

Sudan University of science and Technology
College Of Graduate Studies



Fault Tolerance Analysis in Fuel Control System Using SIMULINK Software

تحليل خطأ السمامح في منظومة التحكم بالوقود باستخدام
برنامج (Simulink)

*A thesis submitted in Partial Fulfillment for the Degree of
M.Sc. Degree in Mechanical Engineering (Power)*

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Dedication

To my father who give me direction to the sky

To my mother who gives me lovely life

To my brothers and sisters who give me support

To my wife who gives me a wormed Life.

AKNOWLEDGEMENT

First and foremost, I would like to express my sincere Thanks to my thesis supervisor:

Dr. **Ali Mohammed Hamadan Adam** for providing me their precious advices and suggestions. This Thesis wouldn't have been a success for me without their comments and suggestions.

Also I would like to thank Sudan University of Science & Technology for providing me such a graceful opportunity to become a part of its family.

Last I would like to thanks the entire person those are related to thesis directly or indirectly.

Abstract

This research aims to analyze and address the technical study Fault Tolerance in controlling the fuel map by predicting the expected failures to occur in the actuators unit the internal system (Fuel Map) and make the necessary compensatory accounts and estimates to ensure the continuation of the work the engine on an ongoing basis with a failure until the failure treatment or programmatically change the system on part if necessary. Through research was to explain the definition of control on the fuel system and the internal unity of the four main its component and then analyze and clarify the operational equation governing the experimental design for the operation of the system. Through the research results it has been reached that the system can operate in critical operating condition and performance at (70%) parallel to the proportion of the fuel/air ratio tune up (10.22). Evidence has also been through the chart of results that strictly controlled system work to turn off the system when malfunction in more than one sensor of the system so as to ensure the safety of the engine and the reduction of specific fuel consumption and ensure the continuation of the work of high-performance engine effectively future

مستخلص البحث

يهدف هذا البحث لتحليل ودراسة تقنية معالجة تسامح الخطأ (Fault Tolerant) في منظومة التحكم في الوقود من خلال التنبؤ بالأعطال المتوقعة الحدوث في وحدة المشغلات الداخلية للمنظومة والقيام بإجراء الحسابات التعويضية والتقديرية اللازمة لضمان إستمرار عمل المحرك بصورة مستمرة مع وجود العطل لحين معالجة العطل برمجياً أو تغيير جزء المنظومة المعني إذا لزم، ومن خلال البحث تم توضيح وتعريف منظومة التحكم في الوقود ووحدتها الداخلية بمكوناتها الأربعة الرئيسية ومن ثم تحليلها وتوضيح المعادلات التشغيلية التجريبية التصميمية الحاكمة لتشغيل المنظومة. توصلت من خلال نتائج البحث إلى أن المنظومة يمكن أن تعمل في ظروف تشغيلية حرجة وبمعدل أداء (70%) بموازاة نسبة وقود/هواء تصل قيمتها حتى (10.22) ، كما أثبتُ بيانياً أن المتحكم الدقيق للمنظومة يعمل على إيقاف المنظومة عند حدوث عطل في أكثر من حساس للمنظومة وذلك لضمان سلامة المحرك والحد من استهلاك الوقود النوعي وضمان استمرار عمل المحرك بفعالية أداء عالية مستقبلياً.

Content list

Dedication.....	ii
Acknowledge.....	iii
Abstract.....	iv
مستخلص البحث.....	v
List of contents	vi
Abbreviation	ix
List of Table.....	x
List of figure.....	xi

Chapter One: Introduction & literature Review

1.1 Introduction	2
1.2 Research important.....	3
1.3 Objective of research.....	3
1.4 Research approach.....	3
1.5 Previous Studies.....	3
1.5.1 Fault tolerance control for EMS system with sensor failure.....	4
1.5.3 Fault tolerance control for Unmanned Underwater vehicle.....	5
1.5.5 Fault tolerance multi-sensor switching control strategy	8

Chapter Two: Engine Control Unit (ECU) & Fuel sensor

2.1 Preface.....	11
2.1.1 ECU Function.....	9
2.1.2 The ECU Content.....	9

2.2 The ECU Elements	11
2.2.1- Input Condition	11
2.2.1.1. (AMP).....	11
2.2.1.2. (A/D) convertor.....	11
2.3 ECU Processing.....	12
2.4 Memory types.....	13
2.5- Input.....	14
2.6- Sensors.....	15
2.10.1 Manifold Absolute Pressure (MAP).....	16
2.10.2 Oxygen Sensor.....	17
2.11 Signals Output	18
2.11.1- Throttle Position Sensor.....	19
2.12 Speed Sensor.....	20

Chapter Three:

Implementation of fault tolerance Technique in Fuel Control System

3.1 Preface.....	22
3.2 Analysis and Physics.....	22
3.2.2 Intake Manifold.....	23
3.2.3 Intake Mass Flow Rate	23
3.3 Throttle/Manifold Subsystems	24
3.4- Fuel Rate Controller	25
3.4.1 Control Logic.....	28

3.5 Sensor Correction.....	32
3.6 Air Flow calculation	30
3.7 Fuel Calculation	31
3. 8 Faults, failures and malfunctions	32
3.8.3 Malfunction.....	33
3.9 Reliability, Safety, Availability, Dependability and Integrity....	33
3.10 Fault tolerance and redundancy.....	34
Types of Faults.....	36
3.10.2 Process and fault modeling.....	37
Chapter Four: Result & Conclusion	
4.1- Result and Conclusion.....	40
4.2Recommended	46
4.3 3Reference.....	47

Abbreviation	
ECU	Engine Control Unit
EGO	Exhaust Gas Oxygen
P _m	Manifold Pressure
EMS	Electromagnetic suspension
MAP	Manifold Absolute Pressure Sensor
A/D	Analog to Digital Convertor
CPU	Central Processing Unit
AMP	Amplifier
KAM	Keep A life Memory
\dot{m}_{ai}	mass flow rate into manifold (g/s)
\dot{m}_{ao}	Mass flow rate of air out of manifold(g/s)
Θ	Throttle angle (deg)
R	Specific gas Constant
T	Temperature (K)
V_m	Manifold volume (m^3)
V_{cd}	Engine displacement cylinder volume
η	Volumetric efficiency
MEMS	Micro Electro Mechanical Systems
Q	Intake Mass Flow
FTC	Fault Tolerant Control
LEV	Laborious Extra-Orbital Vehicle

λ	Air Flow rate
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List Of Tables		
Table No.	Title	Page No.
Table 3.1	Type for faults failures and malfunctions	35
Table 3.2	Primary Fault Different Components	36

List Of Figure

Figure No.	Title	Page
Fig 2.1	The Engine control unit	10
Fig 2.2	ECU Components	10
Fig 2.3	ECU Diagram	12
Fig 2.4	Random Access Memory	10
Fig 2.5	The ROM	12
Fig 2.6	Keep a Live Memory	13
Fig 2.7	Map Sensor	16
Fig 2.8	Oxygen Sensor	17
Fig 2.9	Feedback Oxygen Sensor	18
Fig 2.10	Throttle Position Sensor	19
Fig 2.11	Speed Sensor	20
Fig 2.1	Fuel control system model	29
Fig 3.2	Fuel rate controller subsystem	27
Fig 3.3	The Control Logic Chart	27
Fig 3.4	Sensor Correction	28
Fig 3.5	Absolute Pressure reconstruction	30
Fig 3.7	Fuel calculation Subsystem	31
Fig 4.1	Comparative result for simulated Air/flow fuel ratio	41
Fig 4.2	Comparative result for simulated fuel flow rate	42
Fig 4.3	Comparative result for simulated when two sensor failed	45

Chapter one:
Introduction and Literature Review

1.1 Introduction:-

There are two main types of combustion engines.

First: external combustion engine; in this type combustion occur outside the engine.

Second: internal combustion engine; the energy is released by burning or oxidizing the fuel inside the engine. The main purpose of internal combustion engines is production of mechanical power from chemical energy contained in fuel. The fuel-air mixture before combustion and burned products after combustion are actual working fluids. The work transfers which provide the desire power output occur directly between working fluids and the mechanical components of the engine. Internal combustion engine mainly is divided to two types Spark-Ignition engines (SI) and Compression-Ignition engines (CI).

In engine control systems fuel measurement is a very important element in control operation which significant related to air-fuel ratio λ . Air-fuel ratio is an important variable for fuel control which based on different control concepts (will discuss in chapter four). A modern fuel control system essentially relies on feedback of sensors located in different position part of automotive. Any effect or miss- position of these sensors will give rise a bad situation to fuel control system operation which no longer result in engine vacation. In fact, there are a different between a fault and error which both used interchangeably (This will discuss in chapter three), and the miss-operation of fuel control system due to sensors limitation is considered a fault for the system which open the gate to use a fault-tolerance control system concepts.

1.2 Research Important:

Programming fuel control system with ability of handling failure mode of sensors in fuel control system is a very important issue due to the following reasons:

- (1) Safe the engine in failure mode from consumption more fuel or give less fuel need to combustion which issued to damage in engine operation.
- (2) Also momentousness is being clear in travelling through faraway location since there is no maintenance / repair workshops.
- (3) Another significant view, the fault-tolerance fuel control system is pertinent to a modern control systems in the automotives return to (MEMS) used in those systems and gradually automotive technology it removes mechanical, electrical, and finally approach to electronic-computational system.

1.3 Objective of the research:

- (1) Explain the Fault tolerance of fuel control system.
- (2) Save the system in safe mode.

1.4 Research approach:

The research aim to using MATLAB / SIMULINK to build a model comprises three main blocksets.

1.5 Previous Studies

There are many researches that fault tolerant system adopted in the address line of sensors, for example:

1.5.1 Fault Tolerant Control for EMS systems with Sensor Failure:

Konstantin Michal, al (control and automatio,2009.Med 09. 17th Mediterranean conference) presents a method to recover the performance of an EMS (Electromagnetic suspension) under faulty air gap measurement. The controller is a combination of classical control loops, a Kalman estimator and analytical redundancy (for the air gap signal). In case of a faulty air gap sensor the air gap signal is recovered using the Kalman filter and analytical redundancy. Simulations verify the proposed sensor Fault Tolerant Control (FTC) method for the EMS system. In recent years, Magnetic LEV citation (MAGLEV) systems have been attractive to the transport industry due to a number of advantages they offer compared to the conventional wheel-on-rail systems. In particular, maglev trains have no mechanical contacts with the rail thus reducing maintenance costs, although in general building maglev rail infrastructure is more expensive than conventional rail infrastructure.

MAGLEV suspensions offer high performance with desirable levels of ride quality; however they are stabilized systems and can be very sensitive to sensor faults since there is high probability of instability under sensor faults. If the EMS system becomes unstable it can either fall off or stick to the track causing possible failures of the whole system. Hence, being a critical fail-safe system substantially increases costs as it is requires a fault tolerant control structure.

1.5.2 Thesis Analysis:

In this paper, a method has been proposed to recover the performance of a MAGLEV suspension in case of a faulty air gap sensor. In this case, no hardware redundancy is required for the air gap measurement thus reducing

cost of the overall control system. The air gap measurement is rather critical for the maglev suspension system controllers, can be expensive and also located in harsh environment i.e. increasing fault probability. A simplified, albeit robust control structure was proposed while the estimator successfully estimates the required signals for the fault tolerant structure. Simulation results on the non-linear equivalent model illustrated the efficacy of the scheme.

1.5.3 Faults-Tolerant Control of Unmanned Underwater Vehicles:

Ni, Lingli et al (2001) present Unmanned Underwater Vehicles (UUVs) are widely used in commercial, scientific, and military missions for various purposes. What makes this technology challenging is the increasing mission duration and unknown environment. It is necessary to embed fault-tolerant control paradigms into UUVs to increase the reliability of the vehicles and enable them to execute and finalize complex missions. Specially, fault-tolerant control (FTC) comprises fault detection, identification, and control reconfiguration for fault compensation. This study presents a hierarchical methodology of fault detection, identification and compensation (HFDIC) that integrates these functions systematically in different levels. The method uses adaptive finite-impulse-response (FIR) modeling and analysis in its first level to detect failure occurrences.

Specially, it incorporates a FIR filter for on-line adaptive modeling, and a least-mean-squares (LMS) algorithm to minimize the output error between the monitored system and the filter in the modeling process.

By analyzing the resulting adaptive filter coefficients, there is ability to extract the information on the fault occurrence. The HFDIC also includes a two-stage design of parallel Kalman filters in levels two and three for fault identification using the multiple-model adaptive estimation (MMAE).

The algorithm activates latter levels only when the failure is detected, and can return back to the monitoring loop in case of false failures. Simulation results demonstrate the ability of the HFDIC to detect failures in real time, identify failures accurately with a low computational overhead, and compensate actuator and sensor failures with control reconfiguration.

In particular, verification of HFDI with Florida Atlantic University (FAU) data confirms the performance of the fault detection and identification methodology, and provides important information on the vehicle performance.

1.5.4 Thesis Analysis:

The analysis of the study can be summarizing follow:

First, develop sliding-mode controllers for Naval Postgraduate School (NPS) UUV steering and diving subsystems, and perform sliding-mode control of simulated subsystem maneuvers. They also compare the performance of the sliding-mode control with that of the PD control for two kinds of steering maneuvers with and without disturbances: course keeping and path tracking. Simulation results show that the sliding-mode control provides effective and robust ways of control, and is superior to the traditional PD control. In the study they formulate the fault detection and identification problem based on this modeling and control.

Second, they propose a fault-detection method based on adaptive LMS modeling and analysis to detect actuator and/or sensor failures. Basically, they use a finite-impulse-response (FIR) filter to model the subsystem adaptively, and use the LMS algorithm to minimize the output difference between the FIR filter and the monitored system. They use the FIR model to approximate the monitored system and analyze the adaptive model history to extract information on fault occurrences.

Third, study designs a hierarchical approach of fault detection and identification (HFDI) by combining our fault-detection method with a multiple-model adaptive estimation (MMAE). study use the adaptive modeling and analysis method in its first level for fault detection, and a two-stage parallel Kalman filters in levels two and three for fault identification using the MMAE. Study activates latter levels only when the failure is detected.

Lastly, study presents a multiple-model adaptive sliding-mode control based on the HFDI to compensate failures. First, study identifies actuator and sensor failures through the HFDI. Then, study design multiple sliding-mode controllers associated with each of the hypothesized failure modes, and reconfigure the control signal with a probability-weighted average of all the elemental control signals.

Study model actuator failures as additive parameter changes in the control input matrix, and sensor failures as additive parameter changes in the output equation of the system. Study considers total failures as well as partial failures, so as to have a comprehensive representation of actuator and sensor failures. In implementation, study simulates single failures, dual failures, and simultaneous failures during the maneuvering. Simulation results have demonstrated effective detection, identification, and compensation of these failures.

Besides validating HFDIC on the steering and diving subsystems of NPS UUV for various simulated actuator and/or sensor failures, study also

verify the HFDI method with realistic data from Florida Atlantic University (FAU). Study formulates the FDI problem according to subsystem models of FAU AUV, and use the actual control command and measurements in the HFDI.

1.5.5 Fault Tolerant Multi-sensor Switching Control Strategy:

(Maria M.seron, Xiang W.Zuho, Jose A. De Dona, John J. Matnez at 2007) present In this paper we propose a novel multi-sensor switching strategy for feedback control. Each sensor of the proposed multi-sensor scheme has an associated state estimator which, together with a state feedback gain, is able to individually stabilize the closed loop system. At each instant of time, the switching strategy selects the sensor-estimator pair that provides the best closed loop performance, as measured by a control-performance criterion. Study establishes closed-loop stability of the resulting switching scheme under normal (fault-free) operating conditions. More importantly, we show that closed-loop stability is preserved in the presence of faulty sensors if a set of conditions on the system parameters (such as bounds on the sensor noises, maximum and minimum values of the reference signal, etc.) is satisfied. This result enhances and broadens the applicability of the proposed multi-sensor scheme since it provides guaranteed properties such as fault tolerance and robust closed-loop stability under sensor failure. The results are applied to the problem of automotive longitudinal control.

1.5.6 Thesis Analysis:

Study has proposed a new multi-sensor switching strategy for feedback control. Study has established closed-loop stability of the resulting switching scheme under fault-free operating conditions. In addition, Study has shown that closed-loop stability of the resulting switching scheme is ensured under a multiple failure scenario if a set of conditions on the parameters of the problem is satisfied. We have discussed how an appropriate selection of the parameters (in particular, sensor-under-fault characteristics and reference signals) can be made to satisfy the required conditions. When compared with other fault tolerant multi-sensor schemes, our strategy has the important advantage that robust closed-loop stability guarantees under sensor failure can be given a priori, provided the aforementioned conditions are satisfied. Study has successfully applied the strategy to an example of automotive longitudinal control.

Chapter Two: Engine Control Unit (ECU) & Fuel Sensor

2.1 Preface:

Through this chapter we are going to search about the following section scrutiny and clarification:

- 1- The main content of Engine Control Unit (ECU).
- 2- Types of input sensor.
- 3- Actuators Type.

2.1.1 ECU Function:

The ECU considered as main element in the engine control system. We can conclude the most important function of ECU in the following points:

- 1- Receiving the signals sent by deferent sensor and switches which monitoring different operational situation and circumstances of the engine.
- 2- Analysis the data issues by deferent sensor and switches and comparing in initial with data fielded saved in lookup table.
- 3- to show operational case report of the engine and issuing order and it to actuators.
- 4- Limitation of the error that take place in the ECU and switching on the check engine.
- 5- Stores the errors in the (KAM) Memory.

2.1.2 ECU Content:

It consists of more than thousands electronic part fixed on transferred chips made of elastic conductor. There is integrated circuit of silicon chips as shown in fig (2.1). The ECU put in metal cover inside the car to prevent it from water, heat and shocks. Element of ECU were printed in label connected to the power as shown in Fig (3.1) other element were fixed on the metal cover to radiate the heat to outside. The sensors, actuators and power supply are connected with unit by connection socket consisting number of connection points according to its used system type, unit and function.



Fig (2.1): The Engine Control Unit (ECU)

The sensors, actuators and power supply are connected with unit by connection socket consisting number of connection points according to its used system type, unit and function.

All the main element of ECU shown in fig (3.2) ECU, memory, (A/D).Amplifier, output unit, input unit, program and buses the ECU must be able to process signal without any fault during the natural drive process under different external temperature degree. The battery volt should be between (6-15) volts. ECU will send constant datum volt of five volt to the some switch and digital sensor.

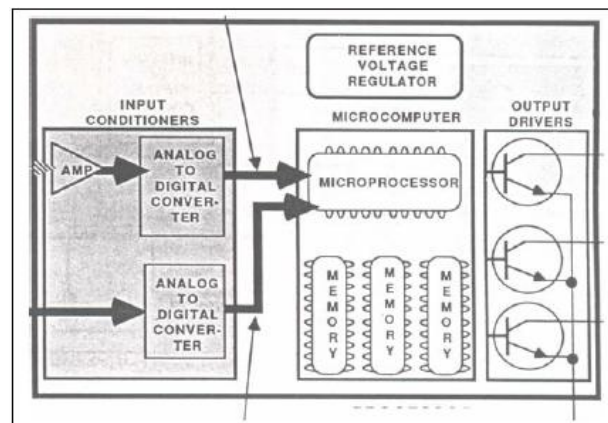


Fig (2.2) ECU Component

2.2 The ECU Elements:

2.2.1- Input Conditioner:

Its devices which receive sends data from sensor and send it to microprocessor to calibration. Its consists of the following elements:

2.2.1.1. (AMP):

It's amplified the sending signal from sensor that low signal i.e.: oxygen sensor

2.2.1.2. (A/D) convertor:

its contain electronic valve to transfer analog number sending from sensor to digital number (microprocessor language).

2.2.2- Microcomputer:

It's receive digital number from input conditioner to comparing it with calibration values stored in memory then achieve operational order.

2.2.3- CPU:

It's important component in system to control different planning stage and do the jobs.

2.2.4- Memory: Store and read the fixed value from lookup table and its contain three type of memory: RAM –PROM -KAM

2.2.5- Busses:

Job of it a collecting data related by major input instrumentation. The ECU is controlled in actuators groups which varieties according to engine type

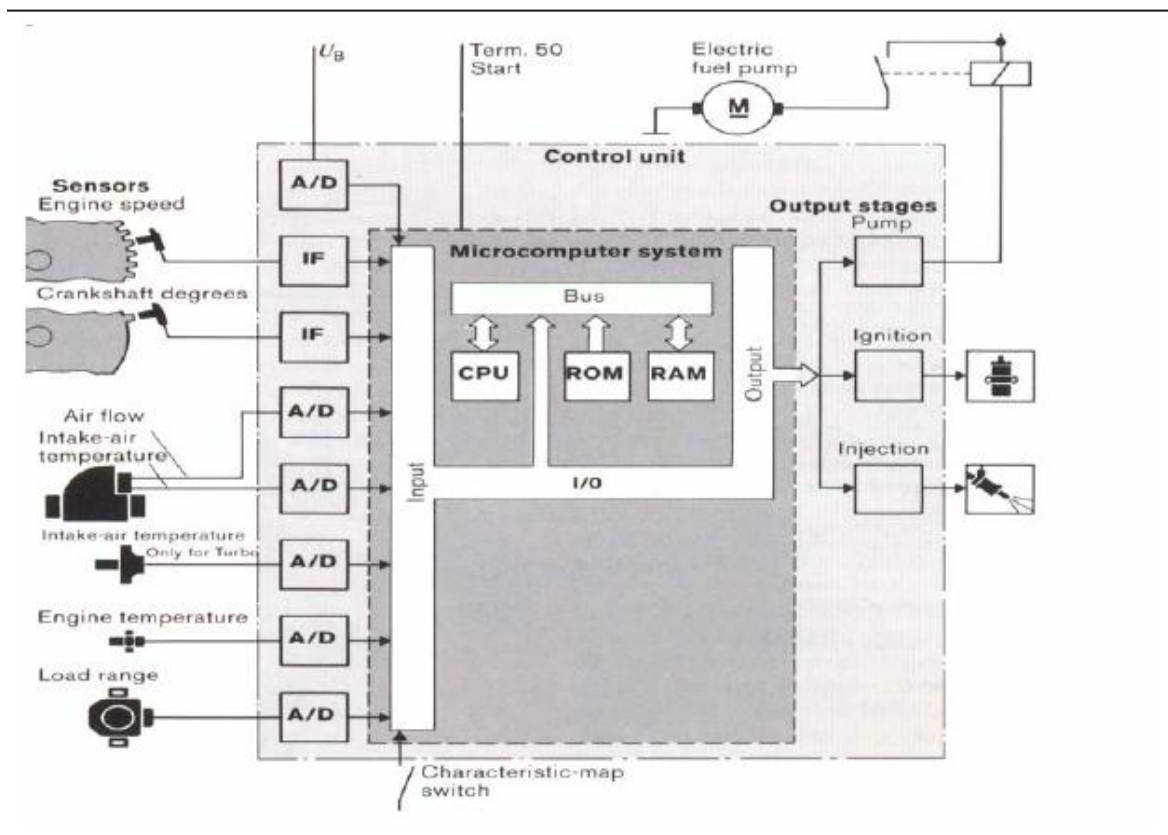


Fig (2.3) Engine Control Unit Cross-section

6- Signals Output: after processing input data the ECU issuing order and send it to output unit then to actuators.

2.3 ECU Processing:

From fig (3.3) all signal send from sensor and switch converted to digital member in (A/D) converter also impulse signals are convert to (IF). This data is collecting in input conditioner which converts the data to buses and then convert to (RAM). From (RAM) data is comparing with data (CPU) and go to stored in lookup table and output it as electrical pulse to control in three main part :

1- Ignition.

2- Injection.

3- Fuel pump.

2.4 Memory Types:

2.4.1- Random Access Memory (RAM):

It is use to safe data temporary the microcontroller have save and read from it .all data are deleted when engine blackout.

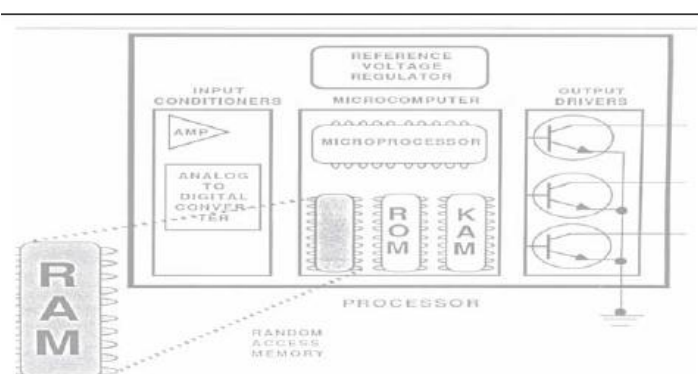


Fig (2.4) Random Access Memory (RAM)

2.4.2- Read Only Memory (ROM):

Its use to sane fixed values microcontroller can read from it but can't write at it. The saved values can't lose when engine blackout or battery disconnected

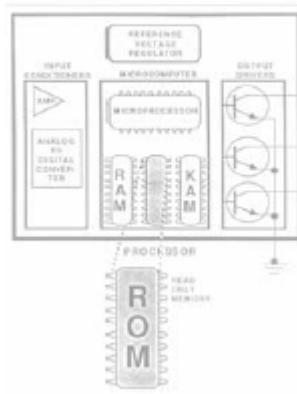


Fig (2.5) ROM

Its contain important data to engine operations such as operational system; equation and calibration data. There are two types of data is saves in memory:

2.4.3- Calibration Tables: Its contains spatial data from vehicles as: number of cylinder, cylinder volume, displacement, intake valve and exhaust

2.4.4- Lookup Tables:

Contain the essential data about how to set engine performance for all cars such as oxygen quantity in idle speed

2.4.5- KAM (Keep a live Memory) Memory:

Have many properties: microcontroller can write save in it.

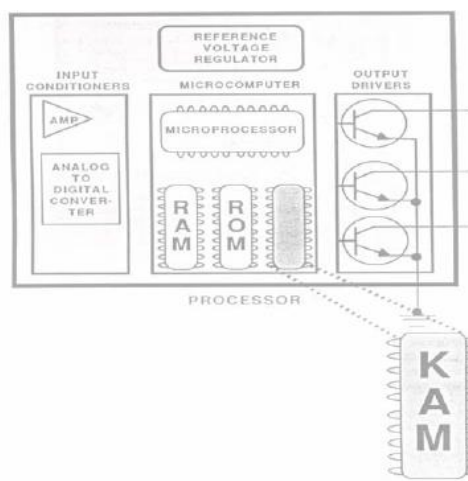


Fig (2.6) Keep a Live Memory

2.5- Input:

ECU brings the data about system performance from sensor fixed on engine. There are many type of sensor but all it contribute in one purpose who providing with ECU by voltage signal. The signal is classified of input data to recognize profiles operation.

Power train sensor reflects case of engine operation as: (manifold absolute pressure, engine speed..., etc) to signal voltage. All sensors as simplified electric device and the common use: switch, solenoid, thermo-time switch. Sensor pulse sends to processor through buses. Some sensor has ground circuit. And another sensors use feedback signal.

Potentiometer, sonolied, switches use in position instrumentation.

Thermostore to temperature instrumentation.

The voltage generated sensor use to measure the oxygen quantity in exhaust.

There are two type of voltage impulse receive from input conditioner:

1- digital.

2- analog.

The input signals conditioning by many method as: (A/D) converter. The small signals are amplified and send to microprocessor. Some sensor and relay supply by datum voltage from processor form (5-9) volts.

2.6- Sensors:

The Potentiometer sensor convert mechanical motion to voltage values and almost use in throttle position, the Potentiometer connected with three sockets:

1- Feedback connection from processor.

2- Feedback connection from sensor to processor.

3- Ground sensor connection.

2.7- Switches:

The switch use to present of position component and order signal: On or off.

2.8- Thermo store:

Its use in temperature measurement and convert it to voltage impulse.

2.9- Voltage Generation Sensor:

It's not supply with datum voltage in processor to generate the voltage automatically. Some sensors use quartz crystal to supply voltage some of the sensor use zirconium component such as oxygen sensor or electromagnetic sensor. Sensors that use quartz crystal in transforming the vibration or movement to the reference voltage and the kind often use to monitor vibration such as knock sensor. Magnetic sensor is used to measure the development of vehicle component such as crank shaft sensor. There is two type of magnetic sensor:

1- Hall Effect sensor.

2-magnetiv the detector

The magnetic sensor made up of wire and coil and hard of permanent magnetic the permanent magnetic generate magnetic filed in and around the wire and coil

2.10- Fuel System Sensor:

2.10.1- Manifold Absolute Pressure:

This sensor work piezoelectric disk to measure the pressure as shown in fig (3.7) change the value of voltage produced by pressure change with the prevailing value of the manifold. The sensor frequency increases with increasing pressure and vice versa. Referring sent to the microprocessor use in determining the engine load and determine the percentage of the mixture and the timing of the spark and control in EGR valve.

It consists of a box with three electrical connection and connected to intake manifold pressure by vacuum hose and manufactured from martial silicon chip the size of 3mm square with a thickness of 250 micrometer.

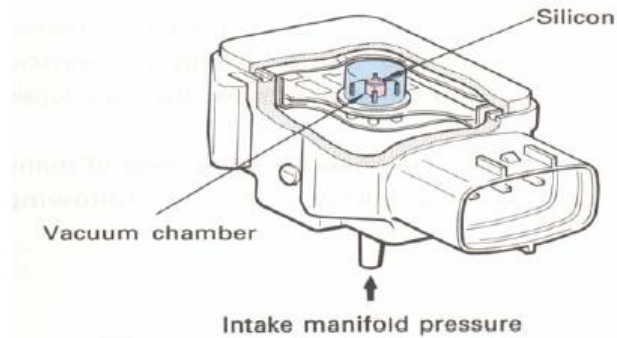


Fig (2.7) MAP Sensor

This design allows flexible movement to the slide into slide moving freely. This chip placed inside a closed chamber with air connected to the air in the upper part of it but the bottom connector pressure inside the intake manifold.

As a result of pressure difference during operation of the engine moves to the bottom of the film, and as a result of this movement changed the film resistance. And four resistors are all resisting reach corner of the pillars of the arch shaped slide connected.

The difference in pressure inside the intake manifold will affect the development of cell free silicon valve from the air and as a result put the crystalline energy and resistance as a result of part so the transmitted signal of control unit.

2.10.2 Oxygen Sensor:

For air/fuel ratio the actual fuel close to the theoretical ratio of mixture has been some engines provide feedback system to achieve the best performance but reducing exhaust gases emitted rate. Riding and oxygen sensor in the exhaust gases from complex to reach the sensor tip into the exhaust so that is touches the outer exhaust gas from the engine.

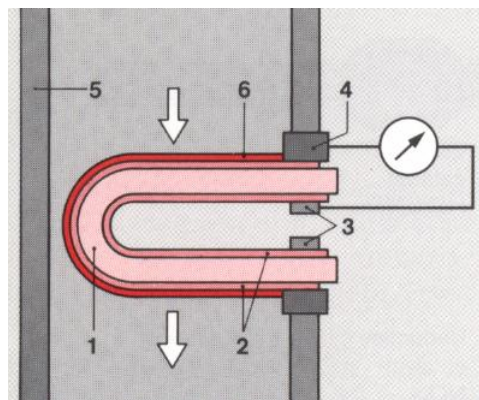


Fig (3.8) Oxygen Sensor riding in the exhaust

- 1- Sensor porcelain 2- fumbling reactor
- 3- Contact point 4- negative contact

5- Stream of exhaust gas 6- protection of ceramic material coating

These sensors generate a voltage between zero volt and one volt based on the case of oxygen in the exhaust gas car whether rich or lean.

The difference between the normal sensor and the hot sensor is hot his sensor have three wires to connect on the heater one of these wires to connect the power supply from the battery through the key switch to heat sensor and the second grounded and third wire transfer sensor voltage.

The oxygen sensor works in a manner feedback with the control unit any sensor will work in the development of open loop and closed loop as shown in the figure below

- 1- Intake air sensor 2- Engine 3- Oxygen sensor
- 4- Catalytic converter 5- Injection valve
- 6- Closed loop of control unit. V_E : injection quantity

U_s : sensor volt U_v : voltage of the injection valves from the control unit

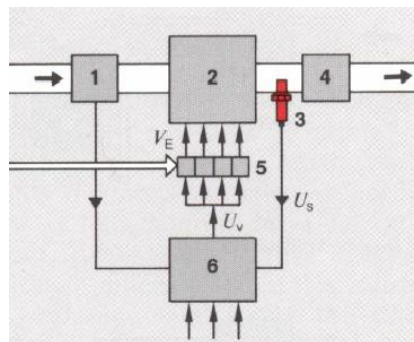


Fig (3.9) Feedback oxygen sensor

2.11- Signal Output:

After processing the analysis of information involved process. It operates the ECU to take appropriate decisions of the state of the vehicle. Hen working in the implementation of these decisions in the form of a digital signal and control the looting of commands are either to view the data or to carry out the work. So what little work on the computer sends command

with two goals: either for the purpose of presenting information or for the operation of actuators.

Microcontroller working on sending a signal to the output voltage regulator which in turn works to control the triggers. Where it work to complete the circle of these ground actuators. The output of output driver is control in the actuators by voltage feeding. Voltage feeding are perfumed by the battery. Where the management the actuators to output regulator operates on-mode. Put the off-mode. And the hardware to convert the electrical signal to respond to the movement where respond to the orders issued by the microcontroller.

There are two types of actuators:

- 1- Solenoids: this type use magnetic property to move the metal hart in order to convert the signal voltage electrical into mechanical movement.
- 2- Relay: kind of electrical devices that are used in the second power control stream contains relay in the control circuit and power circuit.

2.11.1- Throttle Position Sensor:

It used to measured amount of the throttle angle process and use the throttle gauged signal sent to ECU in the control of the following:

- 1- The amount of fuel injected.
- 2- Fuel cut.
- 3- Injection timing.
- 4- Control of the idle speed.

Sensor work method based on the potentiometer theory. Riding on the sensor throttle body and works by the valve arm movement. ECU operates to send 5-volt reference voltage to the potentiometer. When the throttle valve is moving in the open position, the sensor feather moving in potentiometer stream, the amount of this move will affect the amount of value reflect to amount of the throttle angle. This value is called the feedback reference voltage sent to the ECU.

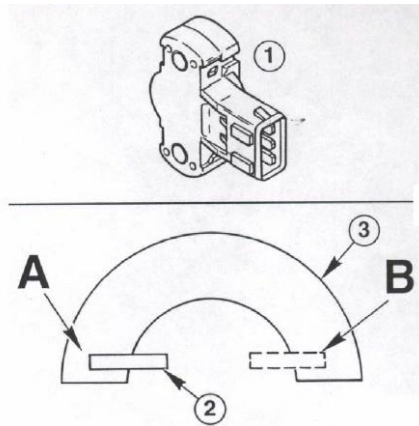


Fig (2.10): Throttle position sensor.

- 1- Throttle Sensor 2- Connecting point
 3- Potentiometer stream A: open B: closed

2.12- Speed Sensor:

Engine speed sensor consist of coil around the heart of the magnet consists riding in the front of it and has a steel disk gap working on moving the magnet field in order to cut view composed by AC as result of cutting the magnetic field

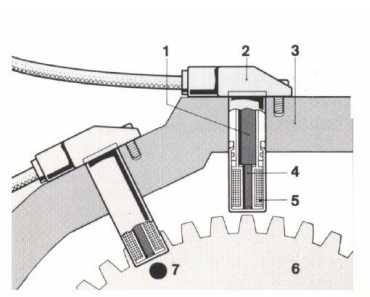


Fig 2.11 Speed Sensor

- 1- Permanent magnet effect 2- Sensor Body 3- Engine Body
 4- Sensor Heart 5- Flywheel teeth 6- Internal packaging lines
 7- Assigning mark

Chapter Three:
Implementation of fault tolerance Technique in
Fuel Control System

3.1 Preface:

Automotive engineers have found simulation to be a vital tool in the timely and cost-effective development of advanced control systems. As a design tool, Simulink has become the standard for excellence through its flexible and accurate modeling and simulation capabilities. As a result of its open architecture, Simulink allows engineers to create custom block libraries so they can leverage each other's work . By sharing a common set of tools and libraries, engineers can work together effectively within individual work groups and throughout the entire engineering department.

In addition to the efficiencies achieved by Simulink, the design process can also benefit from Stateflow, an interactive design tool that enables the modeling and simulation of complex reactive systems. Tightly integrated with Simulink, Stateflow allows engineers to design embedded control systems by giving them an efficient graphical technique to incorporate complex control and supervisory logic within their Simulink models.

The model described below represents a fuel control system for a gasoline engine. The system is highly robust in that individual sensor failures are detected and the control system is dynamically reconfigured for uninterrupted operation.

Parts of project :

- 1- Engine Gas-Dynamics Blocksets .
- 2-Fuel Rate Controller .
- 3- Sensor System .

4.1First : Engine Gas-Dynamics

This presents a model of a four-cylinder spark ignition engine and demonstrates Simulink's capabilities to model an internal combustion engine from the throttle . We used well-defined physical principles supplemented, where appropriate, with empirical relationships that describe the system's dynamic behavior without introducing unnecessary complexity. This model, based on published results by Crossley and Cook (1991), describes the simulation of a four-cylinder spark ignition internal combustion engine. The Crossley and Cook work also shows how a simulation based on this model was validated against dynamometer test data .

The ensuing sections (listed below) analyze the key elements of the engine model that were identified by Crossley and Cook :

- Throttle
- Intake manifold
- Mass flow rate

- Compression stroke
- Torque generation and acceleration

In this project model we exclude the torque generation and acceleration

3.2- Analysis and Physics:

4.2.1 Throttle:

The first element of the simulation is the throttle body. Here, the control input is the angle of the throttle plate. The rate at which the model introduces air into the intake manifold can be expressed as the product of two functions—one, an empirical function of the throttle plate angle only; and the other, a function of the atmospheric and manifold pressures. In cases of lower manifold pressure (greater vacuum), the flow rate through the throttle body is sonic and is only a function of the throttle angle. This model accounts for this low pressure behavior with a switching condition in the compressibility equations shown in Equation 3.1.

$$\dot{m}_{ai} = f(\theta)g(P_m)$$

= mass flow rate into manifold (g/s) where ,

$$f(\theta) = 2.821 - 0.05231\theta + 0.10299\theta^2 - 0.00063\theta^3$$

θ = Throttle angle (deg)

$$g(P_m) = \begin{cases} 1, & P_m \leq \frac{P_{amp}}{2} \\ \frac{2}{P_{amp}} \sqrt{P_m P_{amp} - P_m^2}, & \frac{P_{amp}}{2} \leq P_m \leq P_{amp} \\ -\frac{2}{P_m} \sqrt{P_m P_{amp} - P_m^2} & , P_{amp} \leq P_m \leq 2P_{amp} \\ -1, & P_m \geq 2P_{amp} \end{cases} \quad \text{Equation 4.1}$$

P_m = Manifold pressure (bar)

P_{amp} = Ambient (atmosphere) pressure (bar)

3.2.2 Intake Manifold:

The simulation models the intake manifold as a differential equation for the manifold pressure. The difference in the incoming and outgoing mass flow rates represents the net rate of change of air mass with respect to time. This quantity, according to the ideal gas law, is proportional to the time derivative of the manifold pressure. Note that, unlike the model of Crossley and Cook, 1991(1) (see also references 3 through 5), this model doesn't incorporate exhaust gas recirculation (EGR), although this can easily be added.

$$\dot{P}_m = \frac{RT}{V_m} (\dot{m}_{ai} - \dot{m}_{ao}) \quad \text{Equation 3.2}$$

Where ,

R = Specific gas Constant

T = Temperature (K)

V_m = Manifold volume (m^3)

\dot{m}_{ao} = Mass flow rate of air out of manifold (g/s)

\dot{P}_m = Rate of change manifold pressure (bar/s)

3.2.3 Intake Mass Flow Rate:

The mass flow rate of air that the model pumps into the cylinders from the manifold is described in Equation 4.3 by an empirically derived equation. This mass rate is a function of the manifold pressure and the engine speed.

$$\dot{m}_{ao} = -0.366 + 0.08979NP_m - 0.0337NP_m^2 + 0.0001N^2P_m$$

Equation 4.3

Where ,

N = Engine speed (rad/s)

P_m = Manifold pressure (bar)

To determine the total air charge pumped into the cylinders, the simulation integrates the mass flow rate from the intake manifold and samples it at the end of each intake stroke event. This determines the total air mass that is present in each cylinder after the intake stroke and before compression.

3.3 Throttle/Manifold Subsystems:

Simulink models for the throttle and intake manifold subsystems are shown in Figure (4.1). The throttle valve behaves in a nonlinear manner and is modeled as a subsystem with three inputs. Simulink implements the individual equations, given in Equation 4.1 as function blocks. These provide a convenient way to describe a nonlinear equation of several variables. A Switch block determines whether the flow is sonic by comparing the pressure ratio to its switch threshold, which is set at one half (Equation 4.1). In the sonic regime, the flow rate is a function of the throttle position only. The direction of flow is from the higher to lower pressure, as determined by the Sign block. With this in mind, the Min block ensures that the pressure ratio is always unity or less.

The intake manifold is modeled by the differential equation as described in Equation 3.2 to compute the manifold pressure. A Simulink function block

also computes the mass flow rate into the cylinder, a function of manifold pressure and engine speed (Equation 4.3).

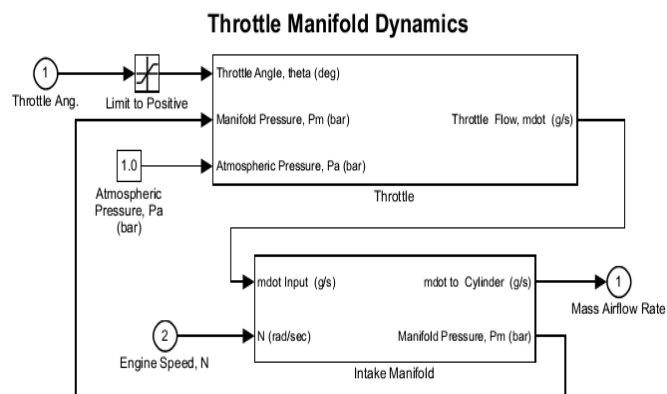
3.4- Fuel Rate Controller

The mass flow rate of air pumped from the intake manifold, divided by the fuel rate which is injected at the valves, gives the air-fuel ratio. The ideal, or stoichiometric mixture ratio provides a good compromise between power, fuel economy, and emissions. A target ratio of 14.6 is assumed in this system.

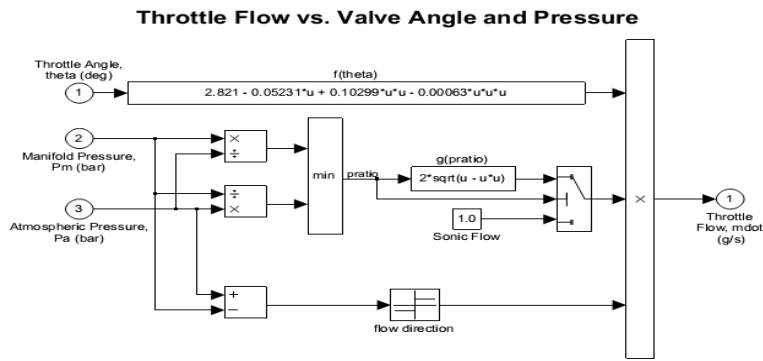
Typically, a sensor determines the amount of residual oxygen present in the exhaust gas (EGO). This gives a good indication of the mixture ratio and provides a feedback measurement for closed-loop control. If the sensor indicates a high oxygen level, the control law increases the fuel rate. When the sensor detects a fuel-rich mixture, corresponding to a very low level of residual oxygen, the controller decreases the fuel rate.

Figure (4.2) shows the top level of the Simulink model, the controller uses signals from the system's sensors to determine the fuel rate which gives a stoichiometric mixture. The fuel rate combines with the actual air flow in the engine gas dynamics model to determine the resulting mixture ratio as sensed at the exhaust.

The user can selectively disable each of the four sensors (throttle angle, speed, EGO and manifold absolute pressure [MAP]), to simulate failures. Simulink accomplishes this with Manual Switchblocks. Double-click on the block itself to change the position of the switch. Similarly, the user can induce the failure condition of a high engine speed by toggling the switch on the far left. A Repeating Tableblock provides the throttle angle input and periodically repeats the sequence of data specified in the mask.

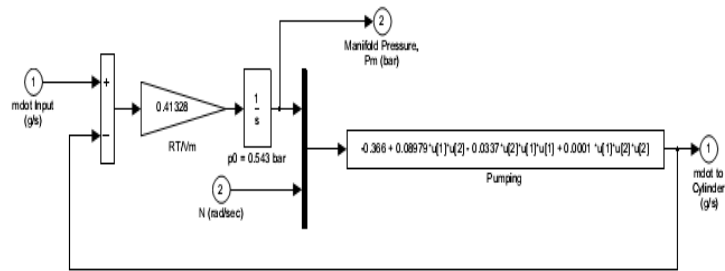


(a)



(b)

Intake Manifold Vacuum



(c)

Fig 3.1: The Throttle and Intake Manifold Subsystems

The user can selectively disable each of the four sensors (throttle angle, speed, EGO and manifold absolute pressure [MAP]), to simulate failures. Simulink accomplishes this with Manual Switchblocks. Double-click on the block itself to change the position of the switch. Similarly, the user can induce the failure condition of a high engine speed by toggling the switch on the far left. A *Repeating Tableblock* provides the throttle angle input and periodically repeats the sequence of data specified in the mask.

Fault-Tolerance Fuel Control System

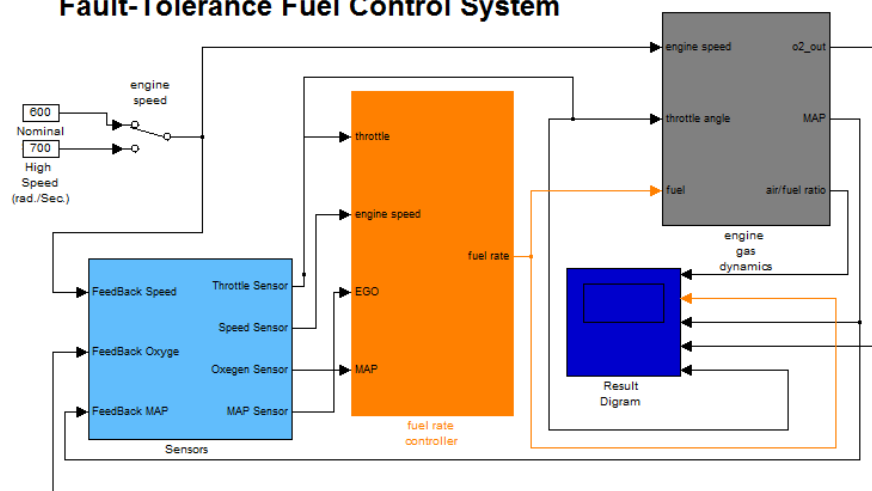


Fig 3.2: Simulink model of System

The controller uses the sensor input and feedback signals to adjust the fuel rate to give a stoichiometric ratio (Figure (4.3)). The model uses four

subsystems to implement this strategy: control logic, sensor correction, airflow calculation, and fuel calculation. Under normal operation, the model estimates the airflow rate and multiplies the estimate by the reciprocal of the desired ratio to give the fuel rate. Feedback from the oxygen sensor provides a closed-loop adjustment of the rate estimation in order to maintain the ideal mixture ratio.

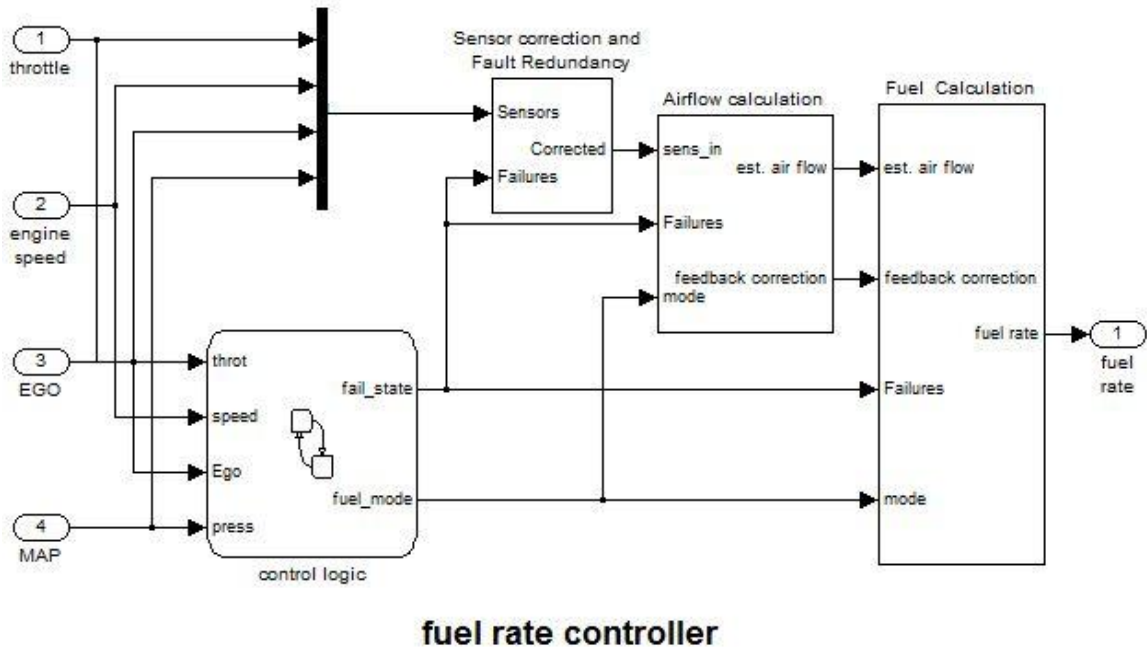


Fig 3.3: Fuel rate controller subsystem

3.4.1 Control Logic:

A single State flow chart, consisting of a set of six parallel states, implements the control logic in its entirety. The remaining two parallel states at the bottom consider the status of the four sensors simultaneously and determine the overall system operating mode. The model synchronously calls the entire Stateflow diagram at a regular sample time interval of 0.01 sec. This permits the conditions for transitions to the correct mode to be tested on a timely basis.

When execution begins, all of the states start in their “normal” mode with the exception of the oxygen sensor. The O2_warmup state is entered initially until time has exceeded the o2_t_thresh. The system detects throttle and pressure sensor failures when their measured values fall outside their nominal ranges. A manifold vacuum in the absence of a speed signal indicates a speed sensor failure. The oxygen sensor also has a nominal range for failure conditions but, because zero is both the minimum signal

level and the bottom of the range, failure can be detected only when it exceeds the upper limit.

Regardless of which sensor fails, the model always generates the directed event broadcast `Sens_Failure_Counter.INC`.

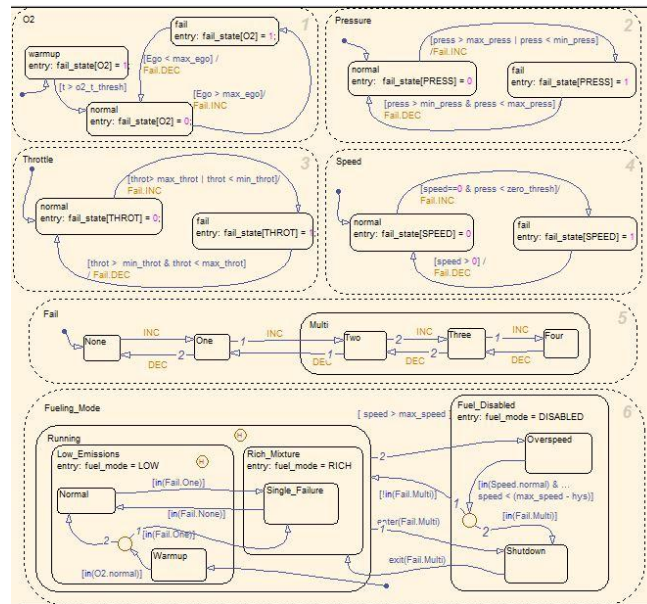


Figure 3.3: Control logic Chart

The bottom parallel state represents the fueling mode of the engine. If a single sensor fails, operation continues but the air/fuel mixture is richer to allow smoother running at the cost of higher emissions. If more than one During the oxygen sensor warm-up, the model maintains the mixture at normal levels. If this is unsatisfactory, the user can change the design by moving the warm-up state to within the Rich Mixture super state. If a sensor failure occurs during the warm-up period, the Single_Failure state is entered after the warm-up time elapses. Otherwise, the Normal state is activated at this time.

We easily added a protective over speed feature by creating a new state in the Fuel Disabled super state. Through the use of history junctions, we assured that the chart returns to the appropriate state when the model exits the over speed state. As the safety requirements for the engine become better specified, we can add additional shutdown states to the Fuel Disabled super state.

3.5 Sensor Correction

The Fault Correction block determines which sensors to use and which to estimate. Figure (3.5) shows the block diagram for this subsystem. The failures input are a vector of logic signals that trigger the application of estimates to each particular sensor. When a component of the signal is nonzero, it enables the appropriate estimation subsystem and causes the switch relating to that signal to send the estimate as the output. Since the

estimation routines are within enabled subsystems, they do not introduce any computational overhead when they are not needed.

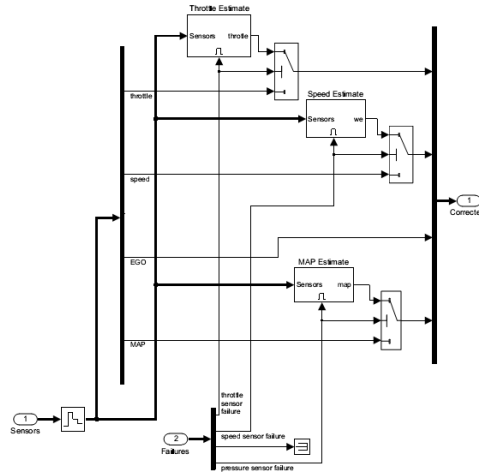


Fig 3.4 : Sensor correction and fault redundancy

The sensors input to the Correction block is the vector of raw sensor values. When there are no faults, the input simply passes on as the output signal. When a fault exists, the appropriate estimation block uses this signal to recover the missing component. Figure (4.6) shows an estimation example of the algorithm for the manifold pressure sensor.

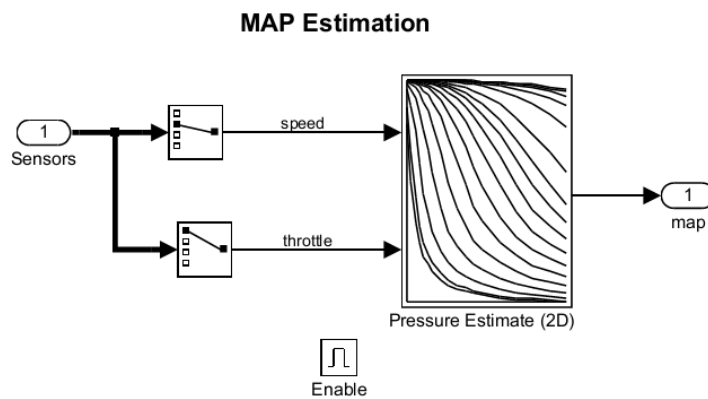


Fig 3.5: Manifold absolute pressure reconstruction

3.6. Airflow Calculation:

The Airflow Calculation block (Figure3.7) is the location for the central control laws. The block estimates the intake air flow to determine the fuel rate which gives the appropriate air/fuel ratio. Closed-loop control adjusts the estimation according to the residual oxygen feedback in order to maintain the mixture ratio precisely. Even when a sensor failure mandates open-loop operation, the most recent closed-loop adjustment is retained to best meet the control objectives.

The engine's intake air flow can be formulated as the product of the engine speed, the manifold pressure and a time-varying scale factor.

$$q = \frac{N}{4\pi} V_{cd} \eta \frac{P_m}{RT} = C_{pump}(N, P_m) N P_m ,$$

- = Intake mass flow
- N = Engine speed (rad/s)
- V_{cd} = Engine displacement cylinder volume
- η = Volumetric efficiency
- P_m = Manifold pressure
- R = Specific gas constant
- T = Gas temperature

C_{pump} is computed by a lookup table and multiplied by the speed and pressure to form the initial flow estimate. During transients, the throttle rate, with the derivative approximated by a high-pass filter, corrects the air flow for filling dynamics. The control algorithm provides additional correction according to Eqs. 4.5:

$$e_0 = \begin{cases} 0.5, & EGO \leq 0.5 \\ -0.5, & EGO > 0.5 \end{cases}$$

$$e_1 = K_i(N, P_m)e_0$$

$$\dot{e}_2 = \begin{cases} e_1, & \text{LOW mode with valid EGO signal} \\ 0, & \text{RICH, DISABLE or EGO warmup} \end{cases}$$

$$e_2 = \text{closed-loop correction}$$

$$e_0, e_1, e_2 = \text{Intermediate error}$$

The nonlinear oxygen sensor, modeled with a hyperbolic tangent in the engine gas Mixing and Combustion subsystem, provides a meaningful signal when in the vicinity of 0.5 volt.

The raw error in the feedback loop is thus detected with a switching threshold, as indicated in Equation 4.5. If the value is low (the mixture is lean), the original air estimate is too small and needs to be increased. Conversely, when the oxygen sensor output is high, the air estimate is too large and needs to be decreased. Integral control is utilized so that the correction term achieves a level that brings about zero steady-state error in the mixture ratio.

3.7 Fuel Calculation:

The Fuel Calculation subsystem (Figure (4.8)) sets the injector signal to match the given airflow calculation and fault status. The first input is the computed airflow estimation. This is multiplied with the target fuel/air ratio to get the commanded fuel rate. Normally the target is stoichiometric, 1/14.6.

When a sensor fault occurs, the State flow control logic sets the mode input to a value of 2 or 3 (RICH or DISABLED) so that the mixture is either slightly rich of stoichiometric or is shut down completely.

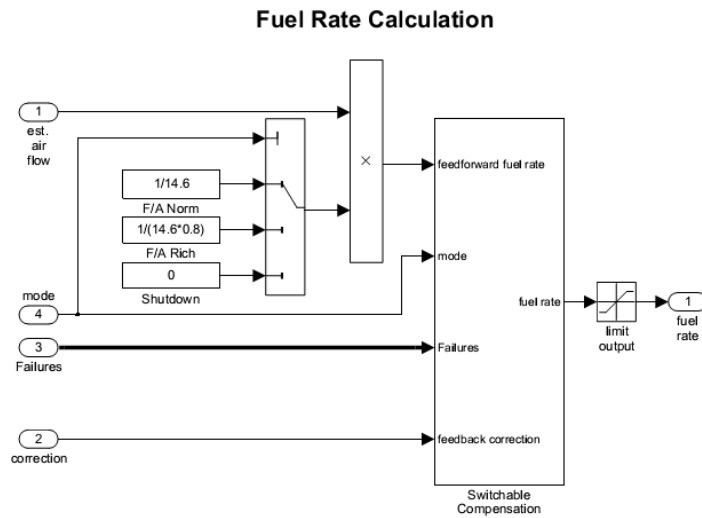


Fig 3.7: Fuel Calculation Subsystem

The Fuel Calculation subsystem (Figure 3.7) employs adjustable compensation (Figure 3.8) in order to achieve different purposes in different modes. In normal operation, phase lead compensation of the feedback correction signal adds to the closed-loop stability margin. In RICH mode and during EGO sensor failure (open loop), however, the composite fuel signal is low-pass filtered to attenuate noise introduced in the estimation process. The end result is a signal representing the fuel flow rate which, in an actual system, would be translated to injector pulse times.

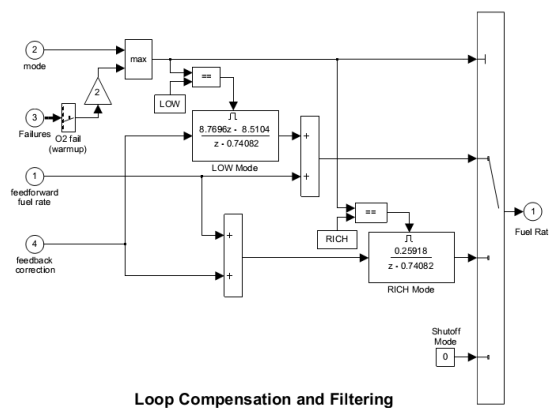


Fig 3.8: Switchable compensation

3. 8 Faults, failures and malfunctions:

3.8.1 Fault:

A fault is an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition. A fault is a state with the system. The unpermitted deviation is the difference

between the fault value and the violated threshold of a tolerance zone for its usual value. A fault is an abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function. There exist many different types of faults, e.g. design fault, manufacturing fault, assembling fault, normal operation fault (e.g. wear), wrong operation fault (e.g. overload), maintenance-fault, hardware-fault, software-fault, operator's fault. (Some of these faults are also called errors, especially if directly caused by humans).

A fault in the system is independent of whether the system is in operation or not. A fault may not affect the correct functioning of a system (like a small rent in an axle). A fault may initiate a failure or a malfunction.

Frequently, faults are difficult to detect, especially, if they are small or hidden. Faults may develop abruptly (stepwise) or incipiently (drift wise).

3.8.2 Failure:

A failure is a permanent interruption of a system's ability to perform a required function under specified operating conditions. A failure is the termination of the ability of a functional unit to perform a required function. A failure is an event. A failure results from one or more faults. Different types of failures can be distinguished:

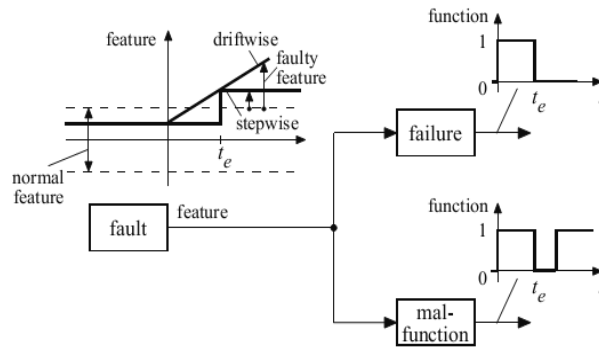
1. Number of failures: single, multiple;
2. Predictability: random failure (unpredictable, as, e.g. statistically independent from operation time or other failures); deterministic failure (predictable for certain conditions); systematic failure or causal failure (dependent on known conditions);

Usually a failure arises after begin of operation or by increasingly stressing the system.

3.8.3 Malfunction:

A malfunction is an intermittent irregularity in the fulfillment of a system's desired function. A malfunction is a temporary interruption of a system's function; a malfunction is an event; a malfunction results from one or more faults; usually a malfunction arises after begin of the operation or by increasingly stressing the system.

Figure 3.9 shows the relation of faults, failures and malfunctions. The fault may develop abruptly, like a step-function, or incipiently, like a drift like function. The corresponding feature of the system related to the fault is assumed to be proportional to the fault development. After exceeding the tolerance of normal values, the feature indicates a fault.



Fig(3.9)Development of events “failure” or “malfunction” from a fault

3.9 Reliability, Safety, Availability, Dependability and Integrity:

3.9.1- Reliability:

Ability of a system to perform a required function under stated conditions within a given scope, during a given period of time.

3.9.2- Safety:

Ability of a system not to cause danger to persons or equipment or the environment.

3.9.3- Availability: Probability that a system or equipment will operate satisfactorily and effectively at any period of time.

3.9.4- Dependability:

Dependability is a property of a system that justifies placing one's reliance on it. It covers reliability, availability, safety, maintainability and other issues of importance in critical systems.

3.9.5- Integrity:

The integrity of a system is the ability to detect faults in its own operation and to inform a human operator.

3.10- Fault tolerance and redundancy:

After applying reliability and safety analysis for the improvement of the design, testing of the product and also corresponding quality control methods during manufacturing, the appearance of certain faults and failures cannot be avoided totally. Therefore, these unavoidable faults should be tolerated by additional design efforts. Hence high-integrity systems must have the ability of fault tolerance. This means that faults are compensated in such a way that they do not lead to system failures after the application. Of principles to improve the perfection of the components the remaining obvious way to reach this goal is to

implement redundancy. This means that

Process	Fault	Feature	Failure	Malfunction
electrical illumination	switch with corroded contacts	occasionally no electrical conductivity	–	interrupted light
	broken wire in cable	no electrical conductivity	no light	–
electrical DC motor	worn brushes	armature resistance high	–	occasionally interrupted torque and changing speed
	broken wire in excitation coil	no electrical flux	no torque, no speed	–
machine tool belt drive	belt with too low pretension	no continuous torque transfer	–	sluggish dynamics piecewise motion
	broken belt threads	no torque transfer	standstill of feed drive	–
pneumatic valve	leak in supply air pressure	slow motion, limited position range	–	closed loop does not follow setpoint for some time
	corroded shaft	mechanical friction too high	no motion permanent control deviation	–

Table3.1: Type for faults failures and malfunctions

in addition to the considered module one or more modules. The function modules can be hardware components or software parts, either identical or diverse. Different arrangements of fault-tolerant systems exist with static or dynamic redundancy, cold or hot standby. In general, the function modules are supervised with fault-detection capability followed by a reconfiguration mechanism to switch off failed modules and to switch on spare modules (dynamic redundancy). The modules are, e.g. actuators, sensors, computers, motors or pumps. For electronic hardware simpler schemes exist with $n > 3$ modules

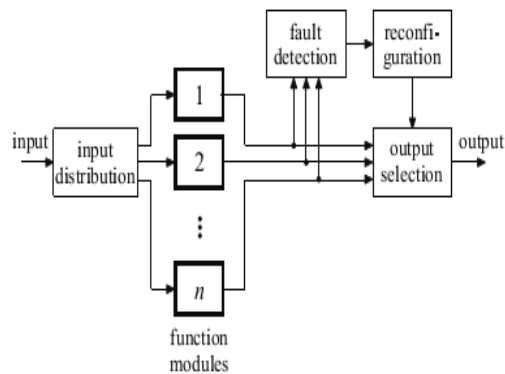


Fig 3.10: Basic Scheme of a fault-tolerant system

3.3.1 Types of Faults:

Faults usually show a characteristic behavior for the various components. They may be distinguished by their form, time behavior and extent, compare Table 3.2. The form can be either systematic or random. The time behavior may be described by permanent, transient, intermittent, noise or drift. The extent of faults is either local or global and includes the size. Table 3.2 gives an overview of a variety of fault types in dependence on the system components. Electronic hardware shows systematic faults if they originate in specification or design mistakes. Once in operation faults in hardware components.

type of faults		components			
		mechanical components	electrical components	electronic hardware	software
form	systematic	✓		✓	✓
	random		✓	✓	
time behavior	permanent			✓	✓
	transient	✓	✓	✓	
	intermittent		✓	✓	✓
	noise		✓	✓	
	drift	✓	✓	✓	
extent	local	✓	✓	✓	✓
	global			✓	✓

Table3.2: Main characteristics (✓) of primary faults for different components are mostly random with all kind of time behavior. The faults or mistakes in software (bugs) are usually Failures of mechanical systems can be classified into following failure mechanisms: distortion (buckling, deformation), fatigue and fracture (cycle fatigue, thermal fatigue), wear (abrasive, adhesive, cavitations), or corrosion (galvanic, chemical, biological), They may appear as drift like changes (wear, corrosion) or abruptly (distortion fracture) at any time or after stress. Electrical systems usually consist of a large number of components with various failure modes, like short cuts, loose or broken connection, parameter changes, contact problems, contamination, etc. Generally, electrical faults appear more randomly than mechanical faults. Table shows mainly the effect of primary faults for the different components and their typical behavior. The extent depends very much on the importance of the considered components and can of course be global for all cases even if the faults primarily appear locally.

3.10.2 - Process and fault modeling:

Model-based methods of fault detection use the relations between several measured variables to extract information on possible changes caused by faults. These relations are mostly analytical relations in form of process model equations but can also be causalities in form of, e.g. if-then rules. Figure 3.3 shows a general scheme for process model-based fault detection. The relations between the measured input signals U and output signals Y are represented by a mathematical process model. Fault-detection methods then extract special features, like parameters θ , state variables x or residuals r .

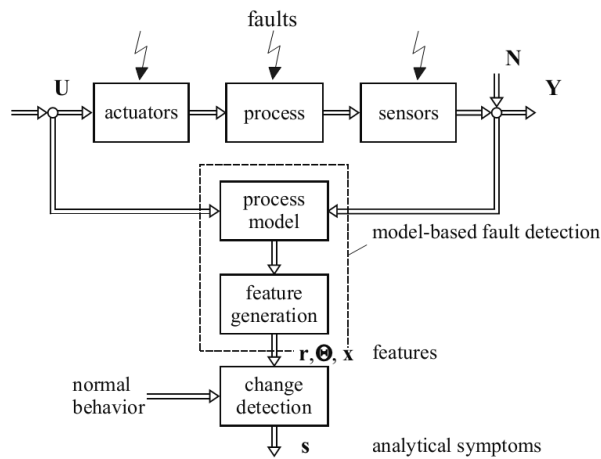


Fig3.11: General scheme of process model-based fault detection

By comparing these observed features with their nominal values, applying methods of change detection, analytical symptoms s are generated.

These asymptotes are the basis for fault diagnosis. For the application of model-based fault-detection methods the process configurations according to Figure 3.11 have to be distinguished. With regard to inherent depended used for fault detection and the possibilities for distinguishing between different faults, the situation improves from a to b or c by availability of more measurements, as will be shown later. The applied process model can be classified to:

1. Continuous model.
2. Discrete – event models.
3. Both in: Continuous time and discrete time.

The continuous models are in general equation based with further subclasses as linear nonlinear time - variant. Discrete event models are e.g. finite state machines, functional diagrams

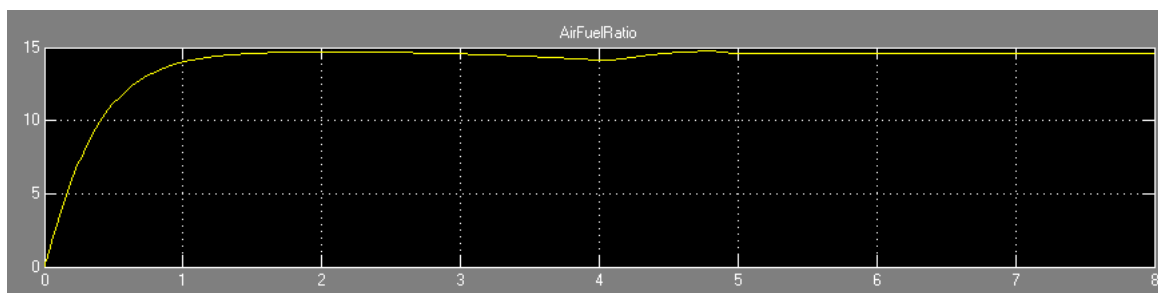
Chapter Four

Results and Recommendation

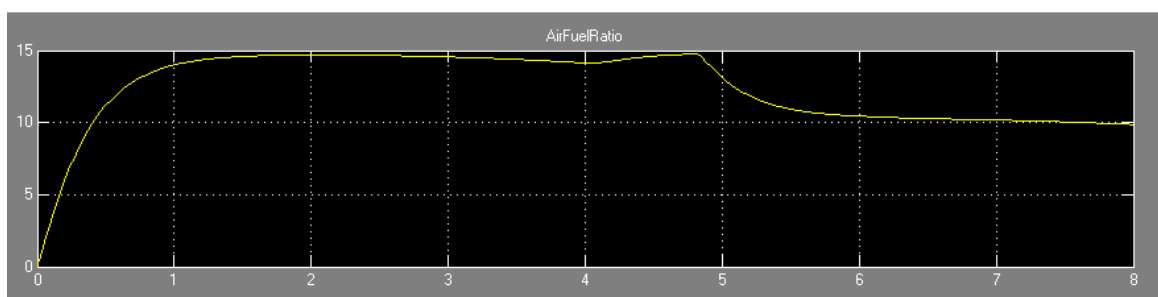
4.1- Result and Conclusion:

Simulation results are shown in Figure 4.1 and Figure 4.2. The simulation is run with a throttle input that ramps from 10 to 20 degrees over a period of two seconds, then back to 10 degrees over the next two seconds. This cycle repeats continuously while the engine is held at a constant speed so that the user can experiment with different fault conditions and failure modes. To simulate a sensor failure, double-click on its associated switch. Repeat this operation to toggle the switch back for normal operation.

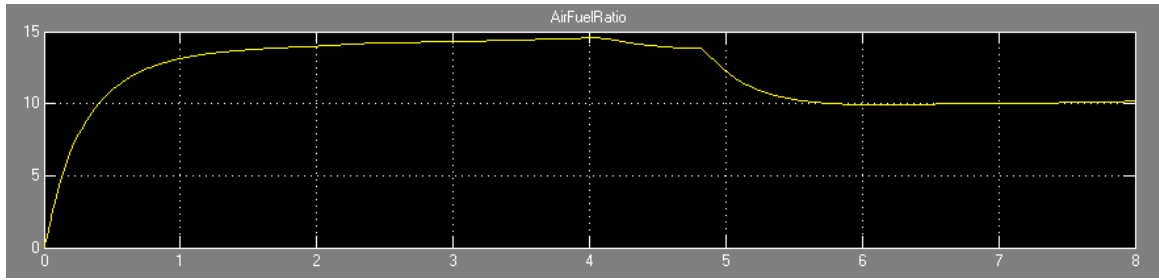
. Figure (4.1) plots the corresponding air/fuel ratio for each case. The baseline plot shows the effects of closed-loop operation. The mixture ratio is regulated very tightly to the stoichiometric objective of 14.6. The rich mixture ratio is shown in the bottom four plots of Figure 5.1. Although they are not tightly regulated, as in the closed-loop case, they approximate the objective of $\text{air/fuel} = 0.7(14.6) = 10.22$.



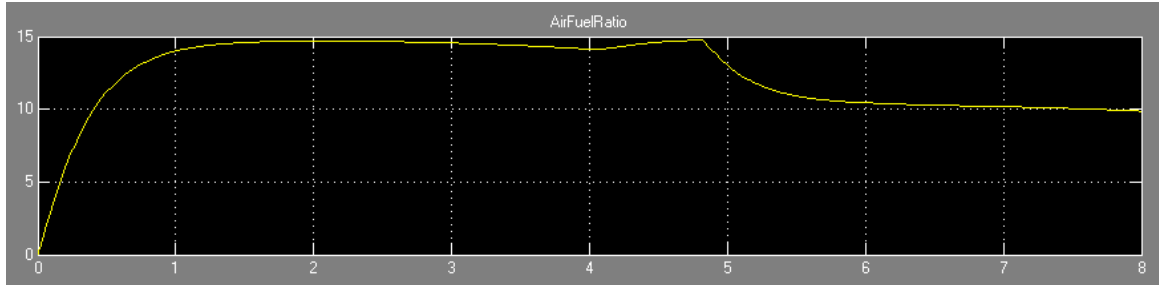
(a) Fault free condition



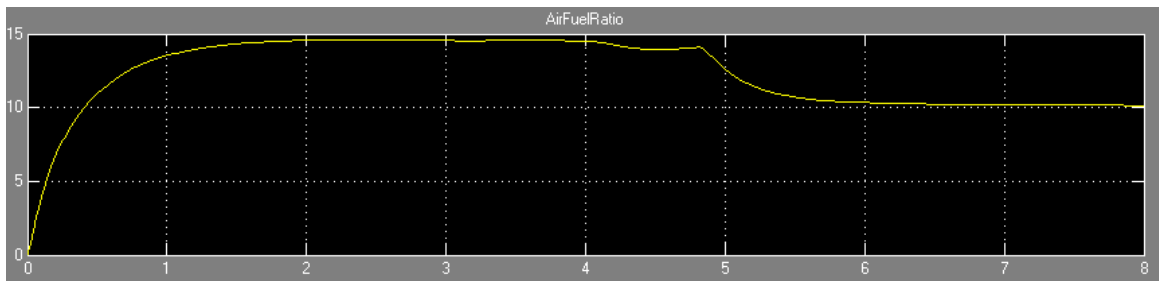
(b) Throttle sensor failed



(c) Speed sensor failed



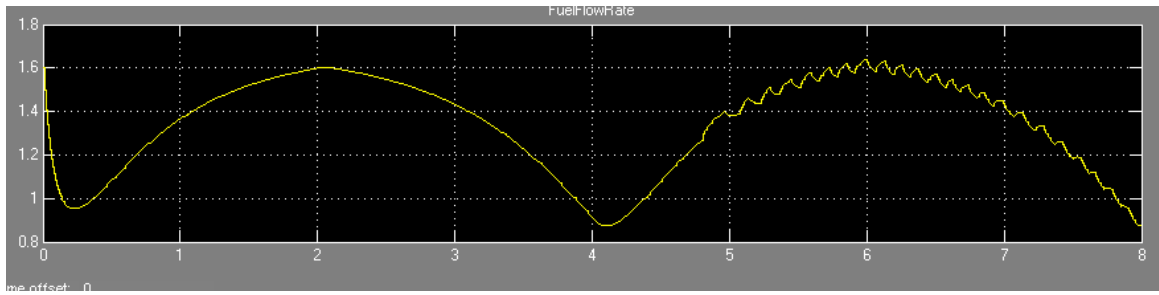
(d) EGO sensor failed



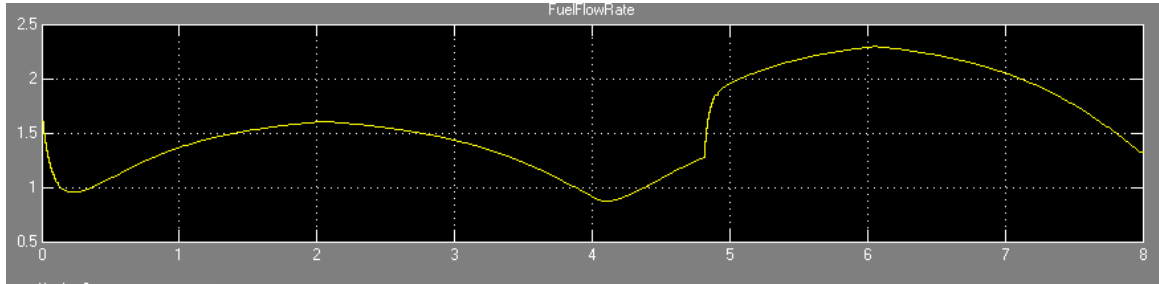
(e) Map sensor failed

Fig 4.1: Comparative results for simulated Air/Fuel Ratio

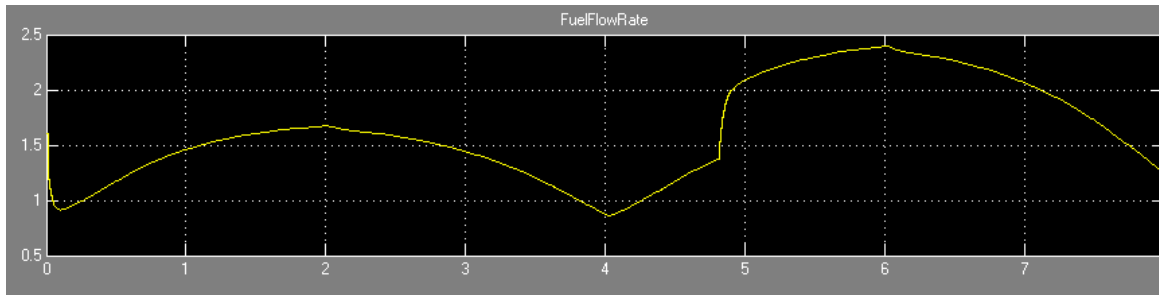
Figure (4.2) compares the fuel flow rate under fault-free conditions (baseline) with the rate applied in the presence of a single failure in each sensor individually. Note in each case, the nonlinear relationship between fuel flow and the triangular throttle command. In the baseline case, the fuel rate is regulated tightly, exhibiting a small ripple due to the switching nature of the EGO sensor's input circuitry. In the other four cases the system operates open loop. The control strategy is proven effective in maintaining the correct fuel profile in the single-failure mode fulfilling the design objective of 70% rich



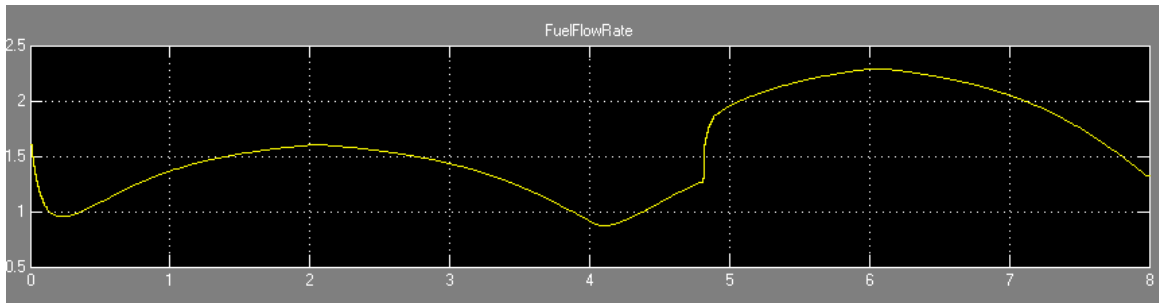
Fault free condition



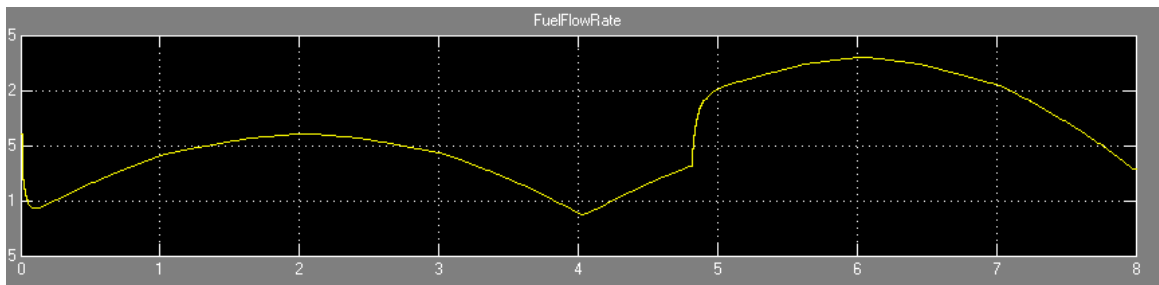
Throttle sensor failed



Speed sensor failed



EGO Sensor failed

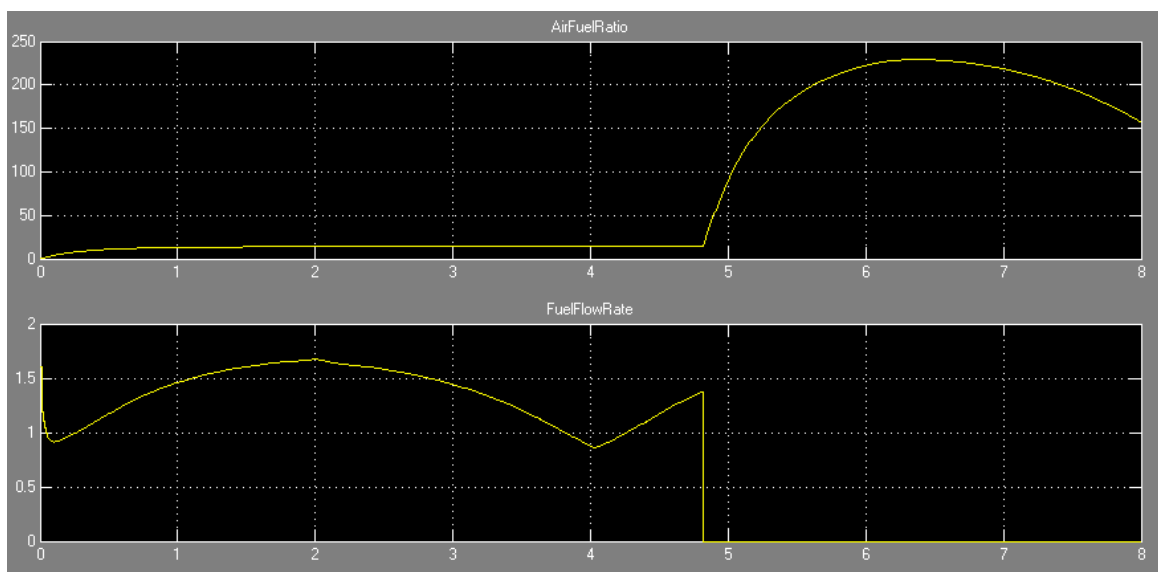


Map sensor failed

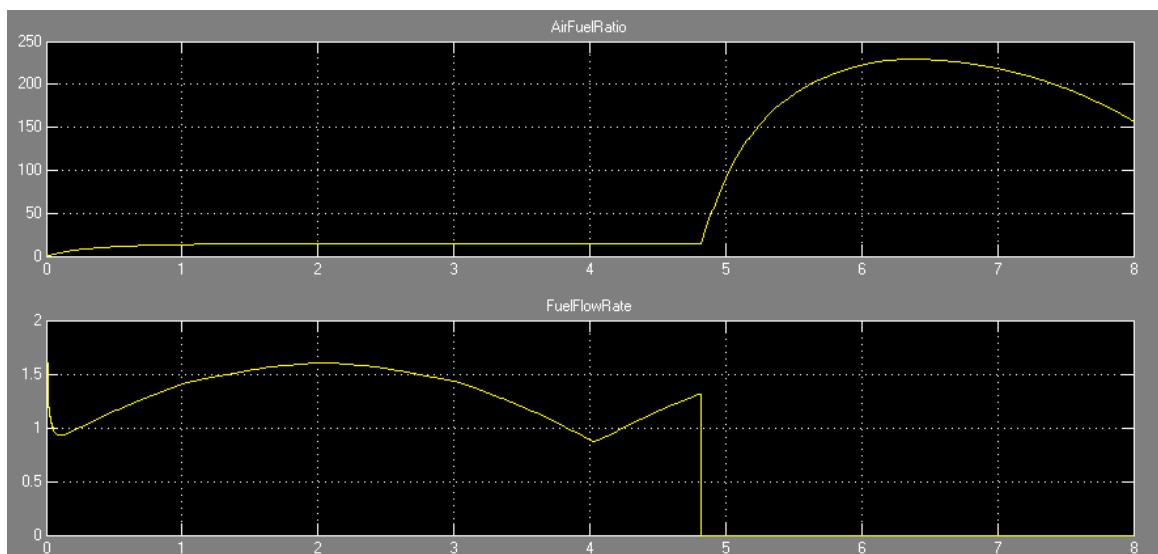
Fig 4.2: Comparative results for simulated Fuel flow Rate

Figure 4.3 is shown which can be happen while two sensor or more are failed to operation, when EGO & speed sensor are failed the system fuel rate is shutdown after 4.8 sec from starting when system air fuel ratio jumped from 4.8 to (6.5) at max then decrease hierarchy to (zero) , this value also represent when EGO & MAP are failure.

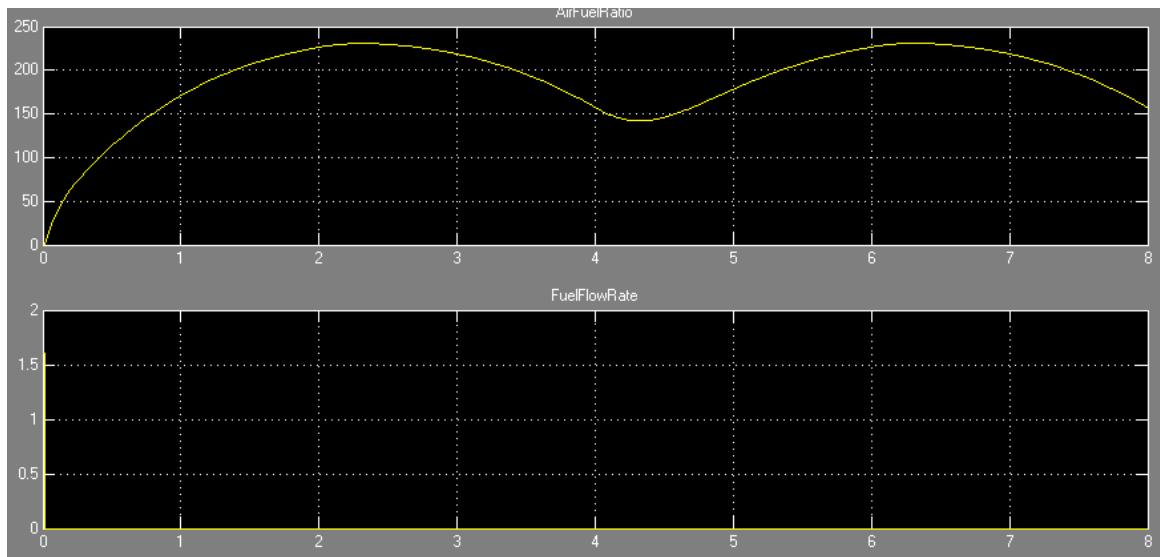
MAP & Throttle failure: the Air/Fuel ratio value out of estimate and fuel floe rate is shutdown from starting of simulation, also that value is represent at MAP & Throttle sensor are failure



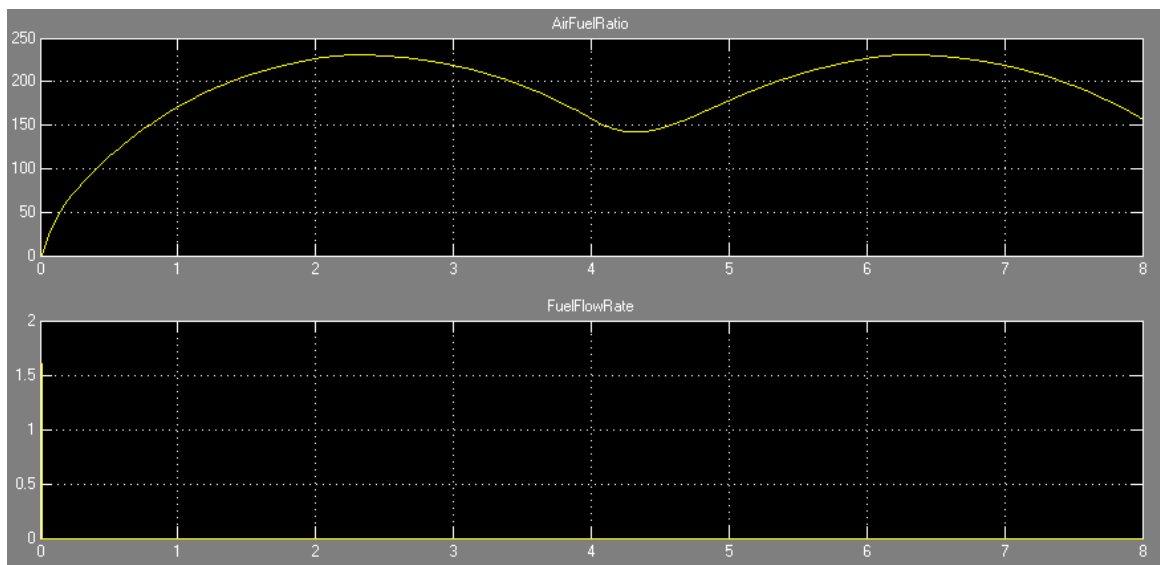
(a) EGO & speed sensor Failed



(b) EGO & Map Failed



(c) MAP & Throttle Failed



(d) Speed sensor & Throttle sensor failed

Fig 4.3: Comparative results for simulated when two Sensor are Failed

4.2 Recommendation:

- I recommended use of fault- tolerance fuel control system in educational purpose of engineer graduate.
- Also, I recommended it for vehicle for long term journey where interrupted give more cost and disquietude.
- A fault – tolerant fuel control can implemented in military occupation more than civilians occupation , I.e. For space shuttle, Aircraft battlefield, discovery submarine.
- I recommended improving the model to contain all fuel control system and chassis sensor.
- I recommended to study fault tolerance in power train system to achieve high performance.

5.3Reference:

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