced by applying weighted ring extreme learning machine which is one of the neural network algorithms. The algorithm is fast enough to be executed in real time in typical controller. Compared to detail physical modelling, neural network may consume less computational power depends on the types of neural network used. The integration of neural network in engine control system is a field which is worth exploring. It is hoped that diesel engine efficiency can be improved through neural network. In this way, diesel engine can be applied in a wider area to prevent the depletion of fossil fuel.

2.4 SOI Timing

Injection parameters are engine parameters which can be adjusted to improve the engine and combustion performance. Injection parameters include SOI timing, mass of fuel injected, sequences of injection such as pilot, main and post injection, dwell time between injections, injection pressure and others. SOI timing is the time or crank angle when the fuel starts to be injected. Pilot injection is the injection performed before main injection while post injection is the injection performed after main injection. Dwell time is the period or crank angle travelled by piston between two consecutive injection. Injection pressure is the pressure applied to force the fuel out of injector with the purpose to atomize the fuel and increase the momentum of fuel so that the fuel can travel for a longer distance encompassing more area in cylinder. The change in these injection parameters can affect the engine and combustion performance including in-cylinder pressure profile, in-cylinder temperature profile, heat release rate profile, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and others. Engine emission characteristics such as amount of carbon, carbon monoxide (CO), NO_x, soot and others can be influenced by injection parameters too.

In this project, SOI timing will be altered in the effort to reduce the cycle to cycle variation of peak pressure, hence the effect of SOI timing on engine and combustion performance will be discussed. According to Amin Yousefi et. al. [28], early SOI timing caused an increase in maximum in-cylinder pressure and BTE for all engine loads being applied when natural gas-diesel duel fuel was used. However, the NO_x emission was observed to increase too. On the other hand, unburned methane and carbon dioxide (CO_2) equivalent emission decreased with advancing injection timing under low load-low speed and medium load-high speed condition. E. Plamondon et. al. [29] found that small retardation of SOI timing reduced the particulate matter and NO_x amount. Haozhong Huang et. al. [30] have studied the multiple injection effects on engine performance of natural gas-diesel dual fuel engine. They observed that the thermal efficiency and NO_x emission increased first and then decreased with the advancing first injection timing. However, the maximum pressure rise rate, CO and methane emissions initially decreased before increasing at greatly advanced injection timing. In reducing particulate matter emissions of diesel engine by using polyoxymethylene dimethyl ether (PODE) additive and altering the injection parameters, Hui Chen et. al. [31] have found that by applying PODE-diesel blends and late injection timing, particulate matter emission can be reduced. However, when the SOI timing happened too close to top dead center (TDC), the concentration of particle number will increase.

H. G. How et. al. [32] investigated about the effect of injection timing and multiple injection scheme on diesel engine combustion and emission characteristics using fuel blended with biodiesel. It was discovered that a significantly low level of NO_x emission can be achieved by performing the injection later with triple injection strategy. B. Ashok et. al. [33] studied the effect of injection timing and exhaust gas recirculation (EGR) on performance of diesel engine using Calophyllum inophyllum methyl ester fuel. They found that by performing the SOI timing later, NO_x emission was only cut down by a limited amount but the engine performance suffered from remarkably loss. Arun Kumar Wamankar et. al. [34] observed that BTE of diesel engine powered using carbon-black-water-diesel slurry is higher when injection timing is performed earlier. Avinash Kumar Agarwal et. al. [35] discovered that earlier injection timing generates greater rate of heat release (ROHR) in the initial combustion stages. Advanced injection timing results in larger brake mean effective pressure (BMEP) and BTE. On the other hand, BSFC and temperature of exhaust gas decreased sharply for early SOI. They also found that advanced SOI caused emission of CO and hydrocarbon (HC) to be lower while NO_x emission amount to be remarkably greater. From the observations of past researches, it can be inferred that SOI timing can be altered to improve many aspects of diesel engine performance. By applying suitable control system algorithm to adjust the SOI timing in the correct way, the diesel engine performance can be enhanced.

2.5 Diesel Engine ECU Alternatives

Diesel engine ECU plays the role to control the actuators in diesel engine such as fuel injector to make sure that diesel engine operates at its optimum performance. It reads the signals from various sensors in engine bay and interpretes the data with multidimensional performance maps or lookup tables. The ECU then activates the engine actuators based on the output. Conventional ECU in typical vehicle is usually unable to be reprogrammed by user. The ECU stores performance maps which cannot be edited to suit different conditions.

When researches on diesel engine are carried out, conventional ECU is usually not used for the purposes due to its inflexibility, especially when different types of algorithm have to be executed by the ECU. Besides, even though conventional ECU is fast enough to interpret the sensors data through performance maps, it may not be computationally powerful enough to run certain algorithms, especially the diesel engine modelling algorithm which is discussed in section 2.3. The clock speed of ECU processor has to be sufficiently high to complete the analysis tasks within the time span of less than one combustion cycle. Hence, alternative for conventional ECU has to be found to continue the research to improve diesel engine performance.

Different controllers have been used as diesel engine ECU to overcome the disadvantages of conventional one. Sarthak Nag et. al. [36] have applied LabVIEW based control system to control the injection timing and duration of hydrogen diesel dual fuel engine with EGR. E. Plamondon et. al. [29] have developed diesel engine ECU by using CompactRio system (cRio-9012) equipped with configurable FPGA chassis (NI cRIO-9104). The injection parameters were adjusted by using LabVIEW program. In studying the potential improvement in reducing particulate matter emission of diesel engine using PODE additive and different injection parameters, Hui Chen et. al. [31] employed Bosch ECU with INCA software and open ECU to have a flexible control on injection parameters. Haozhong Huang et. al. [30] too used INCA6.2 software and open ECU to control injection parameters in investigating effect of multiple injection in natural gas-diesel dual-fuel engine. Y. H. Teoh et. al. [37] have developed diesel engine ECU by using Arduino microcontroller in the study of injection dwell angle effect on engine performance of diesel engine fueled with coconut oil-diesel fuel blends. Adam Vaughan [16] employed Raspberry

Pi to build diesel engine ECU which was capable of performing calculation to predict next combustion cycle combustion phasing of crank angle (CA) 50 in the time span of less than one combustion cycle. From the literature review, it is found that various software and hardware can be used to develop diesel engine ECU with high flexibility. The tools have to be chosen based on the factors such as flexibility, function, computational power, cost and others.

2.6 Current Diesel Engine Technology

There are several diesel engine technologies introduced recently which can contribute in commercializing the diesel engine that employs closed loop system to improve the combustion performance. One of the technologies is the highly flexible fuel injection system. The example of this system is Continental PCRs5 piezo common rail injection system [38]. The system can function at a maximum rail pressure of 2500 bar. It is able to carry out closely spaced split injections with a high accuracy. Delphi DFI21 diesel engine fuel injector can withstand rail pressure as high as 3000 bar without causing obvious fuel consumption [39]. It also allows more flexible multiple injection scheme to be conducted. DFI21 injector has been used in F3 common rail system which is equipped with closed loop system. The electronics embedded in injector monitor its performance and tune the injector operation to improve its life span. On the other hand, Denso has developed i-ART technology, which is a tiny pressure sensor embedded in injector [40]. In this way, the in-cylinder pressure profile can be obtained and fed into ECU so that closed loop system can be established to adjust the engine operating parameters in order to improve engine performance. The embedded pressure sensor can save the cost required to modify the structure of diesel engine to fit in pressure sensor in order to incorporate closed loop system into a conventional vehicle.

CHAPTER 3 : METHODOLOGY

3.1 Introduction

In this project, a diesel engine ECU which is capable of implementing closed loop system is developed to improve the efficiency of diesel engine. BSFC is one of the indicators of efficiency of diesel engine. It is the ratio of fuel consumption rate to power generated. The lower the BSFC the higher the efficiency of engine. As power is the product of torque and rotational speed, efficiency can be improved when a larger torque is produced with the same fuel consumption. Large torque can be generated by applying a high pressure on the engine piston during combustion. The ECU developed aims to perform injection at the crank angle such that the start of combustion will result in the peak pressure crank angle which produce a large torque consistently. The peak pressure should occur shortly after TDC when the volume of engine cylinder is slightly greater than the minimum value. The injection parameter which is controlled by the ECU will be the SOI crank angle. During combustion, the peak pressure will suffer from cycle to cycle variation. This causes the peak pressure position to be away from the optimum position. Hence, the SOI crank angle has to be adjusted correctly to ensure that peak pressure always occurs at the optimum position.

The architecture of the ECU which is developed in this project is shown in Figure 3.1. Raspberry Pi 3 B is used as the ECU loaded with closed loop system. Piezoelectric pressure sensor is used to measure in-cylinder pressure. As the pressure sensor only output milli-coulomb of charge, charge-to-voltage converter and voltage amplifier are used to convert pressure sensor charge to voltage which is large enough to be measured. As

Raspberry Pi 3 B only can receive digital signal, an analog to digital converter (ADC) is used to convert voltage from amplifier to digital signal. To reduce the voltage to the range which can be received by ADC, a potential divider is constructed between amplifier and ADC. Rotary encoder is used to measure the crank angle. An Arduino Mega is used to receive signals from rotary encoder. Based on the signals, it will fire another signal to Raspberry Pi 3 B to start the in-cylinder pressure measurement. The signal from Arduino Mega to Raspberry Pi has to be stepped down using potential divider to suitable value too. The signals from rotary encoder is also fed into Raspberry Pi 3 B through a potential divider to enable the crank angle measurement. A simple closed loop algorithm will be coded in real time development platform, Xenomai. With crank angle and in-cylinder pressure as input, the suitable SOI timing will be determined. Raspberry Pi 3 B will transmit a signal at the right SOI timing to another Arduino Mega. The Arduino Mega is used as microcontroller to activate injector driver at the correct timing. As the output voltage of Raspberry Pi 3 B is too low to activate interrupt in Arduino Mega, an operational amplifier is used to amplify the signal from Raspberry Pi 3 B before it reaches Arduino Mega. By monitoring the change in engine performance when closed loop system is activated or deactivated, the evaluation on the performance of ECU can be made. It is expected that through suitable SOI timing, the crank angle where peak pressure occurs can be adjusted to the optimum value to improve the diesel engine efficiency.

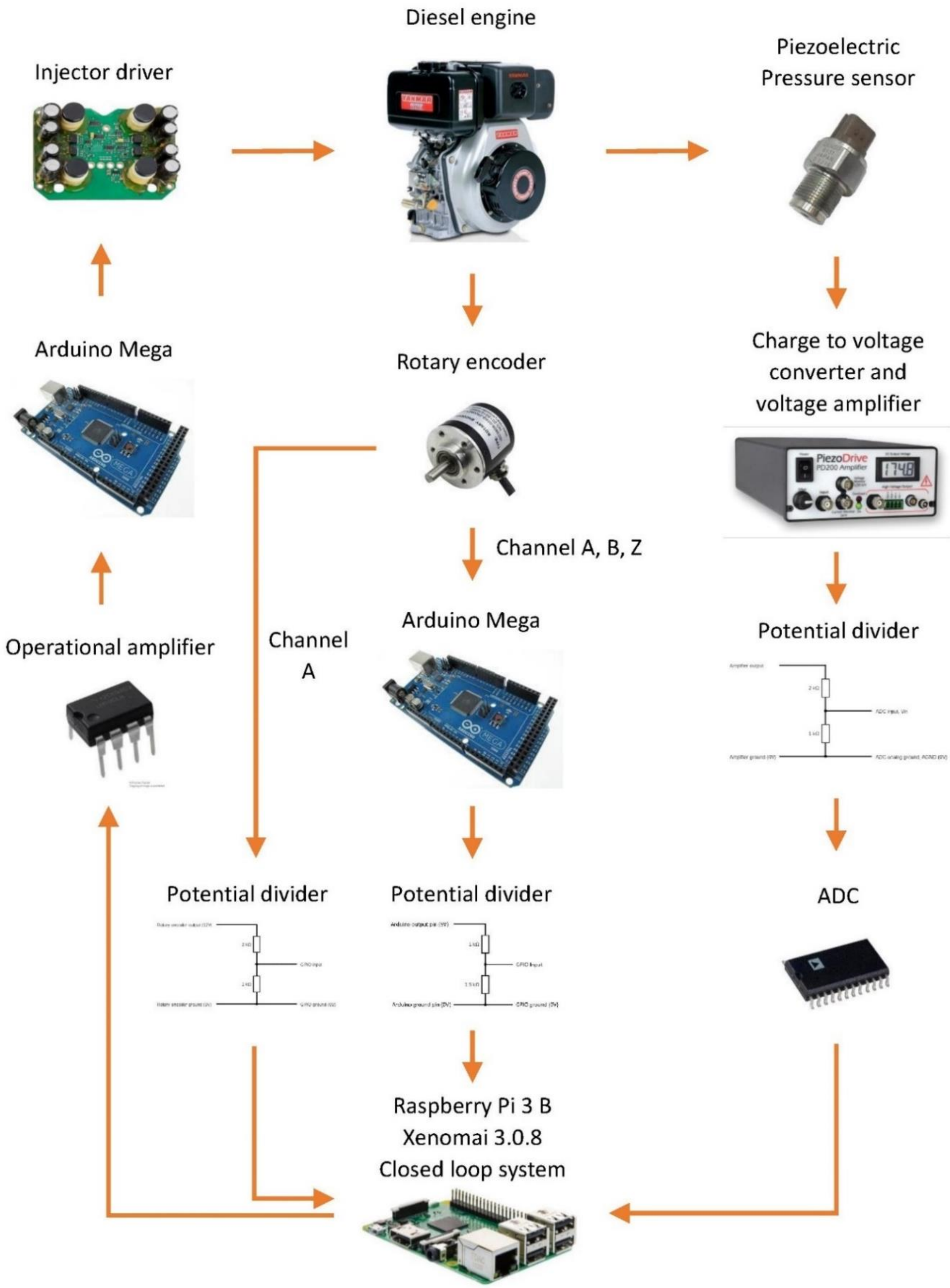

Figure 3.1: Diesel engine control system

3.2 Diesel Engine Specifications

The single cylinder diesel engine used in this project is a modified YANMAR L48N6 air-cooled single-cylinder compression ignition diesel engine as shown in Figure 3.2. The mechanical fuel injection system of the diesel engine has been replaced with electronic fuel injection system. The specification of the diesel engine is shown in Table 3.1. The fuel injection system will be modified again to be adapted to ECU which is developed using Raspberry Pi 3 B.

Figure 3.2: YANMAR L48N6 single cylinder diesel engine

Table 3.1: Specification of YANMAR L48N6

Parameter		Unit
Bore	70	mm
Stroke	57	mm
Displacement	219	cm^3
Rated power	3.5	kw
Rated speed	3600	rpm
Compression ratio	20.1:1	

3.3 ECU Specifications

Raspberry Pi 3 B will be used to build the ECU of the diesel engine. It is shown in Figure 3.3. Raspberry Pi 3 B is selected compared to other microcontrollers as it is a microcomputer which serves different functions such as the ability to store data directly in its internal storage which is secure digital (SD) card. Besides, Raspberry Pi 3 B can be connected to monitor to view the real time performance of diesel engine. Its random access memory, RAM (1 GB) and clock speed (1.2 GHz) is also considered as sufficient to provide the necessary computational power. As its operating system, Linux is open source, it is easy to obtain developed tools and technical supports from Internet. The cost of Raspberry Pi 3 B is also low at around 35$ (RM145). Table 3.2 shows some specifications of Raspberry Pi 3 B.

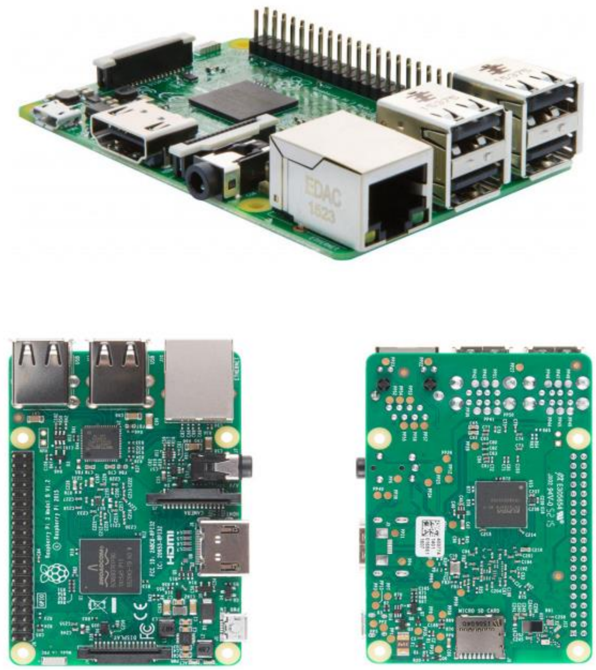

Figure 3.3: Raspberry Pi 3 B

Table 3.2: Raspberry Pi 3 B specifications

Specifications	**Value**
Processor	• Broadcom BCM2387 chipset. • 1.2 GHz Quad-Core ARM Cortex-A53 (64 Bit)
GPU	Dual Core Video Core IV® Multimedia Co-Processor
RAM	1 GB LPDDR2
Operating system	Linux, Raspbian
General purpose input output (GPIO) connector	• 40-pin 2.54 mm (100 mil) expansion header: 2x20 strip • Providing 27 GPIO pins as well as +3.3 V, +5 V and GND supply lines

3.4 Rotary Encoder

Raspberry Pi 3 B will receive signals from rotary encoder and pressure sensor. The signals will be processed by closed loop algorithm and appropriate response can be produced by sending signal to fuel injector. Rotary encoder is used to measure the crank angle of diesel engine. The digital rotary encoder used has three terminals, which are labeled as terminal A, B and Z. Terminal A and B can generate 720 pulses every rotation which corresponds to 0.5 ° crank angle resolution if the rise of pulse is read and 0.25 ° resolution if change in signal is read while terminal Z generates one pulse every rotation. As terminal B pulse has a phase difference of 90 ° compared to that of terminal A, both pulses can be read to obtain a finer resolution of 0.25 ° (rise of pulse is read only) or 0.125 ° (change in signal is read).

The pulses will be used as interrupts to trigger Raspberry Pi 3 B so that it read signals from pressure sensor. In this way, the in-cylinder pressure at each crank angle measured by rotary encoder can be obtained. The finer the crank angle resolution, the closer the predicted crank angle where the peak pressure occurs to the real value. However, due to the limitation of clock speed, a less fine crank angle resolution has to be applied. Raspberry Pi 3 B cannot receive interrupts with frequency higher than 20 kHz. In this experiment, the test case involves an engine rotational speed of 1500 rpm. From the calculation, 0.5 ° crank angle resolution is selected as finer crank angle resolution will result in interrupts frequency which is greater than 20 kHz. Hence, only terminal A of the rotary encoder is connected to Raspberry Pi 3 B. As the output of rotary encoder is 12 V, the signal cannot be channeled directly to Raspberry Pi 3 B with GPIO which can read a maximum digital input of 3.3 V. Hence the output should be stepped down to slightly below 3.3 V before it is read by GPIO. The output can be stepped down by using the potential