ELECTRONICALLY-VARIABLE AUTOMOTIVE SUSPENSION FOR HIGH PERFORMANCE VEHICLE

by

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15315

Dissertation submitted in partial fulfilment of

the requirement for the

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CERTIFICATION OF APPROVAL

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Approved by,

____

(Mr. Saiful Azrin Bin Mohd Zulkifli)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

SEPTEMBER 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AKMAL HAKIM BIN ABD SALAM

ABSTRACT

Vehicle suspension system plays a crucial role to ensure vehicle stability and ride comfort. A suspension system controls the vehicle body from excessive rolling and pitching while reduce the effect of shock forces from the road. Soft suspension system promotes good ride comfort while stiffer suspension promotes better car handling. Both comfort and good handling can be achieved by a variable suspension system. In the existing adjustable suspension unit, driver needs to stop the car, pop-up the hood and turn the selector knob manually to select the desired stiffness. By implementing a servo motor to replace the knob, the system now become an electronically – variable automotive suspension system that use motorized mechanism to control the suspension stiffness. With this system the driver can select suspension setting from inside the car while driving using touchscreen GUI. The system can have either selectable fixed-stiffness settings (*fixed mode*) or be made to respond to dynamic inputs - such as lateral G-force or vehicle speed – (*adaptive* mode), to become a semi-active suspension system.

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CHAPTER 1 - INTRODUCTION

1.1 Background of Study

1.1.1 Automotive Suspension

Suspension system play crucial role to ensure the stability and ride comfort of a vehicle. Suspension system consist of a spring, shock absorber (damper) and linkage assembly which connects the vehicle to the wheels. The suspension system stabilize vehicle movement during acceleration, braking and cornering while isolating the road roughness from the passenger compartment [1].

Suspension system supports the weight of the vehicle, maintain the correct vehicle ride height, and reduce the effect of shock forces from the road [2].

Thus, the vehicle suspension system serve two main purpose:

- Vehicle control
- Passenger comfort

The control of a vehicle is acheived by keeping the car body from excessive rolling and pitching , and to ensure good road contact between the tire and road surface. Passanger comfort is acheived by isolating the passanger cabin from the road bumps, vibration road noise and other external effects.

1.2 Problem Statement

Many variable suspension systems for high-end automotive market use a pneumatic (air suspension) system to vary the suspension's stiffness. The pneumatically variable height suspension system is achieved by using many complex components such as air compressor, air pressure sensor and complex airline thus consuming a lot of power from the car electrical system and increase overall vehicle weight. The complexity of the pneumatic suspension system leads to higher manufacturing cost thus limiting the usage of pneumatic suspension only for the high-end vehicle segment [3].

The project shall upgrade an existing mechanically-adjustable suspension system to be electronically controlled by using a motorized system with associated electronic circuitry. The outcome of the project is to produce a motorized variable suspension stiffness that can be manually preset with 3 fixed damper settings (soft, medium & hard) or automatically varied according to certain car handling performance.

The control circuit can be upgraded in the future to transform the existing system to become a semi-active suspension system that can be adapted with car G-sensor and speed sensor. The potential market for the product is aftermarket part for performance enthusiast to enhance their car handling performance and improve ride quality. In the long run, the project will eventually benefit to allow nation mass-market car to be equipped with OEM adjustable-suspension mechanism.

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1.3 Objectives and Scope of Study

The objective of this project is to design and develop an electronically-variable automotive suspension system using motorized mechanism to vary suspension stiffness. Throughout the duration, both minor and major project's requisites that lead to the final conclusion have been identified as the objectives as listed below:

- To study the type of automotive suspension and system requirements for mechanical variation of the automotive suspension unit.
- To determine the suitable type of electric motor e.g. DC, brushless DC, stepper or servo motor to provide for the shift for the variable suspension such as motor specifications, power requirements
- To design and fabricate a 12V electronic control system to interface with the motor and control input from the driver.

CHAPTER 2 - LITERATURE REVIEW

For conducting this research, a number of relevant literatures has been reviewed to get clear idea on this topic. Most of the adjustable suspensions use a pneumatic system that pump air into the cylinder of the adjustable suspension to control the stiffness of the suspension system. By using the pneumatic system, it consist of a complex system with a lot of sensors to feed the air pressure inside the suspension precisely. [2]

A motorized electronic adjustable suspension will eliminate the need of complicated pneumatic-drive system to operate the system. A motorized system will save a lot weight because the system uses servo motor to control stiffness of the suspension system.

The system will be integrated and receive feedback from the car's accelerometer. The suspension's stiffness can be varied depending on the G-force reading characteristic of the vehicle. As the vehicle turns in high speed cornering, acceleration and braking, the suspension system will adjust its stiffness on certain wheel to ensure more stability and maximum road contact of the car. By increasing stability and maximum road contact of the car, safer driving can be achieved.

To achieve proper control on semi-active suspension, a number of methods were studied to choose the best method for controlling it optimally. To choose the method of controlling the semi-active suspension, it needs further understanding on the vehicle dynamic.

2.1 Passive suspension system

Majority of automotive suspension that has been conventionally used in the automotive industry is the passive type suspension where the system consists of preset spring tension and preset damper rate to control reaction of the suspension [4]. The passive system indicates that the suspension component does not supply energy to the system. A passive system controls the motion of the vehicle body by limiting the relative velocity that gives a desired ride characteristic.

The passive system has a tradeoff between maintaining ride comfort and vehicle stability. To achieve a high degree of vehicle stability, a stiffer suspension system is used. However, stiffer suspension component reduces vehicle ride comfort quality. Thus, the passive suspension has a limitation of performance depending on the road surface. The passive system is represented in the figure below.

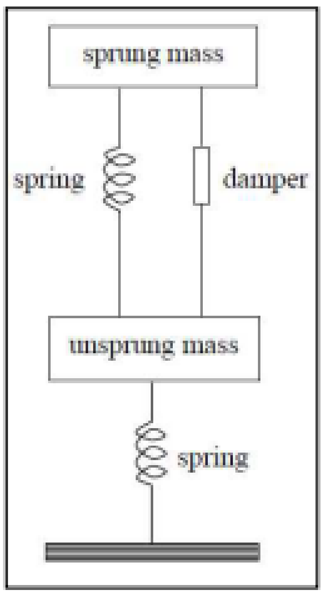


Figure 1: Passive suspension system diagram [7]

2.2 Semi-active suspension system

In the late 80's semi-active suspension system emerges in the automotive sector but was only limited for certain model of car and manufacturer because of the cost, reliability and complexity of system. The semi-active suspension system consists of a preset spring tension with electronic control damper to vary the valve orifice opening in the suspension to control movement of the suspension according to road surface [5].

There are two types of semi-active suspension system: selectable and continuously-variable semi-active system. The selectable system allows the driver to electronically select between a comfort-oriented and a significantly firmer, aggressive performance damping mode with a simple push of a dash-mounted button. A continuously-variable system adapts the suspension stiffness in real time according to road surface. The common method for controlling a continuously-variable system is by using fuzzy logic and closed-loop control. The semi-active system is represented in the figure below

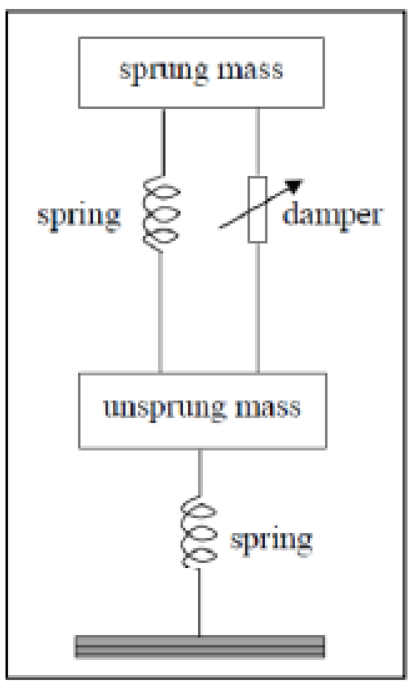


Figure 2: Semi-active suspension system diagram [7]

2.3 Air suspension system

Air suspension system also can be classified as a semi-active system. By varying the height of the suspension system, it can affect a handling, traction and the stability of a car since it can adjust the car's center of gravity. In a high-performance car, by reducing the height of a ride, it can vastly affect stability of the car during high speed and hard cornering. During normal ride, the suspension will revert to the higher position to maximize comfort and ground clearance.

Audi's adaptive air suspension is an example of an adjustable-height suspension system. The system uses a pneumatic system to lift and lower the vehicle position to the desired height and according to vehicle speed, or manually selected mode. The drawback of the system is the system uses complicated pneumatic system and control. The system also adds a significant amount of weight to the entire car.

Figure 3: Air suspension system diagram [2]

2.4 Comparison of passive, semi-active and active suspension system

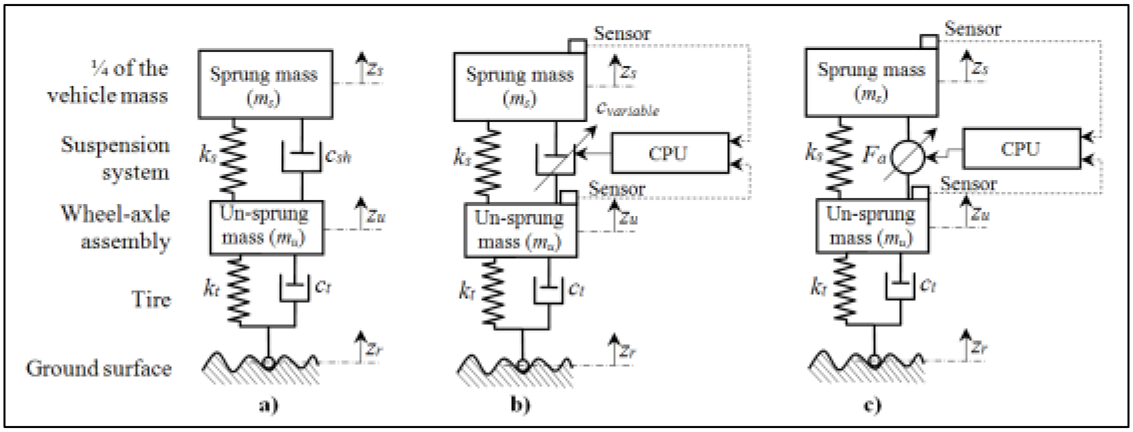


Figure 4: Quarter car model ; a) passive, b) semi-active,c) active suspension system [8]

The passive system consists of conventional spring and hydraulic shock absorber. Shock absorber damping works on the principle of fluid friction through small orifice in the shock absorber piston [9]. In the passive system, the spring and the shock absorber characteristics are non-adjustable and fixed to certain value. Although the system has a certain limitation, it is widely used in automotive sector due to lower cost and less complexity.

The semi-active system contains a fixed spring value but it have a variable shock absorber as an active damping force. The damping force is control by a controller (CPU) by a feedback from certain sensor connected to the system. The force of damping in the shock absorber can be changed by adjusting the orifice area in the shock absorber piston [10].

In the active suspension system, the shock absorber is entirely replace by an active force actuator. The operation of the force actuator are continuously control by sensor that measures the sprung mass and un-sprung mass. From the sensor signal, CPU will ensure the correct impulse to the actuator that creates the active damping force [8]

2.5 Modelling of Passive and Semi-Active Suspension

2.5.1 Quarter-Car Model

A quarter-car model is used to represent the response of one wheel of the car during simulation and mathematical calculation. For the quarter-car model, it is represented by the classic 2 degree of freedom (2DOF) for each wheel of the car [7]. A simplified model of the quarter passive and semi-active suspension is shown in the Figure 4 below, where (a) represent the passive quarter-car model while (b) represents a semi-active quarter-car model.

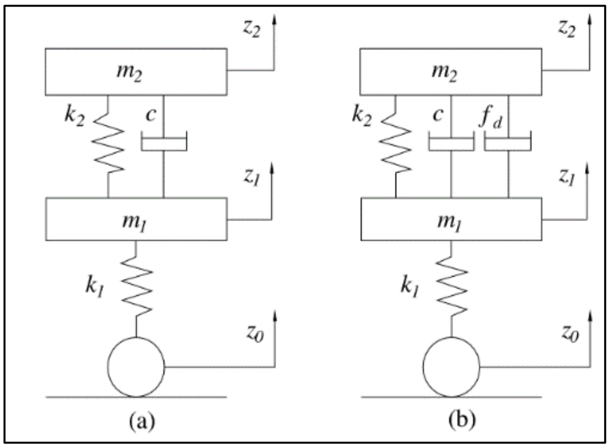


Figure 5: 2DOF of quater-vehicle passive and semi-active suspension model [7]

Referring to the semi-active suspension model, the equation is as follow:

$$\begin{cases} m_1\ddot{z}_1 = -k_1\left(z_1 - z_0\right) + c\left(\dot{z}_2 - \dot{z}_1\right) + k_2\left(z_2 - z_1\right) - f_d \\ m_2\ddot{z}_2 = -c\left(\dot{z}_2 - \dot{z}_1\right) - k_2\left(z_2 - z_1\right) - f_d \end{cases}$$

Where, m_1 —Unsprung mass of semi-active suspension, kg

m_2 —Sprung mass of semi-active suspension, kg

k_1 —Radial tire stiffness, N/m

k_2 —Suspension stiffness, N/m

c —Suspension damping, $\mathrm{N \cdot s/m}$

f_d —Damping force, N

z_2 —Body vertical displacement, m

z_1 —Tire vertical displacement, m

z_0 —Road excitation, m

2.6 Block Diagram for Semi-Active Suspension System

The block diagram below (Figure 6) represent a mechanism of the semi-active suspension system of a quarter-car model.

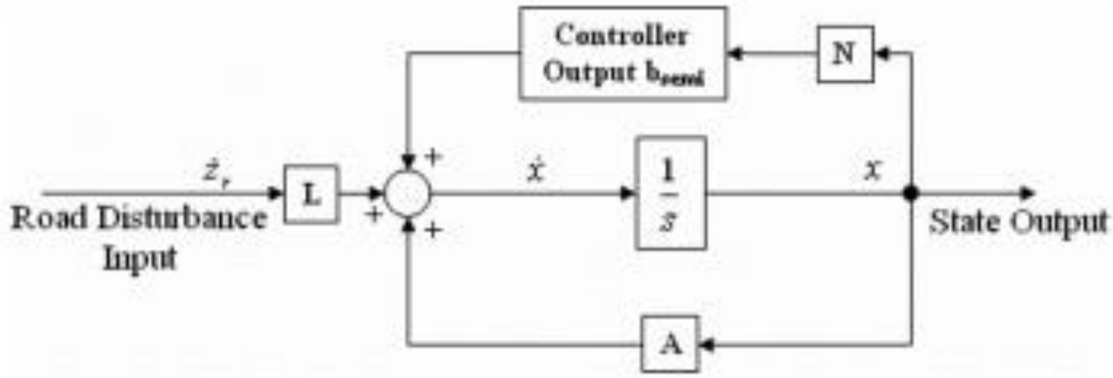


Figure 6: Block diagram for semi-active suspension system [11]

The diagram represents block diagram for the semi-active system and passive system. For the passive system, the damping coefficient of the variable damper is zero [11]. By changing the variable damping coefficient, the model can be used to represent both semi-active and passive suspension system without the need of another block diagram to represent the passive system.

2.7 Fuzzy Logic Control for Semi-active Suspension System

Fuzzy logic control for semi-active suspension system is designed to operate on the feedback data from the suspension system based on the sprung-mass velocity and vehicle body acceleration [12]. For the input of the fuzzy logic system, vertical velocity and the vehicle body acceleration are used and the output of the fuzzy logic system is damping force. When compared with passive suspension, the semi-active system has a greater advantage to reduce the vehicle body acceleration by using the fuzzy logic controller [11]. Fuzzy controller does not need an accurate model of the control plant. It is also not sensitive to changes of the parameters in the process of parameter variation of the control plant, and has strong robustness.

In the fuzzy logic control, there are 4 design process requirement

1. Fuzzification – where this process modifies the input data from numerical value into the fuzzy value for interpretation in next processing
2. Rule Base – the rule base contain the form of If-Then rules that will be used to provide desired system performance
3. Inference Engine – this section chooses the best control method for the application to control the plant activities
4. Defuzzification interface – convert the fuzzy result into real mathematical values and supply to the plant

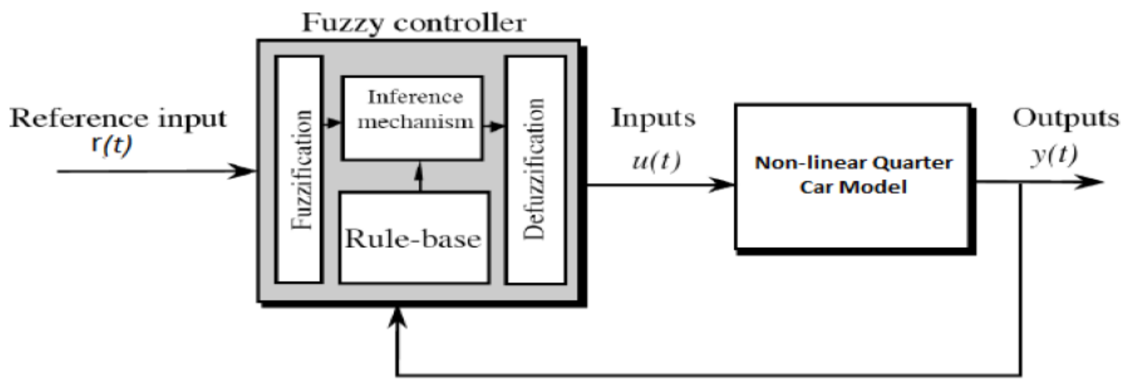


Figure 7:The application of Fuzzy logic controller in quarter-car model [12].

In the fuzzy logic system for quarter-car model, the sprung-mass velocity and the vehicle body acceleration is taken as the input for the system while the damping rate is the output of the controller [12].

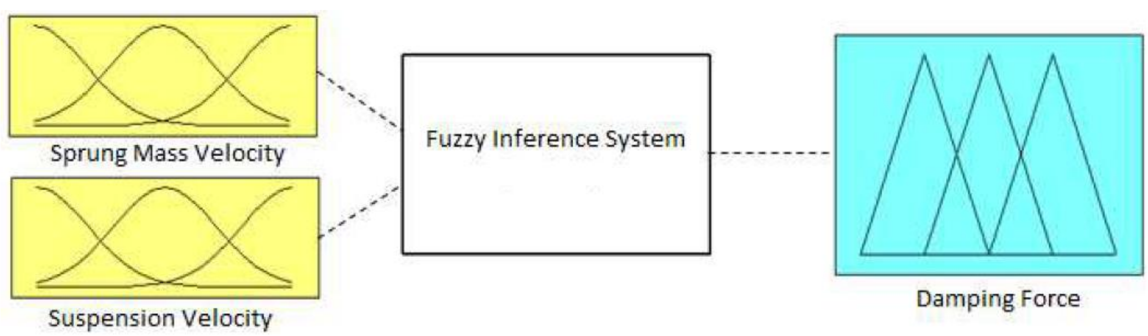


Figure 8: Input and output for fuzzy logic controller in quarter-car model [12]

2.8 Vehicle dynamics

To design a suspension system, vehicle dynamics must be understood in details. The basic information required to understand vehicle architecture as well as dynamic behavior of a four-wheel vehicle .The vehicle coordinate system shown in Figure 9 is explained below:

- Longitudinal motion - Linear motion along x direction.
- Roll - Rotational motion on x axis.
- Lateral - Linear motion along y direction.
- Pitch - Rotational motion on y axis.
- Vertical Motion - Linear motion along z direction.
- Yaw - Rotational motion about z axis.

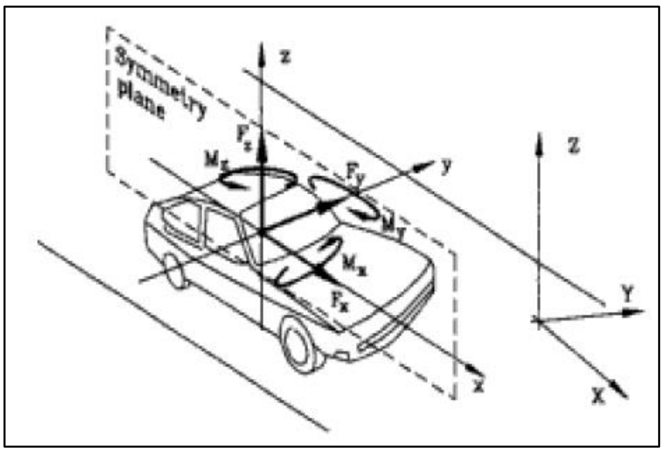


Figure 9: Vehicle dynamic motion direction [13]

CHAPTER 3 – METHODOLOGY

3.1 Working Principle

A car suspensions work on the principle of fluid friction. The damping effect is created by fluid-flow through a small-hole orifice in the shock absorber piston.A non-adjustable suspension system has a fixed orifice opening thus making the system have a preset setting only. On the other hand, an adjustable suspension unit has an adjustable orifice hole opening .

By controlling the fluid-flow through the orifice, different settings of suspension stiffness can be achieved . The driver can adjust suspension stiffness by turning the knob on the top of the suspension unit as shown in the Figure 10 below.

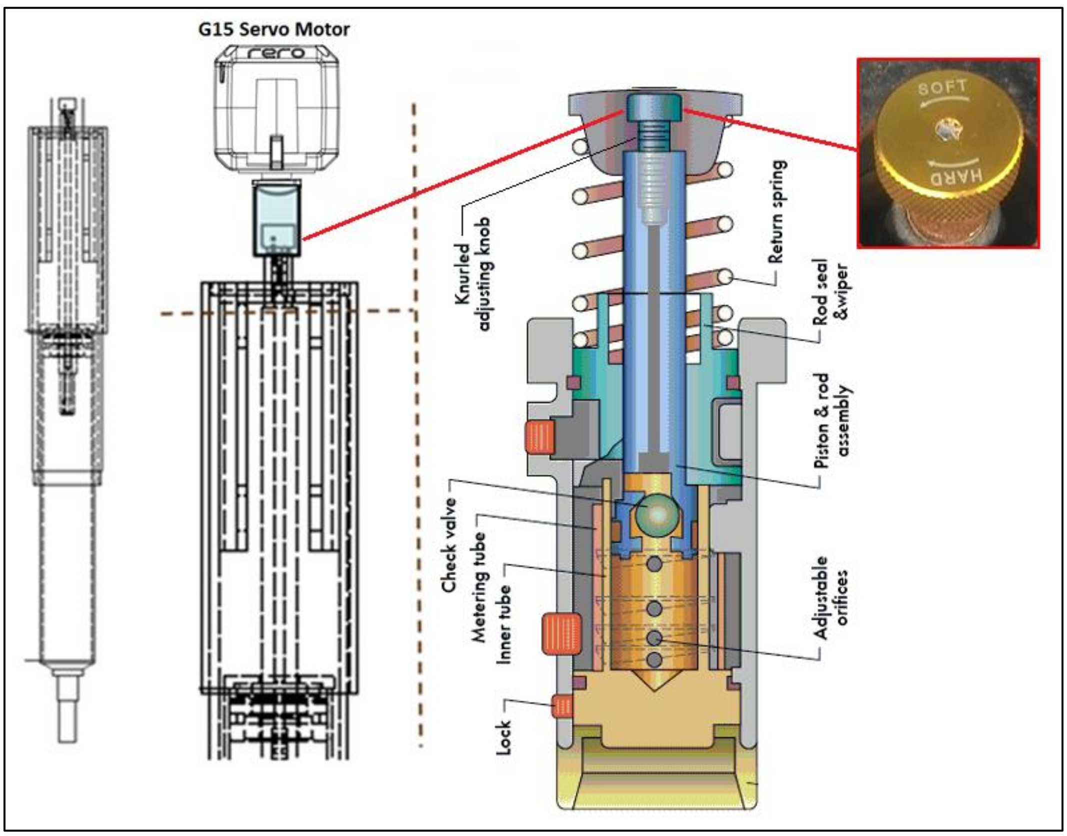


Figure 10: Adjustable suspension diagram

In the normal mechanically-adjustable suspension unit, driver need to stop the car and pop up the hood and turn the selector knob manually to select the desired stiffness.

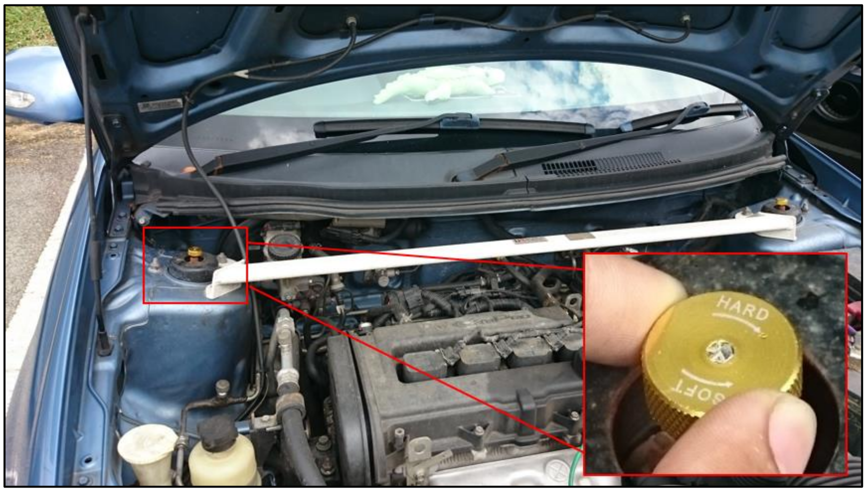


Figure 11: Manually adjust Soft-Hard suspension setting

To overcome this problem, this project will replace the selector knob with a servo motor thus making the system electronically-variable . With the servo motor implementation, driver can now adjust the prefered suspension setting inside the car while driving without the hassle to stop the car and pop up the hood in order to adjust the suspension set manually.


Figure 12: Servo motor implementation on suspension system

By implementing the servo motor to the to control the suspension stiffness automatically, the system becomes a semi-active suspension system by varying the the suspension stiffness with the input of vehicle dynamic properties such as vehicle G-force reading ,body roll and pitch.

3.2 System block diagram

Figure 13(a) and 13(b) shows the all components of the system. The components are divided into 3 subsystems. Stabily control system, user interface system and motor drive system

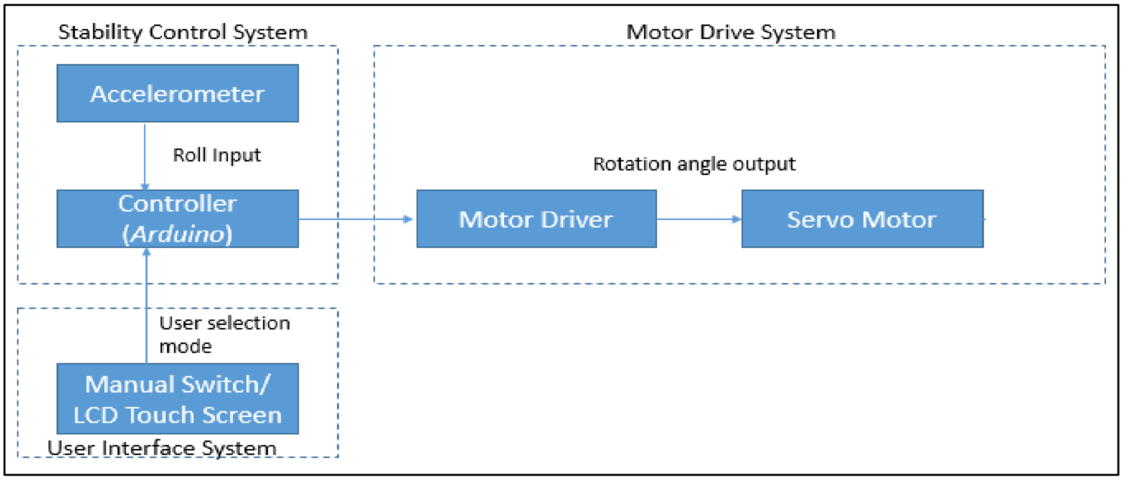


Figure 13(a): Subsystem block diagram

This project will enable driver to select the desireble suspension stiffness by using selector switch while driving. LCD touch screen module will replace the selector switch in further development as the LCD screen can display more information about the suspension setting.

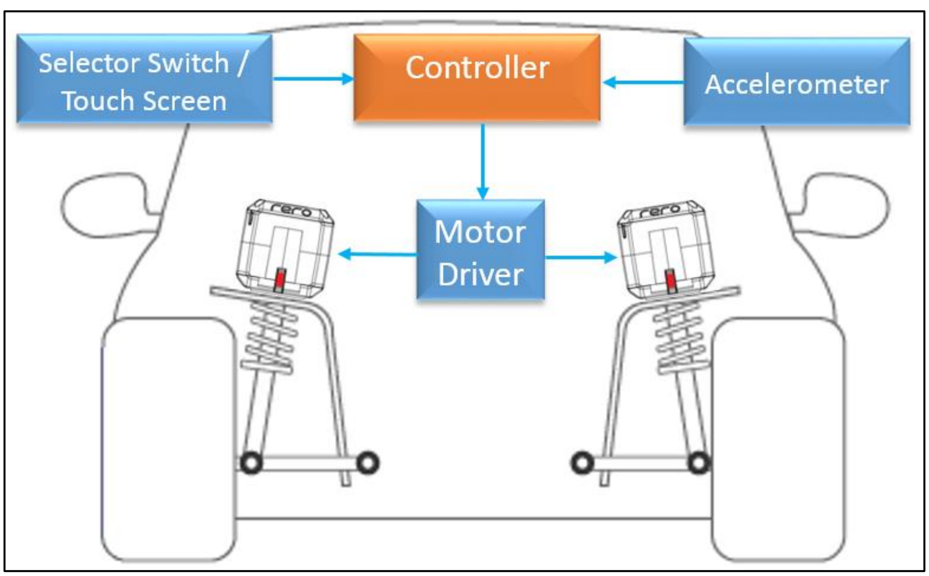


Figure 13(b): Subsystem block diagram on vehicle

3.3 Circuit diagram

The circuit connection is shown in Figure 14. *Arduino Mega* function a the main controller for this project. The controller will process the related signal from the accelerometer and from the user interface to control the motor. After the processing, controller will send signal to the motor driver to rotate the servo motor to desired position.

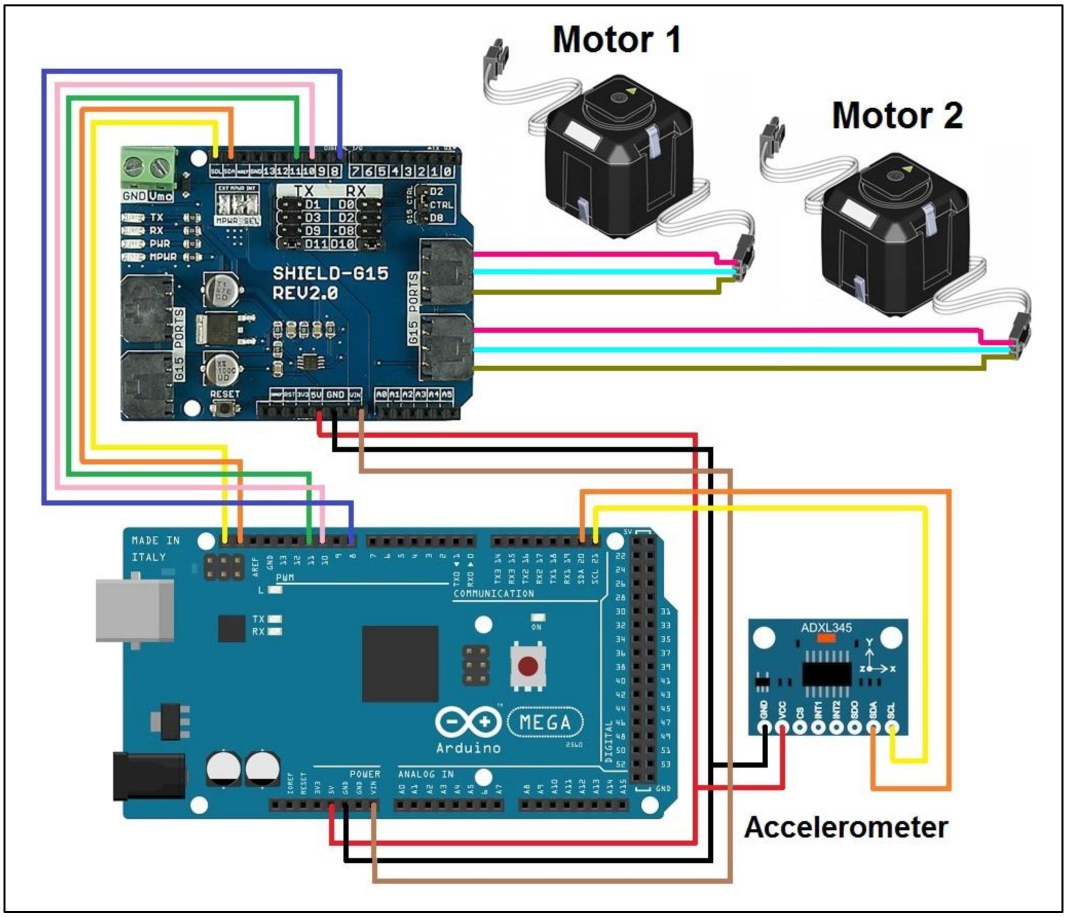


Figure 14: Circuit assembly

The supply voltage for the whole system is 12 Volts. The system, does not need a converter circuit because the car system also runs on 12 Volts system. During testing, the circuit can operate on external battery of direct wire from car electrical system.

3.4 Motor Selection

For the type of motor that will be used for this project, there are two candidates suitable for the motor: servo motor and stepper motor. Both of the motors are capable of turning to the specific desired angle. Below are parameters for selecting the motor for this project:

- Motor rotation angle
- Torque requirement
- Response time
- Motor voltage

During FYP1, stepper motor was chosen for the project. A limitation of the stepper motor is that it does not have position encoder to measure the angle of motor rotation. Stepper motor also have low torque. Because of this limitation, for the latest prototype, a servo motor is used. Cytron G15 servo motor has a special characteristic : it can rotate to full 360° while most servo motors are limited to 180°. The G15 servo motor also can be programmed to rotate continuously during operation.

Figure 15: Cytron G15 servo motor

The compactness and the power of the servo motor make it is the best option to replace the stepper motor used in the previous test model.

The specifications and the dimension of the motor is shown in the Table 1 below.

Parameters	**Details**
Operating voltage	12V
Current Consumption (12V)	1.5A
Max Operating Temp.	80 °C
Weight	63g
Stall Torque	12kg.cm at 12V
Positioning Resolution	0.33 °
Operation Angle	360 ° endless turn, electrical position control
Max Speed (no load)	63 RPM at 12V

Table 1: Motor specification

Figure 16 shows motor drawing and dimension

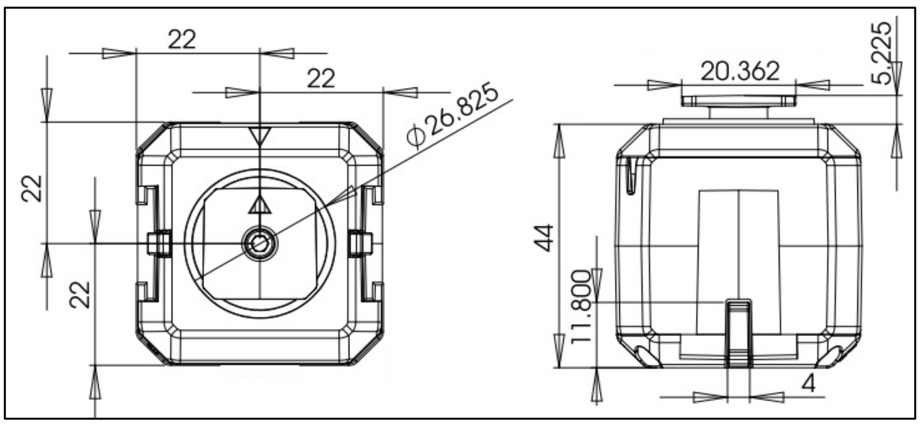


Figure 16: Motor dimension in mm

3.5 Flow Diagram

The objective of the variable suspension system is to control the stiffness of the suspension system according to certain parameters (adaptive mode), or manual selection mode for user to select the suspension system stiffness manually.

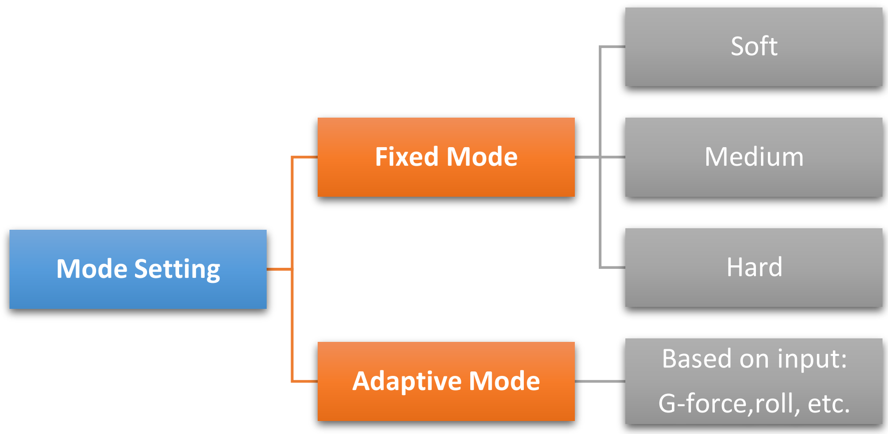


Figure 17: Control interface mode flow diagram

The control interface has a two main selection modes : In the **Fixed Mode**, the driver will select the prefered suspension setting (soft, medium or hard) via a selector switch.

In the **Adaptive Mode**, the suspension setting will depend on the car's lateral G-force. The lateral G-force rate is measured by an accelerometer. In adaptive mode, during normal driving in a straight line, the suspension setting will be on Medium setting. When the car enters a hard cornering, the suspension setting will be change to soft or hard dependingo n the G-force reading from the accelerometer.

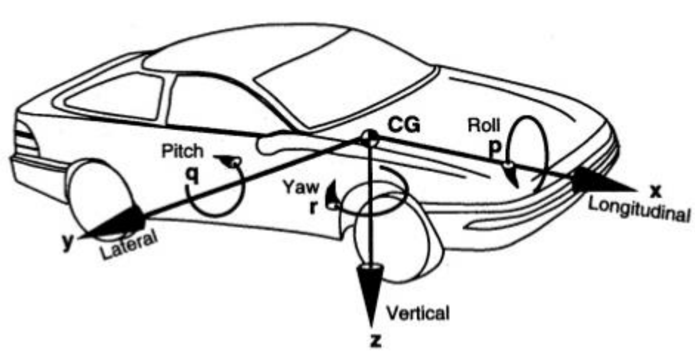


Figure 18: Vehicle dynamic force

3.6 Adaptive and Manual Mode Control Flow Chart

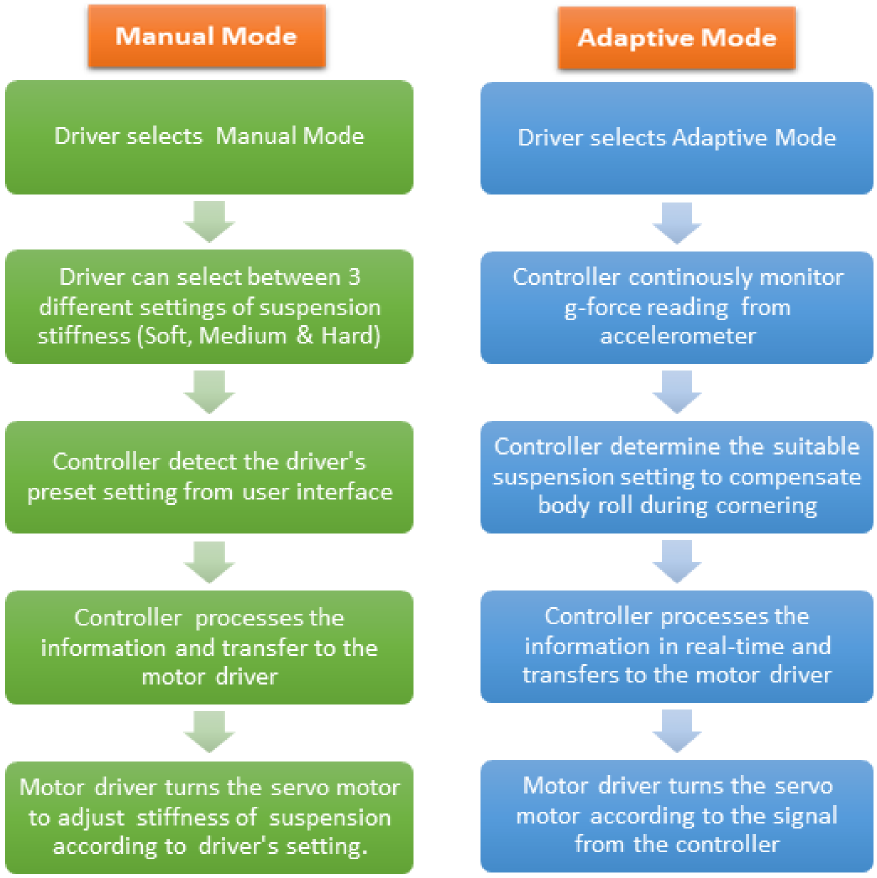


Figure 19: Adaptive & manual mode flow diagram

3.7 Body roll during cornering

Body roll occurs when a vehicle makes a cornering. As the car begins to turn, the weight distribution is shifted on the outer wheels during causing the car to roll in that direction.

Figure 20: Body roll during cornering

Due to body roll during cornering, the outer wheel's suspension system is more heavily loaded when compared with the inner wheel's suspension system. Figure 20 and 21 show that the car with softer suspension setting tends to roll more during cornering compared to the car with stiffer suspension. Less body roll during cornering contribute to greater handling and better cornering response.

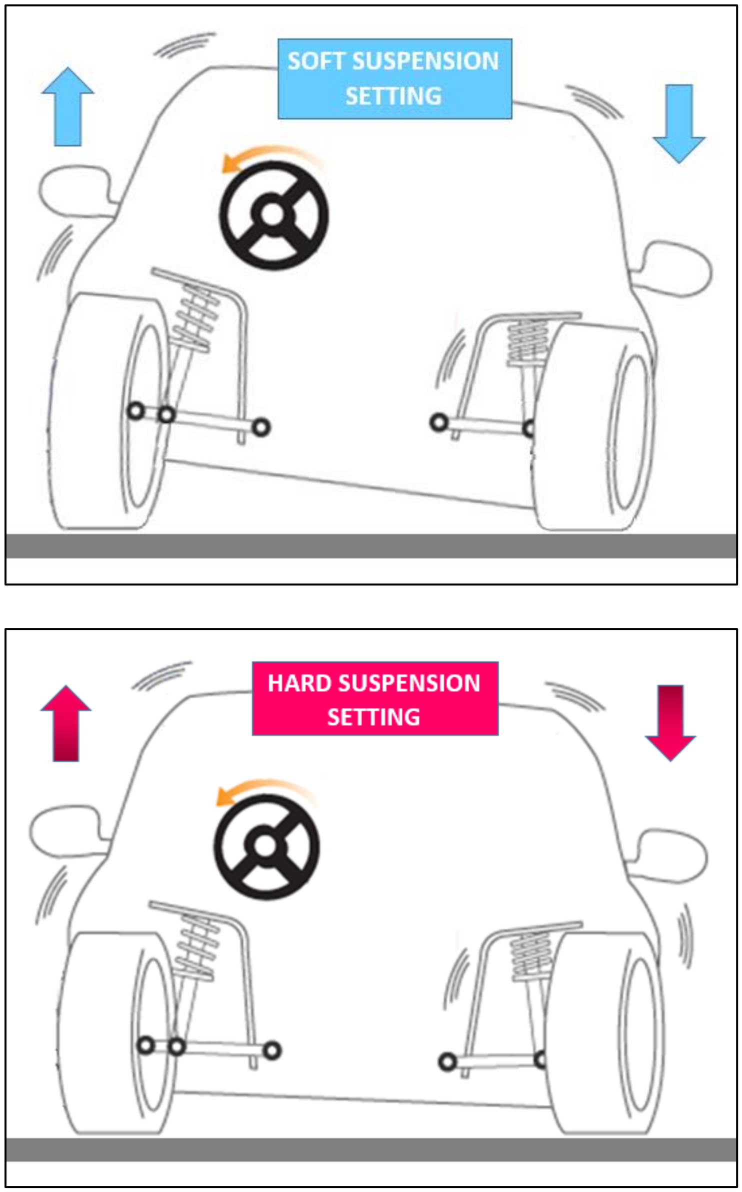


Figure 21: Body roll comparison on soft and hard suspension system

3.8 Adaptive Mode

A stiffer suspension system reduces body roll thus promoting better handling and response during cornering. A stiffer suspension system gives more ‘feel’ towards the driver during cornering compared to soft suspension setting. The drawback of stiffer suspension setting, it will reduce cabin comfort as more road vibration will reach the driver and passanger. To achieve both comfort and better handling, the suspension system must be variable to compensate the changes in vehicle dynamics.

In the Adaptive Mode , the controller will adjust the suspension stiffness according to the lateral G-force reading. During normal driving, the controller will set the suspension stiffness to medium setting. When accelerometer detect the car entering a corner, the controller will set the suspension stiffness to hard setting in real-time.

The lateral G-force value during,hard right corner and hard left corner on a street vehicle can achieve approximately +1G (10 m/s^2). During right cornering the the G-force reading from accelerometer show positive value. On left cornering, accelerometer record a negative value. From the accelerometer lateral G-force reading, the controller can detect how hard the car turns into corner [21].

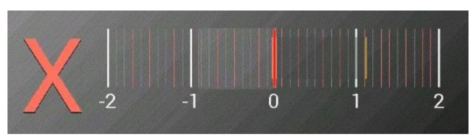
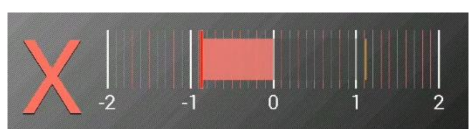
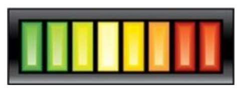
Straight Line	
Right Corner	
Left Corner	

Figure 22: Sample of lateral g-force reading during driving condition

Figure 23(a) - 23(c) below show how the Adaptive Mode react to the driver's driving style. 3 condition are simulated:

- Straight Driving
- Right Cornering
- Left Cornering

In Figure 23-25 , soft, medium and hard Setting will be shown in the LED bar graph.

• **SOFT**	
• **MEDIUM**	
• **HARD**	

During straight driving, the accelerometer detects no g-force changes on the car thus the controller will send signal to servo motor to rotate to center position to select medium setting on the shock absorber.

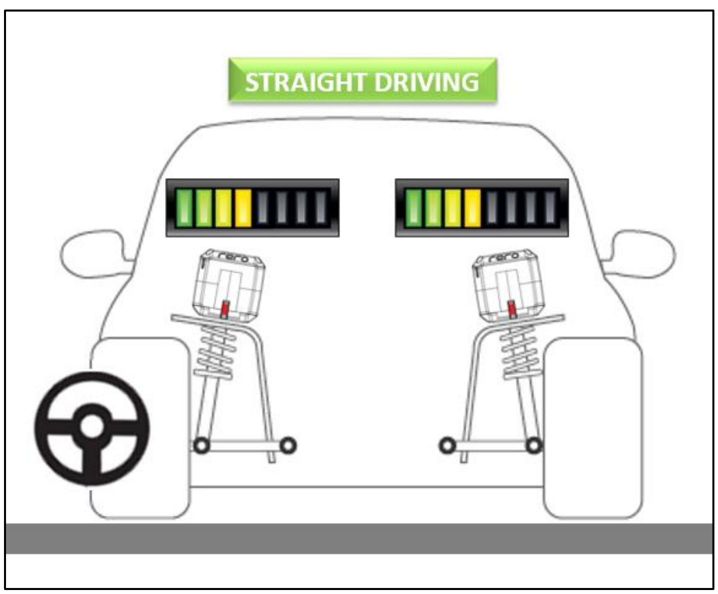


Figure 23(a): Adaptive Mode straight driving simulation

When lateral G-force reading changes during right cornering, controller will send signal to servo motors. The left servo will rotate clockwise to select hard setting at the shock absorber. Right servo will turn anti-clockwise to select soft setting for the shock absorber.

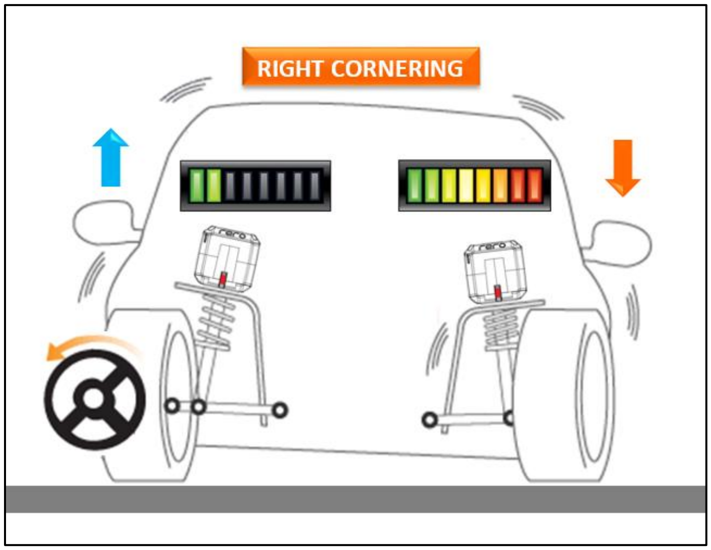


Figure 23(b): Adaptive Mode right cornering simulation

When lateral G-force reading changes during left cornering, controller will send a signal to servo motors. The right servo will rotate clockwise to select hard setting at the shock absorber. Left servo will turn anti-clockwise to select soft setting at the shock absorber.

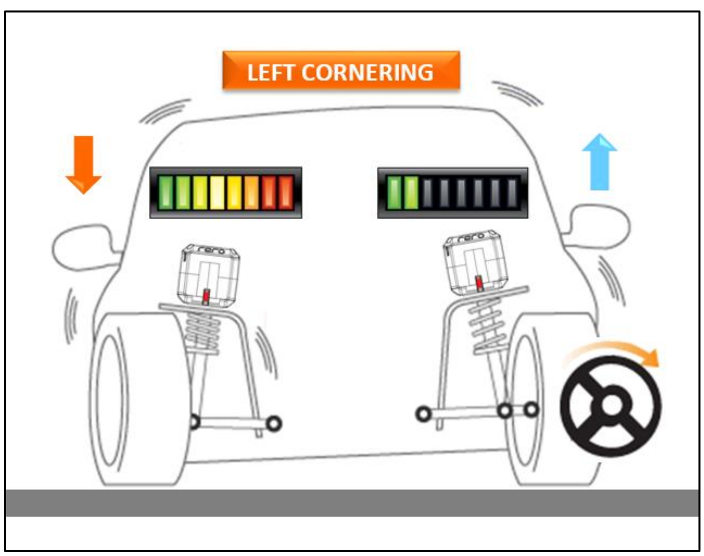


Figure 23(c): Adaptive Mode left cornering simulation

3.9 Gant Chart

Final Year Project 1

	Activity	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	First meeting for FYP1 and title selection	■	■												
2	Study of mechanical specifications and system requirements for mechanical variation of the automotive suspension unit	■	■												
3	Determine type of electric motor, e.g. DC, brushless DC, stepper or servo motor to provide for the shift for the variable suspension – motor specifications, power requirements etc.			■	■	■	■								
4	Submission for extended proposal defence						■								
5	Determine an electronic interface board for interfacing to 12V power input, electric motor and control inputs from the user/driver					■	■	■	■						
6	Proposal Defense								■						
7	Design controlling method to control the rotation of motor to adjust absorber damper value via user selection or automatic selection.									■	■	■	■		
8	To analyze response of the motor when it is attached with the controller.												■	■	■
9	Interim report preparation												■		
10	Interim draft report submission													■	
11	Interim Final Report Submission														■

Table 2: Gant chart for Final Year Project (FYP 1)

Final Year Project 2

	Activity	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Study of vehicle dynamic of car during certain driving condition	■	■												
2	Accelerometer data gathering during different driving condition		■	■	■										
3	Component and circuit assembly				■	■	■								
4	Test model assembly					■	■	■	■						
5	Test model bench-test and simulation							■	■						
6	Conduct In-car test model testing & simulation								■	■	■				
7	Progress Report									■					
8	Connecting the test model with actual suspension unit									■	■	■			
9	Electrex											■			
10	Test with actual variable suspension assembly										■	■	■	■	
11	Draft report submission													■	
12	Final Report Submission														■

Table 3: Gant chart for Final Year Project (FYP 2)

CHAPTER 4 - RESULTS

4.1 Data recording from accelerometer.

Since the controlling of the suspension stiffness is achieved by getting the G-force reading from the accelerometer, understanding vehicle dynamics is very important. The accelerometer is used to record the lateral G-force of vehicle during certain condition when driving. By studying data from the accelerometer, a precise control of suspension system can be achieved by knowing the car limits and behavior during different driving conditions.

An accelerometer and its data recording systems is placed on a car dashboard to monitor and record the data reading during certain driving condition. 3 sets of accelerometer were used for measuring the data to ensure the robustness of the data, 1 set from *Arduino* controller and 2 set from mobile devices. Only the X-axis lateral g-force reading is recorded because body roll mostly only effect X-axis. The test platform is on Honda Civic 1.8S.

Figure 24: Accelerometer data recording

4.2 Test Road

The test road for cornering data recording is situated in Jalan Pulau Meranti, Puchong, Selangor. The road consist of set of hard left and hard right cornering as well as normal left and right cornering. The map below show the details of the cornering section.

Figure 25: Test road

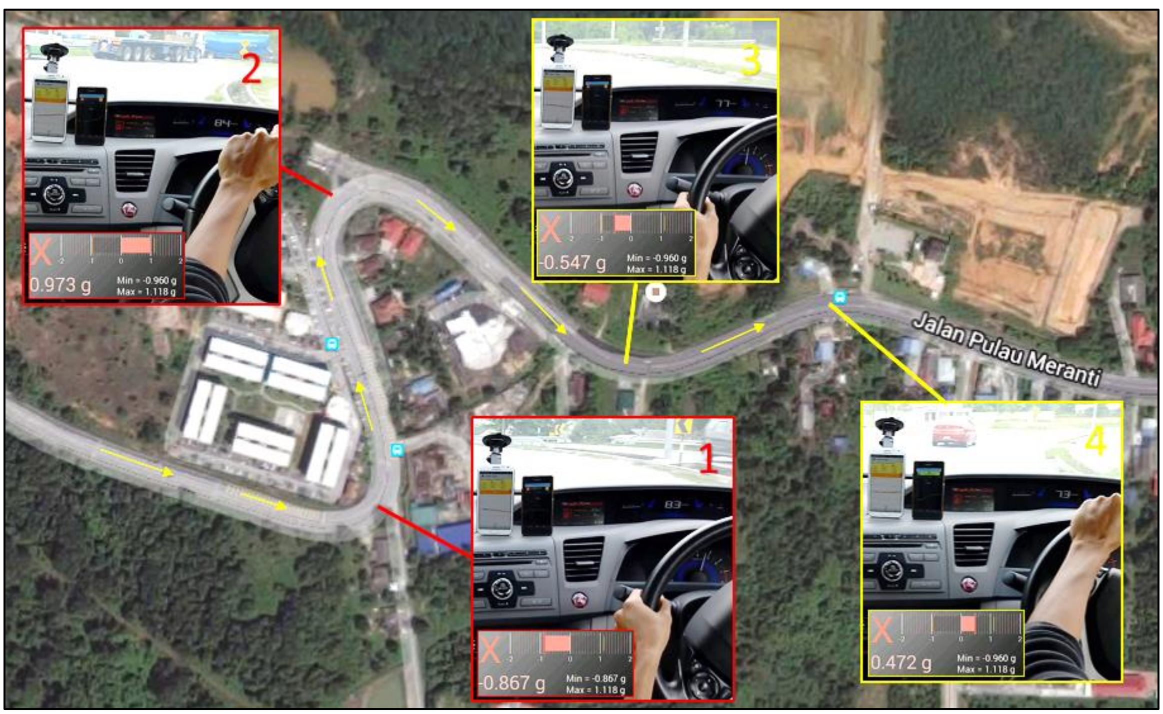


Figure 26: Accelerometer reading(max) and actual driving footage

4.3 Accelerometer Data

The 4 sets of graph below show the data recorded when a car enter a corner at the test road. The red ripple in the graph indicates the actual reading collected by the accelerometer during cornering. The ripple in the data recording is cause by vibration from uneven road surface. The dark red line is the filtered and smoothened data by using a moving average sampling filter.

a) **Hard Left Cornering** – the graph below shows the accelerometer reading during left cornering on the test road. The G-force value peak at -0.8G.

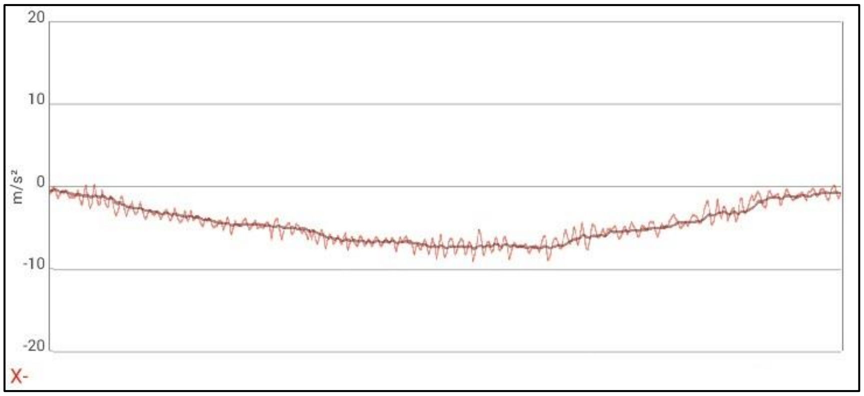


Figure 27(a): Hard left cornering lateral g-force

b) **Hard Right Cornering** – the graph below shows the accelerometer reading during right cornering. The G-force value peaks on +0.9G. Fluctuation in the G-force reading during peak cause by uneven surface on the test road caused by slight understeer on the car.

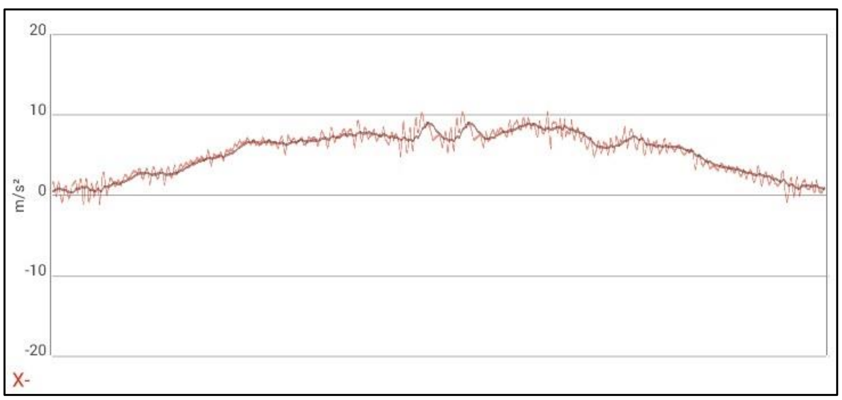


Figure 27(b): Hard right cornering lateral g-force

c) Medium Left Cornering – the graph below shows the accelerometer reading during medium left cornering on the test road.The G-force reading peaks at -0.5G.

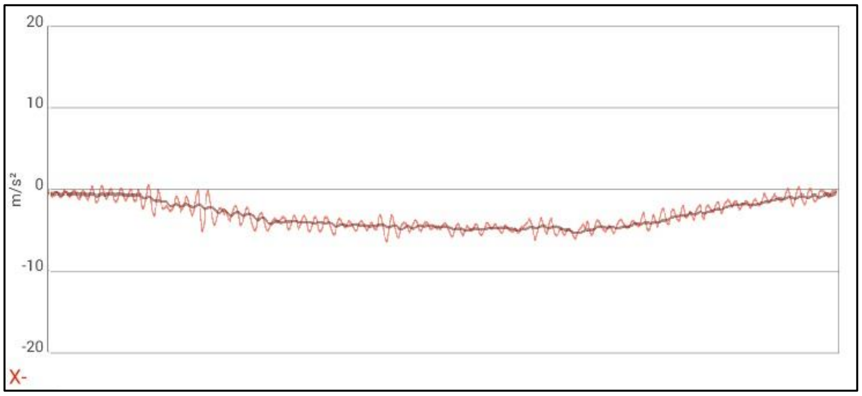


Figure 27(c): Medium left cornering lateral g-force

d) Medium Right cornering – the graph below shows the accelerometer reading during left cornering on the test road. The G-force value peaks at -0.4G.

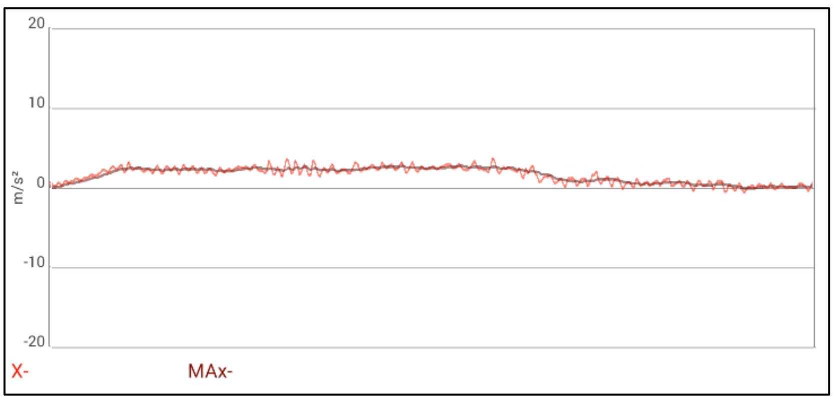


Figure 27(d): Medium right cornering lateral g-force

4.4 Accelerometer Data Filtering

Accelerometer data fluctuation and ripple mostly due to uneven road surface and the vibration from the vehicle engine itself. Because the control of servo motor is directly fed from the accelerometer signal, unfiltered accelerometer signal will cause jitter in motor movement.

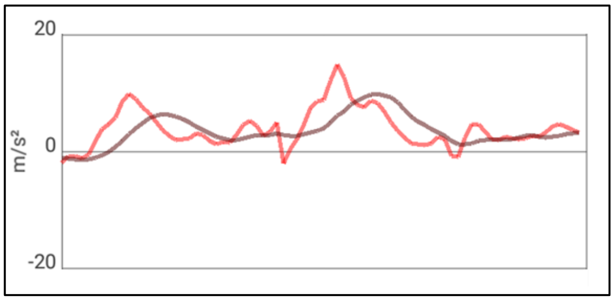


Figure 28: Graph of accelerometer reading with moving average filtering

For the accelerometer reading during driving condition, moving average filtering technique was used to smoothen the data curve. The red colored graph above represents the original reading from the accelerometer. The smooth dark red curve is the filtered reading. The filter will smoothen the fluctuation of the accelerometer reading.

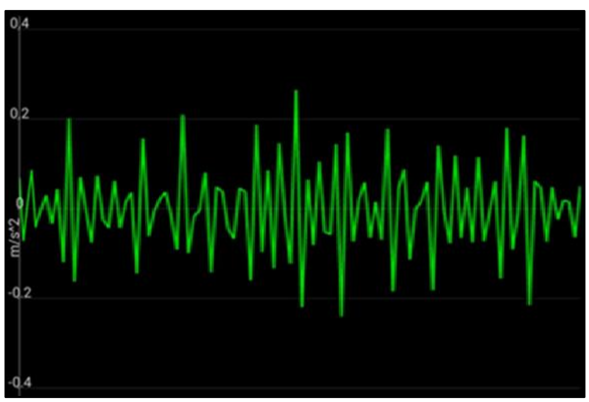


Figure 29: Engine vibration reading during idling

Vibration from the vehicle engine also contributes to the fluctuation in the accelerometer reading. From the data recording in the graph on figure 29, during car idling the accelerometer reading show a peak value of 0.28 m/s^2 (0.028G) and the average reading is around 0.2 m/s^2. By obtaining the accelerometer data from engine vibration during idling, a low pass filter can be set in the controller to 0.3 m/s^2 to remove vibration noise.

4.5 Test Model

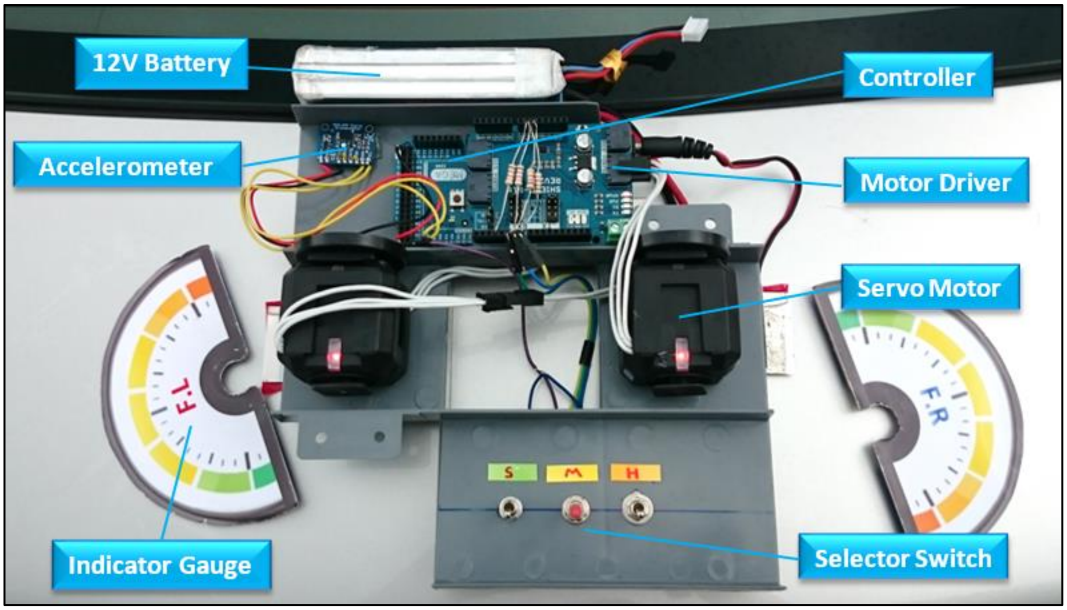


Figure 30: Test model assembly

For simulation and testing purpose, indicator gauge and needle were placed on the motor to show the motor movement that will control the stiffness of the suspension system.

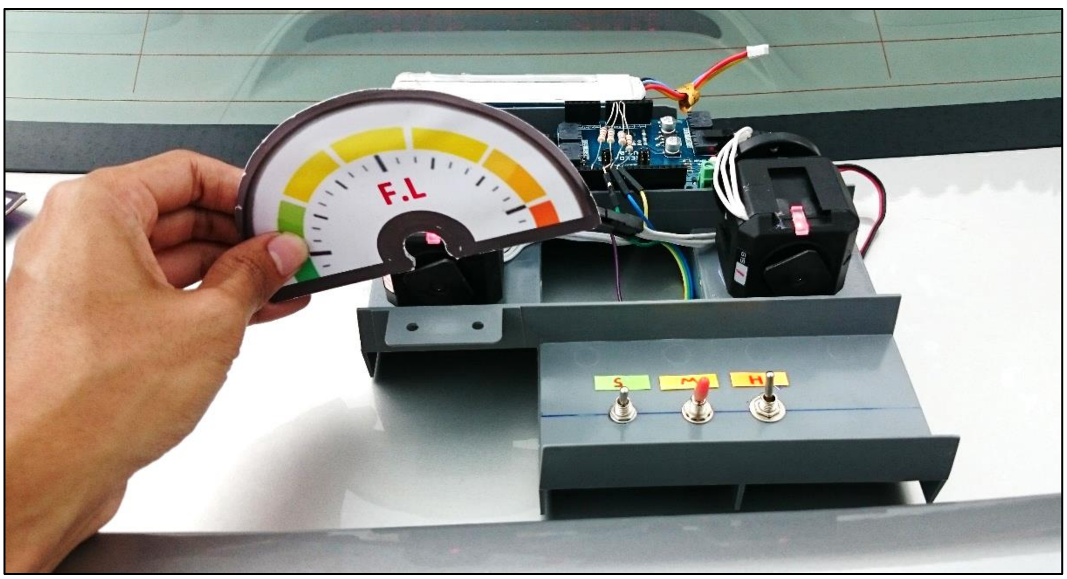


Figure 31: Placing the indicator gauge on the motor.

Complete assembly of the test model with the indicator gauge and needle to show the movement of motor during Manual Mode and Adaptive Mode. The needle is place on the rotated part of the motor .The right blue needle will show the movement of right motor that will control the front right suspension . The left red needle will show the movement of right motor that will control the front-right suspension. Although the servo motor capable to rotate 360 °, for simulation and testing purpose, the motor rotation limit is set to 180°.

Figure 32: Complete test model assembly with indicator gauge and needle

4.6 Manual Mode Testing

On Manual Mode, driver will select the preferable suspension stiffness (Soft, Medium & Hard) via a selector switch.

Figure 33: Selector switch

4.6.1 Manual Mode - Soft Setting

The user select (S) Soft setting on the selector switch, controller will turn the motor counter clockwise. When the servo motor were attach to actual suspension system the motor will rotate the soft-hard knob of a shock absorber.

Figure 34(a): Manual Mode – Soft setting

4.6.2 Manual Mode - Medium Setting

When the user select M (Medium) setting on the selector switch, controller will turn the motor on center position.

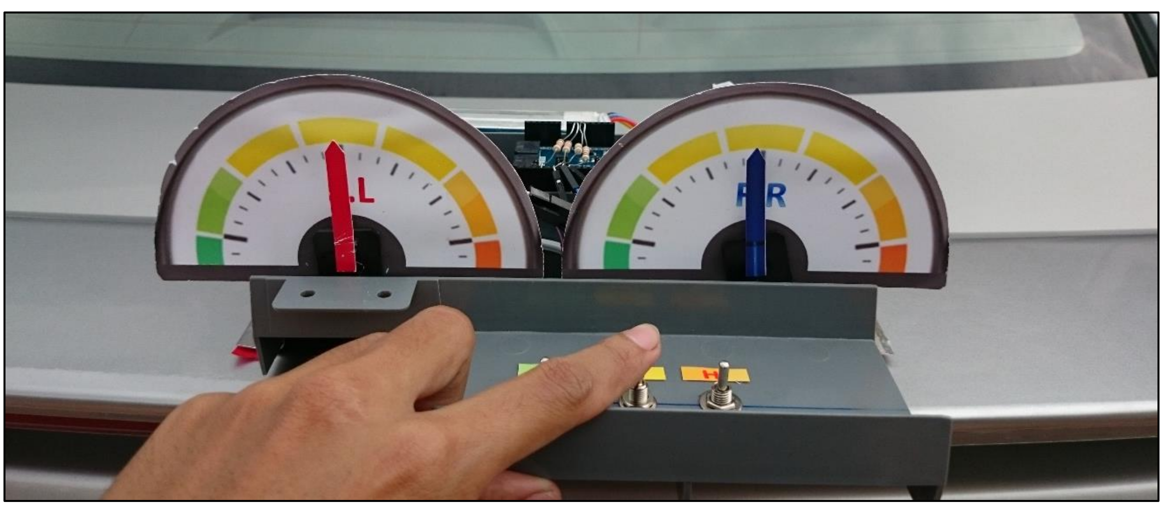


Figure 34(b): Manual Mode – Medium setting

4.6.3 Manual Mode - Hard Setting

When the user select (H) Hard setting on the selector switch, controller will turn the motor clockwise.

Figure 34(c): Manual Mode – Hard setting

4.7 Adaptive Mode Testing

For the adaptive mode testing, the test model were placed on the car dashboard for data capturing and snapshot recording.

In the Adaptive Mode **,** controller will adjust the suspension stiffness according to the car's lateral g-force reading. During straight line, the controller will set the suspension stiffness to Medium Setting. When accelerometer detect the car entering a corner, the controller will set the suspension stiffness to Hard on the specific side of the suspension system.

4.7.1 Adaptive Mode - Straight Line Driving

During straight line driving, controller set the both left and right suspension setting to Medium

Figure 35(a): Adaptive Mode – Straight line driving

4.7.2 Adaptive Mode – Left Cornering

During hard left cornering, controller adjust the right suspension to hard setting and left suspension to soft setting. The servo motor rotation is shown in the figure below. The right servo rotate clockwise while left servo rotate counter-clockwise. This setup will reduce the car body roll to ensure maximum road contact during cornering.

Figure 35(b): Adaptive Mode – Left Cornering

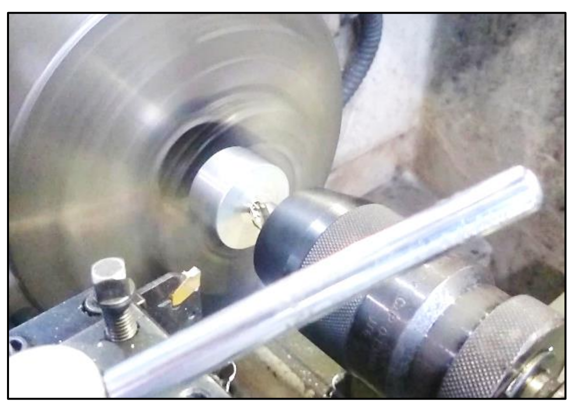
4.7.3 Adaptive Mode – Right Cornering

On hard right cornering, controller adjust the left suspension to hard setting and right suspension to soft setting. The servo motor rotation is shown in the figure below. The left servo rotate clockwise while right servo rotate counter-clockwise.

Figure 35(c): Adaptive Mode – Right cornering

4.8 Test Rig Setup

4.8.1 Suspension-Motor Coupling Fabrication and Assembly



Fabrication and assembly process of coupling that will connect the servo motor and the actual suspension stiffness setting knob.

Figure 36: Suspension-Motor Coupling Fabrication and Assembly

4.8.2 Test Rig Assembly

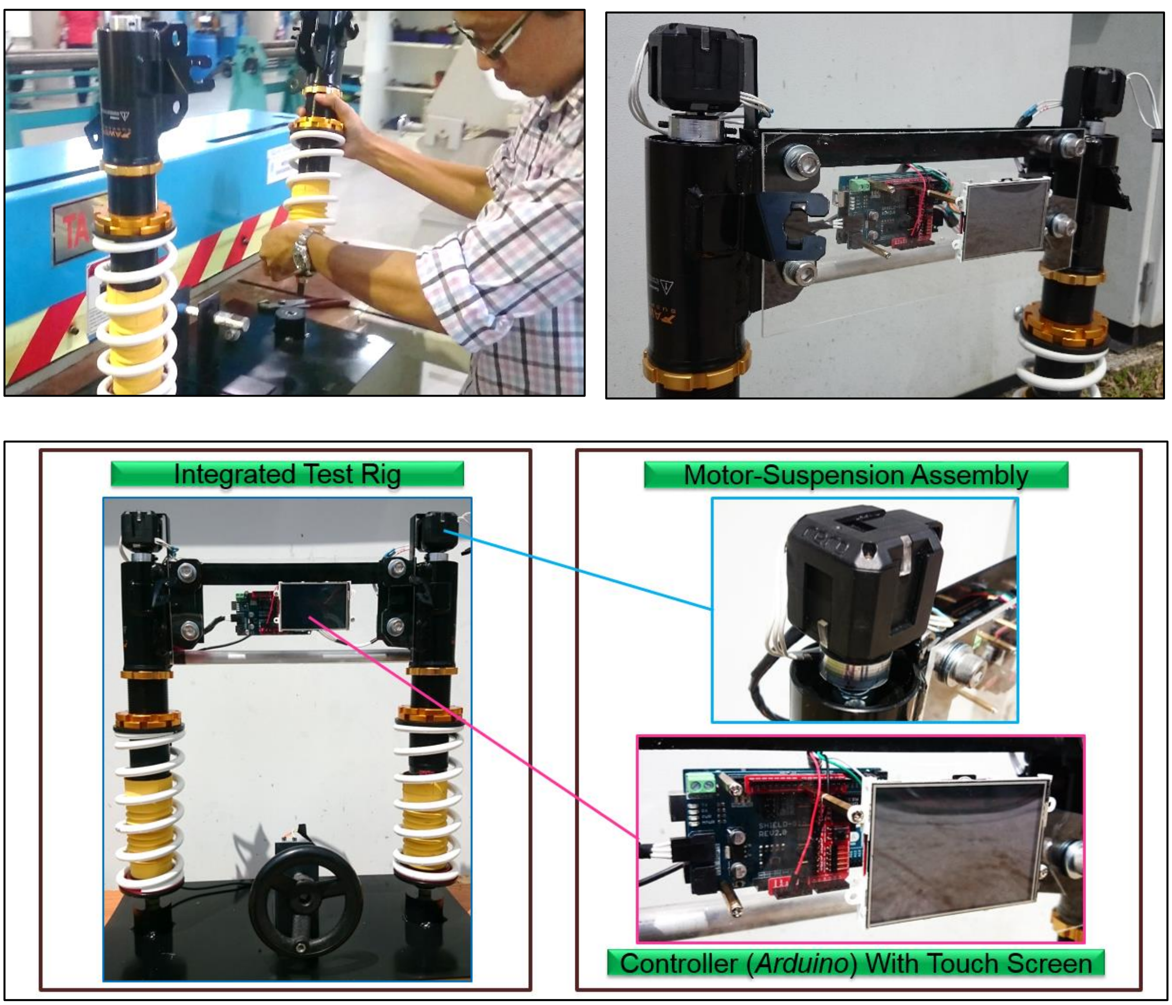


Figure 37: Test rig assembly

4.8.3 Touchscreen GUI

The system use 4D System uLCD-35DT 3.5" LCD Display as the GUI for the system. Driver can select the mode of the system via the touchscreen interface. The system also display the response of right and left suspension in the colored gauge. In the current GUI, to select soft, medium and hard Setting, driver just need to push the green, yellow and red button on the touch screen module.

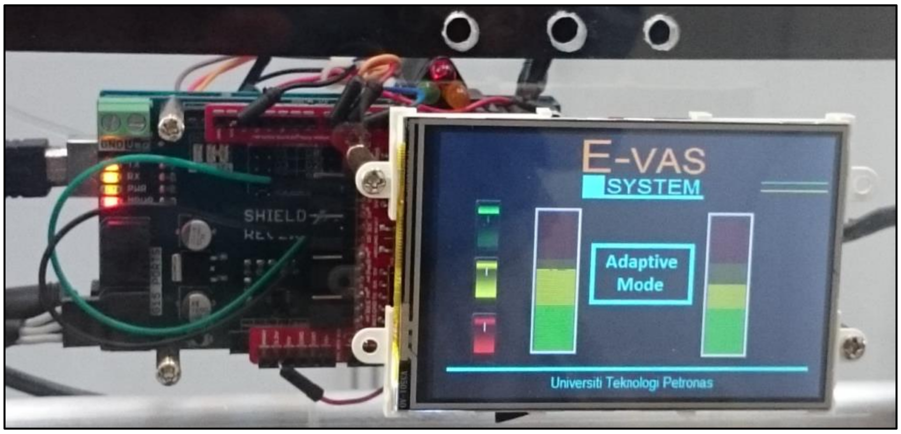


Figure 38: LCD Touchscreen GUI

4.8.4 Test Rig –Actual Road Test

The test rig is placed inside a car on the backseat for the testing and to show how the system response during actual driving condition.. The test rig accelerometer's is placed on the car center console for reading the car lateral G-force during cornering.

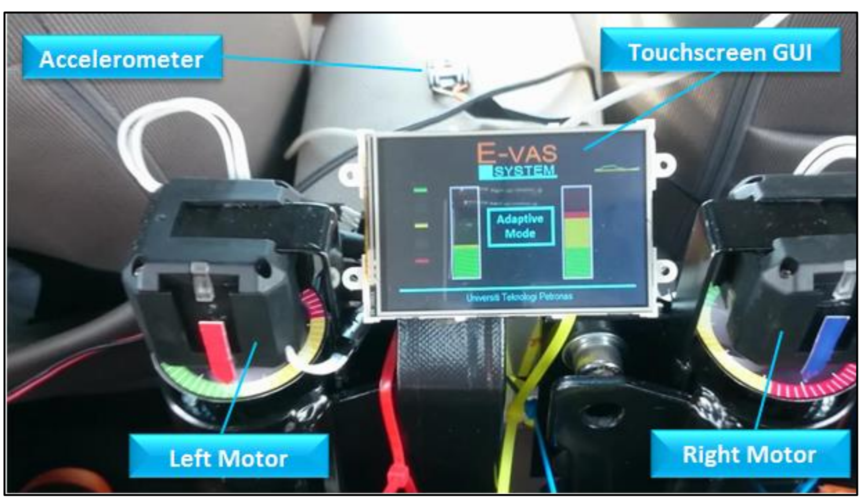


Figure 39: Test rig testing on car.

4.9 Road Test Data With Test Rig (Adaptive Mode)

The scale of the accelerometer is from -10 to 10 m/s^2. 10 m/s^2 is approximately 1 G of force. The positive value (0 to 10) indicate that the car corner to the right. The negative value indicate that the car corner to the left (0 to -10 m/s^2).

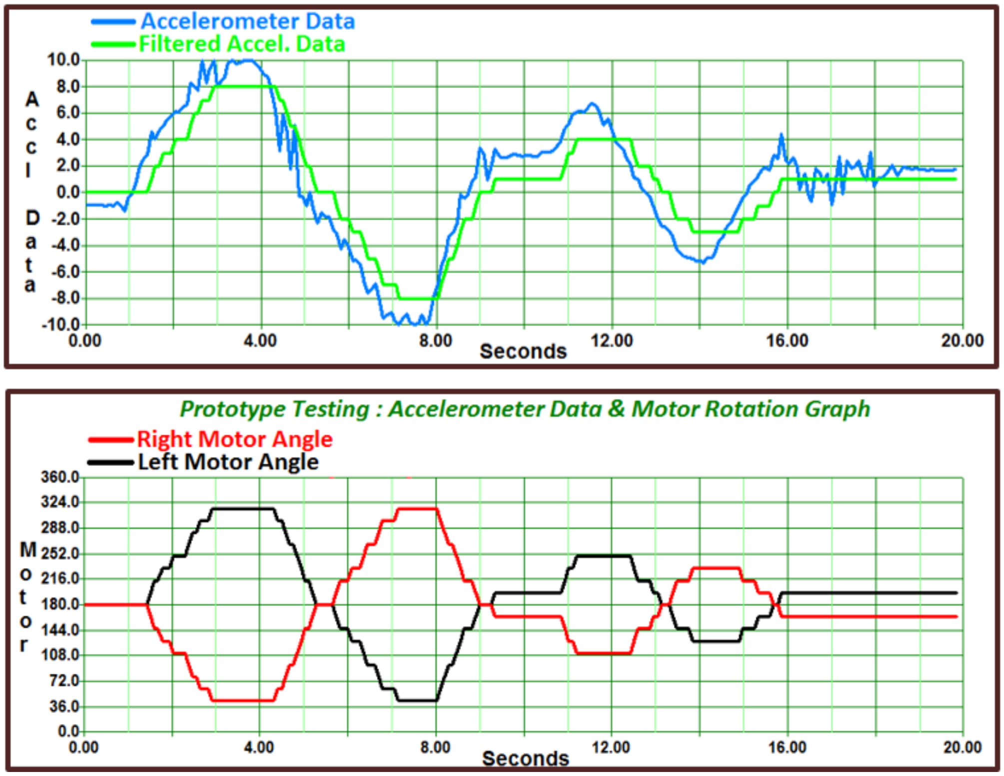


Figure 40: Accelerometer data and motor rotation graph

During right cornering, the left servo motor will rotate clockwise to select hard setting on the suspension and the right servo will rotate counter-clockwise to the soft setting. On left cornering, the right servo motor will rotate clockwise to select hard setting on the suspension and the left servo will rotate counter-clockwise to the soft setting. The degree of motor rotation is depend on the lateral G-force reading that acting on the car body.

With this setup, the car will achieve better handling and increase safety during cornering on winding road. During straight driving, this setup will ensure maximum comfort for the driver and passenger.

4.9.1 Test Rig –Slalom Test (Adaptive Mode)

The test is done on empty parking lot. The car was driven into hard and left corner to test the rig to the maximum setting. Figure 41 & 42 is the video snapshot during the test. The graph of G-Force reading is shown on the top left of the snapshot. Test rig response is shown on the bottom left of the snapshot.

During hard right cornering, driver manage to pull near 1G of lateral g-force. The system response by setting the left suspension to the max setting. Noted that the steering wheel position shown left because of counter-steering to compensate the oversteer.

Figure 41: Slalom test – Hard Right Cornering

During hard left cornering, 1G of lateral g-force were recorded. The system response by setting the right suspension to the max setting. Noted that the steering wheel position shown right because of counter-steering to compensate oversteer.

Figure 42: Slalom test – Hard left Cornering

4.9.2 Test Rig –Road Test (Adaptive Mode)

The road test was done at federal road, Gelong Pepuyu - Beruas roadway. Data during straight line driving and winding road were recorded. On the G-force graph, the blue line is the accelerometer raw data and the green line is filtered accelerometer data. Black line is left motor rotation and red line is right motor rotation.

Figure 43: Road test – Straight line driving

Figure 44: Road test – Right Cornering

Figure 45: Road test – Right Cornering

The video snapshot on the Figure 43,44 and 45 show the result of servo motor response corresponding with the lateral G-force during real road test. The test achieved its objective where the system will control the behavior of servo motor response based on G-force during cornering and set the suspension system to medium setting during straight road driving condition.

CHAPTER 5 – CONCLUSION

5.0 Conclusion and Recommendation

The outcome of the project is to produce a manually-adjustable suspension system is incorporated with a DC servo motor to make the system electronically-variable, via an *Arduino* controller. The system can have either selectable fixed-stiffness settings (*fixed mode*) or be made to respond to dynamic inputs - such as lateral G-force or vehicle speed – (*adaptive* mode), to become a semi-active suspension system.

By using a variable suspension system , the car will change its stiffness setting depend on the lateral g-force as the car turn into a hard corner the suspension system will change its stiffness to hard setting to reduce car body roll and maximize road contact. During normal driving condition, the suspension setting is on soft-medium setting to ensure maximum driving comfort for the driver. This system will ensure more safety for the driver and passenger.

Recommendation for this project is on the controller circuit. The filtering of the accelerometer data can be optimized by using Kalman filter sampling to produce smoother signal fed to the controller circuit. The algorithm that control the motor response can be upgrade by implementing PID or Fuzzy Logic control to produce robust control and sensitivity towards the system.

In future development, the system can be fully integrated with various sensors in a car such as steering position sensor, yaw sensor, speed sensor and load sensor. By integrating the variable suspension system with the various sensor in a car, the project will produce a refinement of suspension tuning in automotive industries.

6.0 REFERENCES

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APPENDICES

Appendix 1 : Arduino Code

```
#include <genieArduino.h>
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_ADXL345_U.h>
#include <Servo.h>
#include <SoftwareSerial.h>
#include <Cytron_G15Shield.h>

Genie genie;
Cytron_G15Shield g15(10, 11, 8); // SoftwareSerial: Rx, Tx and Control
pin
//Cytron_G15Shield g15(8); // HardwareSerial: Control pin

#define G15_0 0
#define G15_1 1
#define G15_11 11
#define LED 13

//Filter Parameter
int sensorVal       = 0;    // store the value coming from the sensor
int smoothedVal     = 0;    // smoothed result
int samples         = 3;    // amount of samples


#define RESETLINE 4 // Change this if you are not using an Arduino
Adaptor Shield Version 2 (see code below)

int x, y, z;
int rawX, rawY, rawZ;
int mappedRawX, mappedRawY;
int Motor1;
int Motor2;
int Motor3;
int Motor4;


/* Assign a unique ID to this sensor at the same time */
Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified(12345);

void displaySensorDetails(void)
{
  sensor_t sensor;
  accel.getSensor(&sensor);
  //Serial.println("------------------------------------");
 // Serial.print  ("Sensor:       "); Serial.println(sensor.name);
 // Serial.print  ("Driver Ver:   "); Serial.println(sensor.version);
 // Serial.print  ("Unique ID:    "); Serial.println(sensor.sensor_id);
 // Serial.print  ("Max Value:    "); Serial.print(sensor.max_value);
Serial.println(" m/s^2");
 // Serial.print  ("Min Value:    "); Serial.print(sensor.min_value);
Serial.println(" m/s^2");
 // Serial.print  ("Resolution:   "); Serial.print(sensor.resolution);
Serial.println(" m/s^2");
```

```
//  Serial.println("------------------------------------");
  //Serial.println("");
  delay(500);
}

void displayDataRate(void)
{
  //Serial.print  ("Data Rate:    ");

  switch(accel.getDataRate())
  {
    case ADXL345_DATARATE_3200_HZ:
      Serial.print  ("3200 ");
      break;
    case ADXL345_DATARATE_1600_HZ:
      Serial.print  ("1600 ");
      break;
    case ADXL345_DATARATE_800_HZ:
      Serial.print  ("800 ");
      break;
    case ADXL345_DATARATE_400_HZ:
      Serial.print  ("400 ");
      break;
    case ADXL345_DATARATE_200_HZ:
      Serial.print  ("200 ");
      break;
    case ADXL345_DATARATE_100_HZ:
      //Serial.print  ("100 ");
      break;
    case ADXL345_DATARATE_50_HZ:
      Serial.print  ("50 ");
      break;
    case ADXL345_DATARATE_25_HZ:
      Serial.print  ("25 ");
      break;
    case ADXL345_DATARATE_12_5_HZ:
      Serial.print  ("12.5 ");
      break;
    case ADXL345_DATARATE_6_25HZ:
      Serial.print  ("6.25 ");
      break;
    case ADXL345_DATARATE_3_13_HZ:
      Serial.print  ("3.13 ");
      break;
    case ADXL345_DATARATE_1_56_HZ:
      Serial.print  ("1.56 ");
      break;
    case ADXL345_DATARATE_0_78_HZ:
      Serial.print  ("0.78 ");
      break;
    case ADXL345_DATARATE_0_39_HZ:
      Serial.print  ("0.39 ");
      break;
    case ADXL345_DATARATE_0_20_HZ:
      Serial.print  ("0.20 ");
      break;
    case ADXL345_DATARATE_0_10_HZ:
```

```
      Serial.print  ("0.10 ");
      break;
    default:
      Serial.print  ("???? ");
      break;
  }
  //Serial.println(" Hz");
}

void displayRange(void)
{
  //Serial.print  ("Range:         +/- ");

  switch(accel.getRange())
  {
    case ADXL345_RANGE_16_G:
      Serial.print  ("16 ");
      break;
    case ADXL345_RANGE_8_G:
      Serial.print  ("8 ");
      break;
    case ADXL345_RANGE_4_G:
      Serial.print  ("4 ");
      break;
    case ADXL345_RANGE_2_G:
      //Serial.print  ("2 ");
      break;
    default:
      Serial.print  ("?? ");
      break;
  }
  //Serial.println(" g");
}




void setup(void)
{
  g15.begin(19200);
  Serial.begin(19200);
  Serial1.begin(19200); // Serial1 @ 9600 Baud
  genie.Begin(Serial1);


  //genie.AttachEventHandler(myGenieEventHandler); // Attach the user
function Event Handler for processing events

  pinMode(RESETLINE, OUTPUT); // Set D4 on Arduino to Output (4D
Arduino Adaptor V2 - Display Reset)
  digitalWrite(RESETLINE, 1); // Reset the Display via D4
  delay(200);
  digitalWrite(RESETLINE, 0); // unReset the Display via D4

  delay (5000); //let the display start up after the reset (This is
important)
  //genie.WriteContrast(11); // 1 = Display ON, 0 = Display OFF
```

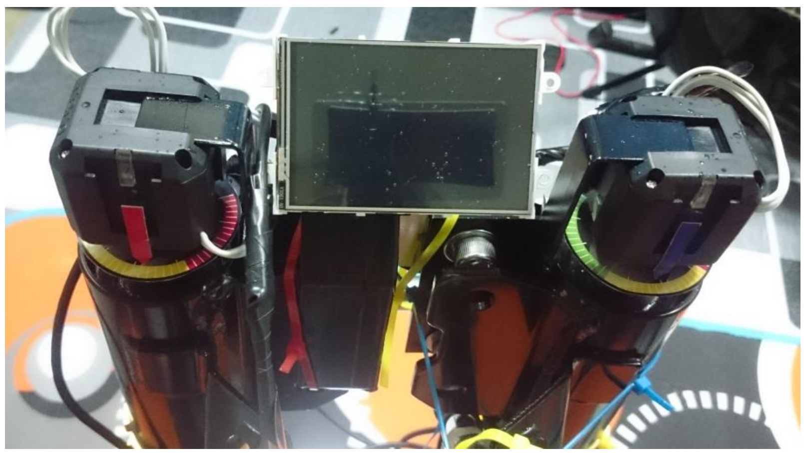
```
  Serial.println("Accelerometer Test"); Serial.println("");

  /* Initialise the sensor */
  if(!accel.begin())
  {
    /* There was a problem detecting the ADXL345 ... check your
connections */
    Serial.println("Ooops, no ADXL345 detected ... Check your
wiring!");
    while(1);
  }

  /* Set the range to whatever is appropriate for your project */
  accel.setRange(ADXL345_RANGE_2_G);
  // displaySetRange(ADXL345_RANGE_8_G);
  // displaySetRange(ADXL345_RANGE_4_G);
  // displaySetRange(ADXL345_RANGE_2_G);

  /* Display some basic information on this sensor */
  displaySensorDetails();

  /* Display additional settings (outside the scope of sensor_t) */
  displayDataRate();
  displayRange();
  //Serial.println("");
  }

  void loop(void)
  {
  //static long waitPeriod = millis();
  //genie.DoEvents(); // This calls the library each loop to process
the queued responses from the display

  /* Get a new sensor event */
  sensors_event_t event;
  accel.getEvent(&event);

  if (event.acceleration.x < -255) event.acceleration.x = -255; else if
(event.acceleration.x > 255) event.acceleration.x = 255;
  if (event.acceleration.y < -255) event.acceleration.y = -255; else if
(event.acceleration.y > 255) event.acceleration.y = 255;


  sensorVal = event.acceleration.x;
  smoothedVal = smoothedVal + ((sensorVal - smoothedVal)/samples);

  //Motor Rotation Mapping
  Motor1 = map(smoothedVal, -10, 10, 10, 350);
  Motor2 = map(smoothedVal, -10, 10, 350, 10);

  //Motor Rotation Mapping to the LCD display
  Motor3 = map(smoothedVal, -10, 10, 10, 100);
  Motor4 = map(smoothedVal, -10, 10, 100, 10);


  //Condition to Set Soft,Medium, Hard And Adaptive Setting
```

```
  // Soft Setting Code

  if (digitalRead (7)== HIGH )
  {
  g15.setLED(G15_1, ON);
  g15.setLED(G15_11, ON);
  delay(1500);
  g15.setLED(G15_1, OFF);
  g15.setLED(G15_11, OFF);

  g15.setSpeed(G15_1, 200);
  g15.setPosAngle(G15_1, 10); // Set G15 (ID = 1) position to 0 deg

  g15.setSpeed(G15_11, 200);
  g15.setPosAngle(G15_11, 10); // Set G15 (ID = 1) position to 0 deg
  delay(10);

  genie.WriteObject (GENIE_OBJ_GAUGE, 1, 20);      // Send motor
rotation value to Gauge0 object on the display
  //delay(10);
  genie.WriteObject (GENIE_OBJ_GAUGE, 0, 20);      // Send motor
rotation value to Gauge1 object on the display
  }

  // Medium Setting Code
  else if (digitalRead (6)== HIGH )
  {
  g15.setLED(G15_1, ON);
  g15.setLED(G15_11, ON);
  delay(800);
  g15.setLED(G15_1, OFF);
  g15.setLED(G15_11, OFF);

  g15.setSpeed(G15_1, 200);
  g15.setPosAngle(G15_1, 180); // Set G15 (ID = 1) position to 0 deg

  g15.setSpeed(G15_11, 200);
  g15.setPosAngle(G15_11, 180); // Set G15 (ID = 1) position to 0 deg
  delay(10);

  genie.WriteObject (GENIE_OBJ_GAUGE, 1, 50);      // Send motor
rotation value to Gauge0 object on the display
  //delay(10);
  genie.WriteObject (GENIE_OBJ_GAUGE, 0, 50);      // Send motor
rotation value to Gauge1 object on the display

  }

  // Hard Setting Code
  else if (digitalRead (5)== HIGH )
 {

  g15.setLED(G15_1, ON);
  g15.setLED(G15_11, ON);
  delay(500);
  g15.setLED(G15_1, OFF);
```

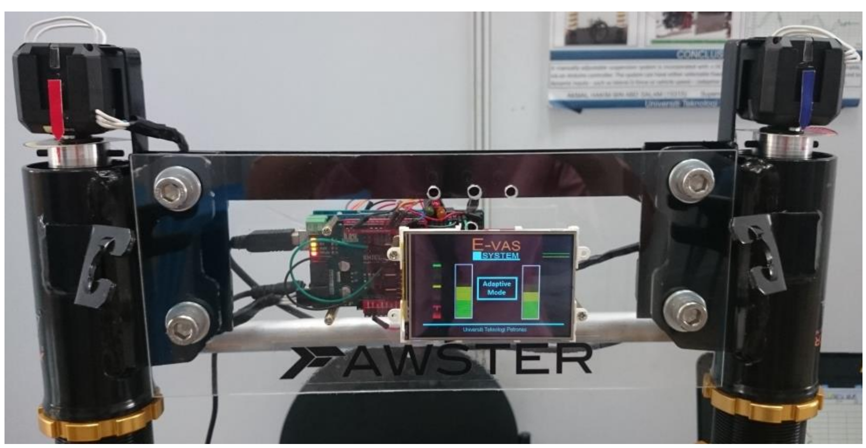
```
  g15.setLED(G15_11, OFF);

  g15.setSpeed(G15_1, 200);
  g15.setPosAngle(G15_1, 350); // Set G15 (ID = 1) position to 0 deg

  g15.setSpeed(G15_11, 200);
  g15.setPosAngle(G15_11, 350); // Set G15 (ID = 1) position to 0 deg
  delay(10);

  genie.WriteObject (GENIE_OBJ_GAUGE, 1, 80);      // Send motor
rotation value to Gauge0 object on the display
  //delay(10);
  genie.WriteObject (GENIE_OBJ_GAUGE, 0, 80);      // Send motor
rotation value to Gauge1 object on the display

  }

  // Adaptive Setting Code
  else
  {
  g15.setLED(G15_1, ON);
  g15.setLED(G15_11, ON);
  //delay(10);
  g15.setLED(G15_1, OFF);
  g15.setLED(G15_11, OFF);

  g15.setSpeed(G15_1, 800);
  g15.setPosAngle(G15_1, Motor1); // Set G15 (ID = 1) position to 0 deg
  //delay(10);

  g15.setSpeed(G15_11, 800);
  g15.setPosAngle(G15_11, Motor2); // Set G15 (ID = 1) position to 0
deg

  genie.WriteObject (GENIE_OBJ_GAUGE, 1, Motor3);      // Send motor
rotation value to Gauge0 object on the display
  //delay(10);
  genie.WriteObject (GENIE_OBJ_GAUGE, 0, Motor4);      // Send motor
rotation value to Gauge1 object on the display
  genie.WriteObject(GENIE_OBJ_SCOPE, 0, smoothedVal);



  /* Display the results in CSV format*/
  //serial print for MakerPlot software

  Serial.print(event.acceleration.x); Serial.print(",");
  Serial.print(smoothedVal); Serial.print(",");
  Serial.print(Motor1); Serial.print(",");
  Serial.println(Motor2);
  //waitPeriod = millis() + 20;
  //delay(10);

      }

  }
```

Appendix 2 : Test Rig

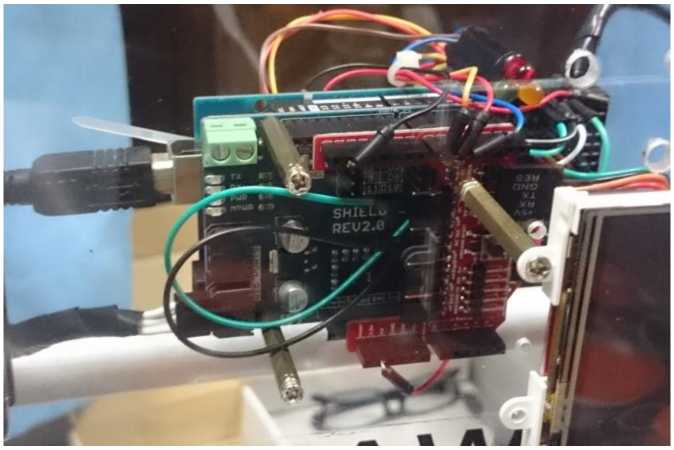
Appendix 2 Figure 1 : Test rig during UTP SEDEX 36



Appendix 2 Figure 2 : Test rig for In-Car testing.



Appendix 2 Figure 3 : Test rig close-up



Appendix 2 Figure 4 : Circuit Assembly

Appendix 2 Figure 5 : Motor-suspension coupling assembly

Appendix 3 : Road test

Appendix 3 Figure 1 : Hard left corner testing.

Appendix 3 Figure 2 : Hard left corner testing.

Appendix 3 Figure 3 : Straight line driving testing.

Appendix 3 Figure 4 : Winding road driving testing.