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Full Length Research Paper

Development of active suspension system for a quarter car model using optical incremental encoder and ultrasonic sensors

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Nowadays in the industrial world, quality factors are the reasons of growth and survival of an automotive unit. Suspension system as an effective part of vehicle can achieve two factors, "safety" and "convenience". It plays an important role in the quality of the car. Therefore, it is necessary to carry out an analysis and evaluation of how the suspension system responds in different vehicles under various conditions whilst improving vehicle quality. Considering the power units and automotive vehicle production capacity in developing countries, the need of a vehicle with features such as durability and accuracy as suitable standard for passenger vehicles was felt. This paper describes the development of a new system able to predict and scan road profile and its condition. Vehicle equipped with this predictor technology use measurement sensors such as Ultrasonic and Optical Incremental Encoder. They can provide enough information about road condition and vehicle position by measuring distance or the angle variation of body and vehicle's chassis in order to present flexible suspension in different conditions such as high speed, rough road, bumps and emergency situations. The quarter car model with active mechanical suspension can illustrate the mentioned characteristics.

Key words: Vehicle suspension system, quarter car model, ultrasonic, optical incremental encoder.

INTRODUCTION

An active suspension system known as Computerized Ride Control is able to adjust the system continuously when the road conditions are changing. Constant monitoring and adjusting of the system artificially is done by extension of the design parameters of the system, thus changing the system character on a continuing process. By applying modern sensors and microprocessors, the information will sense continuously and also spur factors in the system to react to changing road conditions; hence it can be said that active suspension suggests better handling, comfortable ride, quick response and more safety. Most suspension systems in automotive industry use measurement system which is able to simultaneously measure forces on the vehicle body and on the vehicle motion (Muto et al., 2007); however, most times because of lack of adequate processing speed or mechanical part operation speed, the slow sensor or controller cannot collect data, and slow mechanical part such as pneumatic, hydraulic or magnetic cannot perform commands in minimum time which result in less efficiency of system. Many companies are trying to invent and create new systems by high efficiency, fast process and operation. It needs to study a measuring system in order to evaluate the effect of vertical and horizontal forces and inequality of rough road which affect comfortableness, handling and most importantly safety of vehicle (Schofield et al., 2006). Information coming from this measuring system will be processed by a controller and moved to command, damper or effective part in suspension system. Therefore wheel and suspension system have to coincide with road profile and provide the stable and suspended body (Nijmeijer et al., 2007). Creation of a system able to predict road profile and its condition is one of the important challenges in automotive industry. Vehicles

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equipped by this predictor technology can scan and explore all road condition such as roughness, height, snags and bump; therefore the vehicle can decide easily how to react to the predicted condition by changing amount of damping coefficient or vertical position of suspension system. The result will be high handling, quality ride, safety, and comfortableness (Jeong et al., 1990).

In a land vehicle, travel comfort and handling are in opposition with each other; therefore creating the system for vehicles suspension system to follow these characteristics at the same time is difficult. In order to get better around this issue, many control designs carefully plans the structure of computer controlled suspension system such as active or semi-active suspension system. No matter how smooth and flat a road is, it is not a suitable place to move heavy vehicle with high-speed. Therefore the system should be able to reduce impact, shock and vibration due to road conditions.

The usual passive suspension systems innately result in cooperation between the quality of ride and handling. Good vehicle handling is due to an extremely damped suspension (Tamboli et al., 1999). A lower damped suspension may considerably improve the feeling of ride, and also decrease the vehicle stability while ride factor, handling factor, body mount optimization are other critical issues (Naude et al., 2003).

The semi-active suspension system computes the speed of vehicle vibration defined by lateral acceleration sensor as an output. The sensor is fixed on the vehicle body on upper level of the vehicle and makes enough force that agrees with the amount of the vibration speed with an interchangeable lateral damper on the vehicle (Miller, 1986). The system is equipped with an electromagnetic valve which releases the force in the different direction of damping force. An important issue is that when there is a failure part in the system it does not amount to a very dangerous state because when the power switch is turned off, the damper function will act as a normal damper (Gordon et al., 1998). The system objective is to cancel out pitch, heave, and roll. A variety of inputs are needed for control system in semi-active suspensions to measure mentioned items such as vehicle speed, vertical acceleration, brake condition, lateral acceleration, steering angle velocity, vehicle level position, steering angle position (Choi et al., 2000).

Active suspension systems consist of components such as electronic control unit, changeable shock absorber, a series of sensors, and an actuator atop each shock absorber. Controlling an active suspension system is based on amount of information which can be collected by some sensors located in different parts in the vehicle. The sensors begin to monitor the situation, check body motion, rotary-position wheel, steering angle and sense excessive vertical motion and finally send this information to controller (ECU). The controller collects, analyzes and processes the data quickly in about 10 ms. ECU sends a vital message to the servo coil spring. Following this an oil pump sends extra fluid to the servo and this process will increase spring tension, and the result will be decreasing Yaw, Body roll, Spring oscillation (Zaremba et al., 1997).

A number of researches apply pre-control to command dynamic parts and increase the suspension efficiency (Morita et al., 1992). The control act can be better; if the profiles of road distraction are predicted therefore the operation is better than a non-preview system (Prokop et al., 1995). Some methods have been introduced such as the profile meter in order to pre-scan the road profiles (Healey et al., 1977). The laser beams can scan the road to provide a flexible and comfortable car with perfectly responsive ride. The active PRE-SCAN suspension system reduces at least half of the shock and vibration because of sharp bumps or speed bumps before it ever affects on the cabin and dissipates noise (Jeong et al., 1990). One of the important tasks of suspension system is vehicle rollover prevention. The purpose of rollover prevention is to keep away from particular kind of accidents and to make the contact between tire and road surface optimal, thereby improve vehicle handling (Schofield et al., 2006).

Previous active suspension system controller controls the suspension mechanical part with the aid of information provided by sensors like acceleration sensors. The result of this system will be body stability and self-leveling body. In the proposed system, required information are provided by scan road surface directly and control level of body by application of height adjustable suspension according to detected real dimension of road profile.

DEVELOPMENT OF QUARTER CAR MODEL

The main step is recognition and classification of data and information that should be collected by sensors and electronic parts to help the system in creating accurate results and command as outputs. This data can be measured as distance of upper and lower point of road profile or measuring motion of vehicle chassis. The important data in the scan process is the measurement of distance and height of road profile and road profile surface. By processing this information in a controller, the system can adapt to different road profiles. In sensors selection, providing the practical data required for control and feedback process is critical because in most cases the information coming from sensors is associated with errors caused by defective sensors, environmental conditions (temperature, vibration), level of accuracy, and wrong position. According to these requirements the selected sensors should satisfy the controller to provide data which is easy to read by a micro controller. Ultrasonic and Optical Incremental Encoder sensors are selected to collect the required data. Ultrasonic is

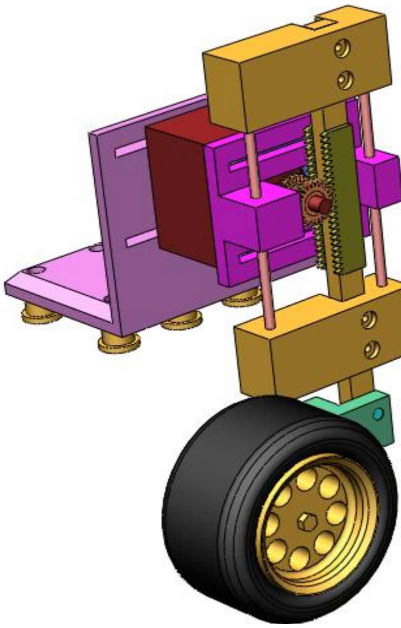


Figure 1. Linear movement mechanism.

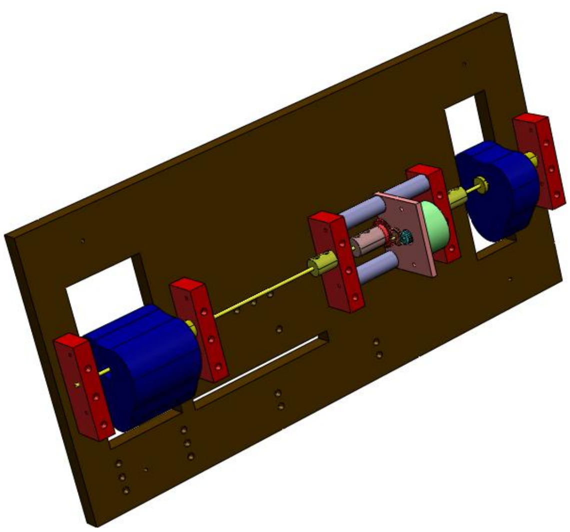


Figure 2. Structure of DC motor, transmission system and cams after assembly on main base.

responsible for scanning the road profile and the second sensor evaluates the scan process and system reaction to a changeable road profile. The third step is the design of mechanical parts and active suspension system for a quarter car model which is able to provide artificial stimulus required for sensors and to respond quickly to command from controller. The next step is to produce mechanical parts of the model and assemble all parts. Assembling of parts provide the final quarter car model. The simplest model of the vehicle suspension system is device simulation of a quarter car model. Another step is the design of controller according to sensors, required outputs and the volume of calculation. Controller provides required command to control different parts of system and provide necessary output in order to control and record the system operation. The last but not least step is to evaluate and analyze the outputs and model by using control system without comparing it to feedback results. Feedback system includes Optical Incremental Encoder Modules. In this step the comparison of data from design software (actual data) and detected data by sensors help to check, how the system is able to scan road profile surface and control linear motion mechanism.

Linear movement mechanism

Movement mechanism is the most important part of the model which can precisely implement the received commands from controller quickly. Different designs for this part were established and the most appropriate design selected was a linear mechanism which is shown in Figure 1.

Direct current (DC) motor, gearbox and cams

To test the model and mechanisms it needs to move the wheel axle on the cam. There are two similar cams which are rotating by transmission system. One of the cams will act as road profile to move up or down the wheel axle according to defined upper and lower limit. Another cam scans by ultrasonic sensor to collect information of cam shape are shown in Figure 2.

Both of the cams can rotate because of power provided by DC motor and gearbox located under the model. The transmission system is controlled by controller and it is shown in Figure 3.

Design of optical encoder holder

The optical encoder consists of two parts. The first part is rotational disk which is located on the shaft. This shaft is connected to a small pinion gear to transmit the movement from big pinion gear to the optical encoder which is affected by moving of arm according to the Figure 4.

The holder is equipped with a ball bearing to provide smooth movement of the shaft as Figure 5. The second part is the optical sensor which is located on holder as Figure 6. The small and big pinion gears are used to increase the number of rotation and rise in accuracy of optical encoder.

Design of ultrasonic sensor holder

Ultrasonic sensor holder is a kind of adjustable holder to

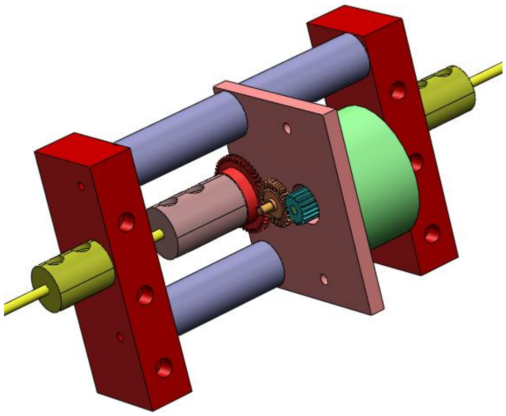


Figure 3. DC motor and transmission system after assembly.

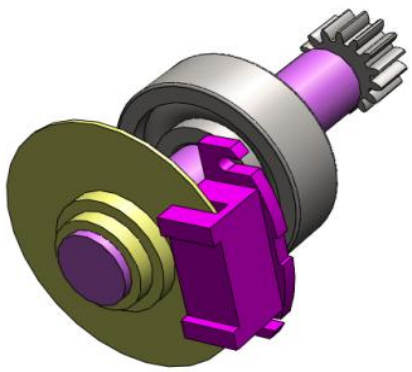


Figure 4. Small pinion gear, bearing and optical encoder disk on the shaft.

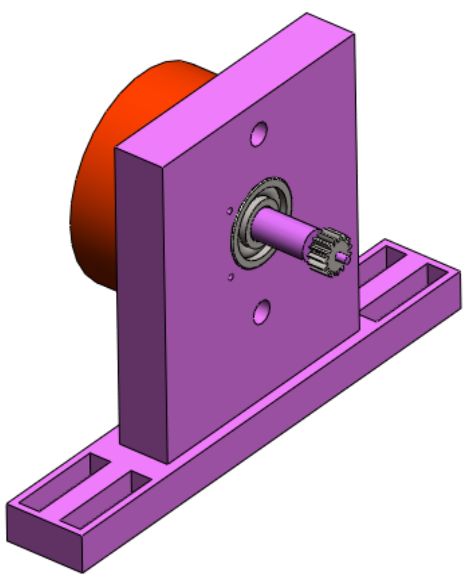


Figure 5. The holder is equipped by ball bearing to provide smooth moving of shaft.

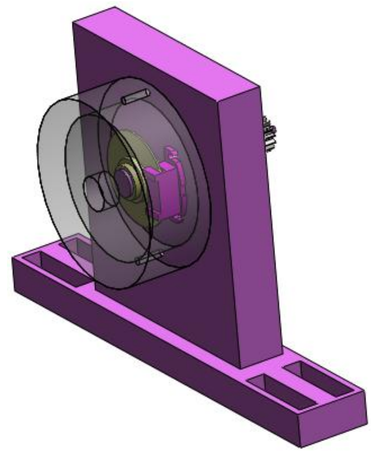


Figure 6. Optical Encoder located on holder.

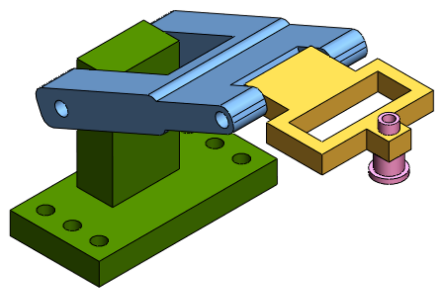


Figure 7. Ultrasonic sensor holder.

select the best situation in order to avoid hidden measure limit. Figure 7 shows the ultrasonic sensor holder.

Design of arm to transmit vertical movement of axle to optical encoder

According to the Figure 8 the first side of arm is connected to the linear movement mechanism and axle and the other side is joined to a big pinion gear. The arm transmits movement of axle and linear mechanism to the optical encoder so that the system can be able to measure the possible angle.

Assembly of parts on the main base

All of these parts should be assembled on the main base. The dimensions of hole and size of main base is very important to make all assembled parts fit together. Figure 9 illustrates the full model after assembly of different parts.

Figure 10 shows the real structure of model, sensors, controller, keyboard and linear motion mechanism after assembly process.

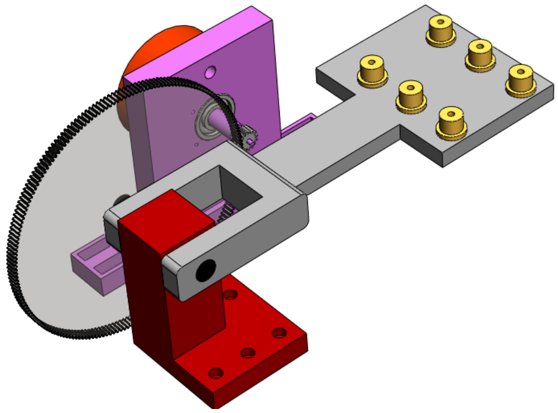


Figure 8. Design of Arm to transmit vertical movement of axle to Optical Encoder.

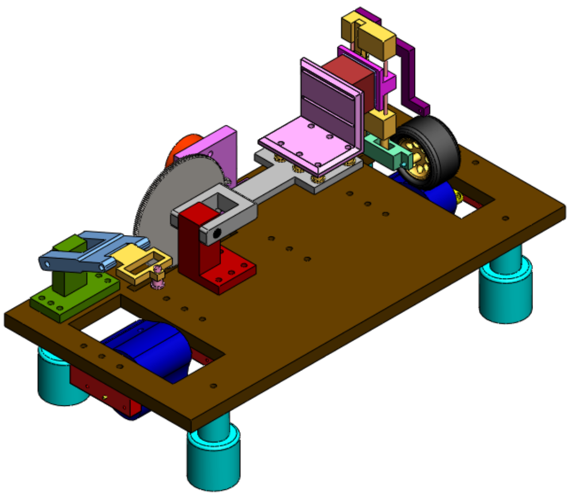


Figure 9. Full model after assembly of different parts.

Controller, PCB and Programming

In control theory, a controller is a device which monitors and affects the operational conditions of a given dynamical system. The operational conditions are typically referred to as output variables of the system which can be affected by adjusting certain input variables. The complexity of the system is directly related to the requirements of the system's application. Controller reads the data coming from the located sensors in model. It needs to plan algorism of devices which are going to setup by Micro controller.

These devices are: Ultrasonic, Optical sensor, LCD, Stepper motor, DC motor, Serial Convertor, Programmer board, and Power control which should be connected to controller.

Power controller is designed according to devices consumption and datasheet information. The system is

Figure 10. Real structure of model after assembly process.

an applied Open-Loop controller with three different programs in order to check the sensors data and model's operation results. Figure 11 shows block diagram of open-loop controller. Some of the parts such as electronic parts, micro controller, drivers and connectors are located on printed circuit board. CodeVisionAVR is used to write the program that tells the chip what to do. Then it needs to compile it, that is, turn the program description into machine code. Next is to program the chip by using a programmer, which will transfer the machine code to the device.

RESULTS

Three different programs are planned to check the data provided by controller in three different conditions to compare the system reaction with and without controlling by controller. These three programs are separately sent to microcontroller by programmer device in three different processes to achieve the requirement data. The results will present obviously the efficiency of system to scan road profile and also adapt the linear motion mechanism to road profile surface.

Evaluate and analysis the outputs

The first program is intended to control DC motor driver to run the rotational part of model such as Cams. This forces the system to rotate and collect data provided by Ultrasonic sensor and send it to a serial convertor and PC in order to record command from controller to stepper motor and use in analysis in the next program, while the linear motion mechanism and stepper motor are under the control by controller. The result will be the dimensions of cam surface (road profile surface) which is detected by the Ultrasonic sensor. The units are defined as millimeter unit. Figure 12 shows the real dimension of Cam surface

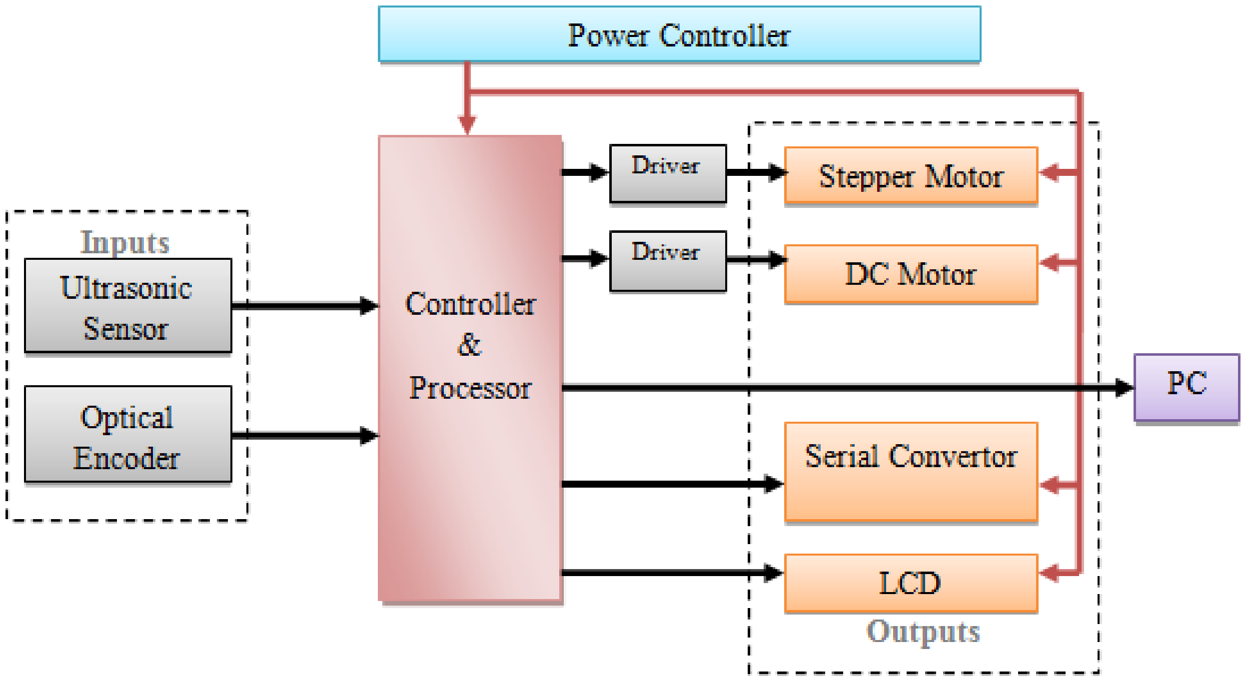


Figure 11. Block diagram of open-loop controller.

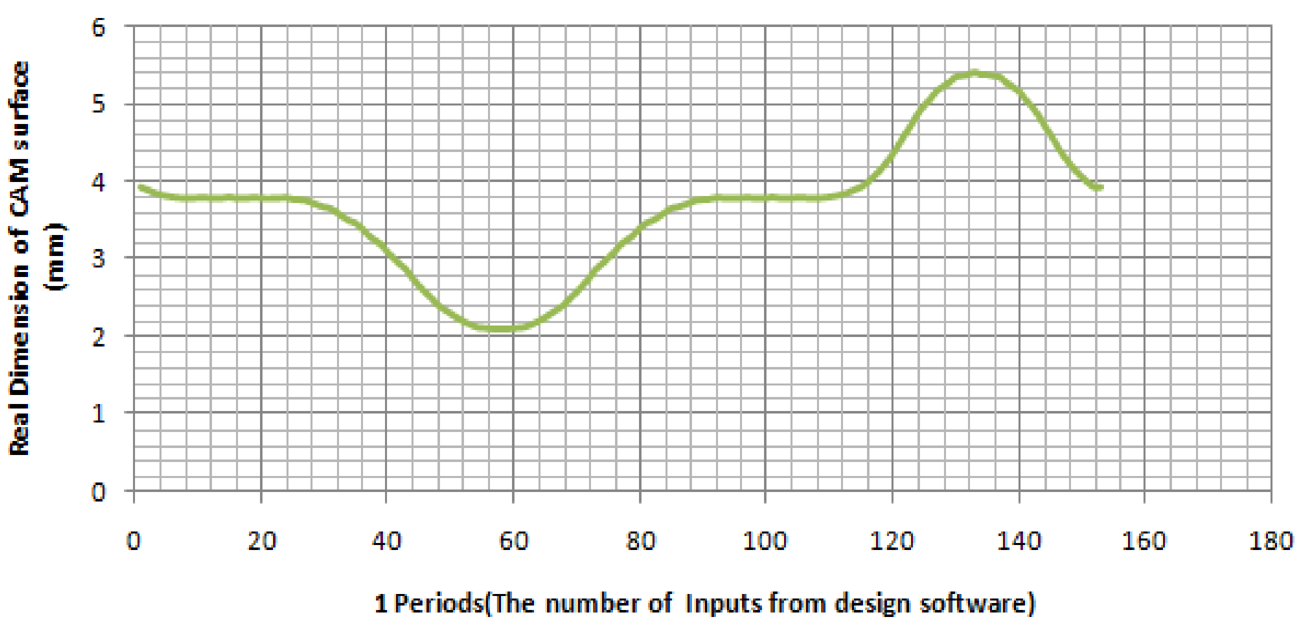


Figure 12. Real dimension of Cam surface in one period (Data from design software).

in one period. Real dimension of cam is coming from design software because the cams are designed for model in design software and real dimension of cam profile is available.

Analyzing data in first program presented as Figure 13 shows detected dimension of cam surface (road profile, Y = Z - X) by Ultrasonic sensor and output data of ultrasonic which results in a scan road profile or Cam surface. Figure 13 shows fluctuations because of errors during the scanning process. These are acceptable for

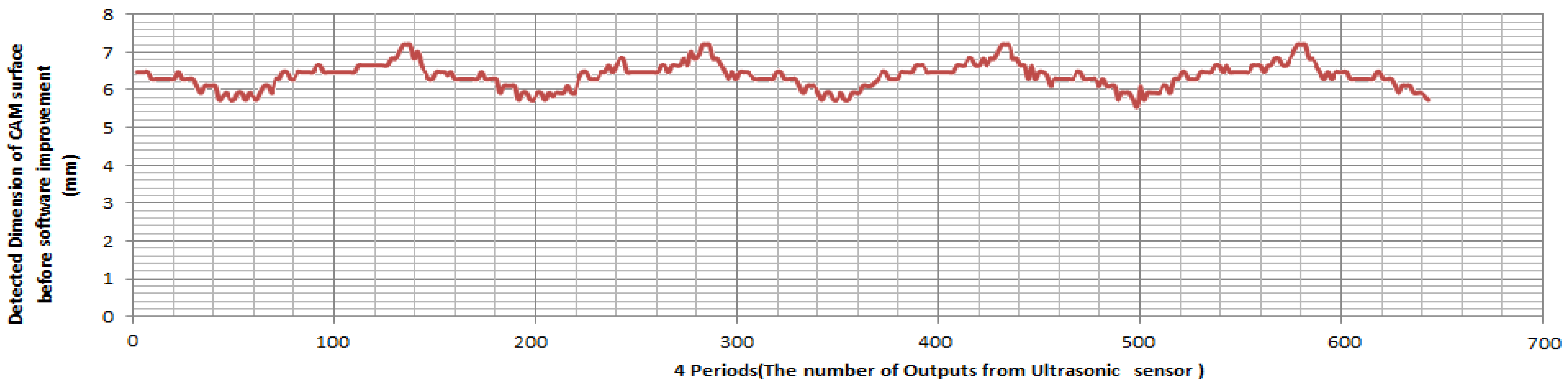


Figure 13. Analyzing of data in first program (Outputs from Ultrasonic).

this simple type of controller. The main reason for these errors could be Ultrasonic operation, low speed of processing and noise in wiring and PCB.

Figure 14 shows the start position on surface cam with $\alpha 1=\beta 1=0$. Figure 15 shows the real dimension of Cam surface in four periods of cam rotation. Comparison of Figure 13 and Figure 15 indicates the levels of ability of system to scan the cam surface. According to the Figure 16 the maximum and minimum points of cam surface is detected by Ultrasonic sensor in the right positions. Figure 16 obviously shows the system is able to scan road profile by considering a limit for probable errors into system.

There are some differences around 2.2 mm between real and detected dimensions particularly in start point that can be improved by changing software of controller. The output data can be controlled and improved by software to achieve the acceptable outputs to control the system. It means this method can help to calibrate the Outputs and Ultrasonic data.

Figure 17 compare real and detected dimension of CAM surface after software improvement and calibration of ultrasonic output. Figures 18 and 19 show the ability of Ultrasonic to scan cam surface (road profile). The green line represents the real dimension of cam when the system is performing at optimum level. However this cannot be achieved as sensors cannot provide results that are 100% accurate. The blue line represents the detected dimension of cam by ultrasonic sensor. The objective is for the blue line to get as close to the green line as possible. The closer the blue line is to the green line the more accurate it is. The yellow line shows the data when the ultrasonic sensor is off or deactivated.

The second program controls the dc motor driver that runs the rotational parts of model such as Cams to force the system to rotate while the linear motion mechanism and stepper motor are repeating the last command in first program. At this point the ultrasonic is off while the optical encoder is recording the movement of arm, minimum and maximum amount of angle $\alpha 1$, $\beta 1$ in Figure 20. This information is sent to the PC via serial convertor by controller. It means this program acts as an examiner to check efficiency of system while the system is under the control by controller. The best operation means to achieve $\alpha 1$ and $\beta 1$ close to zero degree while the control of linear motion mechanism results in the reduction of arm and vertical motion of vehicle which is indicated in Figures 21 and 22. The figures show the system is trying to achieve less $\alpha 1$ and $\beta 1$ (close to zero degree) in the highest and lowest points on the cam surface.

Each 0.5° of $\alpha 1$ and $\beta 1$ is defined as 1 value for controller, therefore the outputs from optical sensor related to the data of $\alpha 1$ and $\beta 1$ is presented in Figure 23 while the system is under the control by controller. The Figure 24 is showing stable situation for model while $\alpha 1=0$ and $\beta 1=0$ means the vehicle is on the flat road profile.

The third program is designed to control the dc motor driver that runs the rotational part of model such as Cams. This program forces the system to rotate while the linear motion mechanism and stepper motor are locked by controller. It means

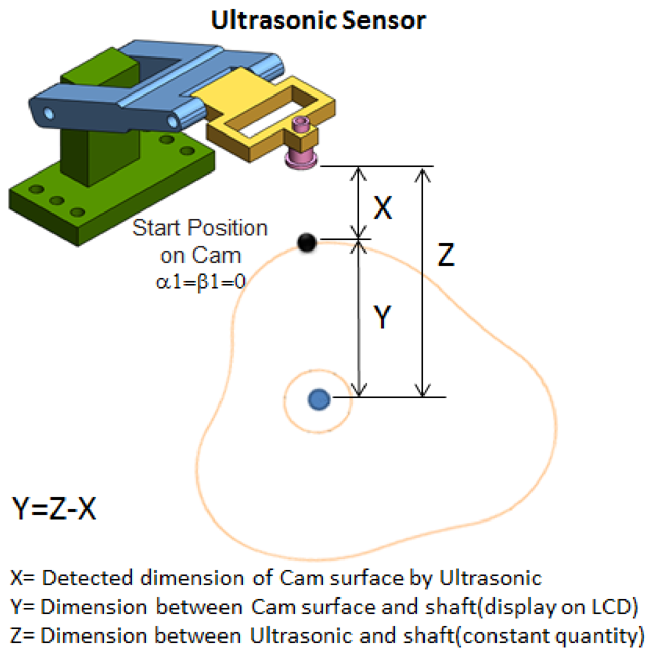


Figure 14. Start position on cam surface.

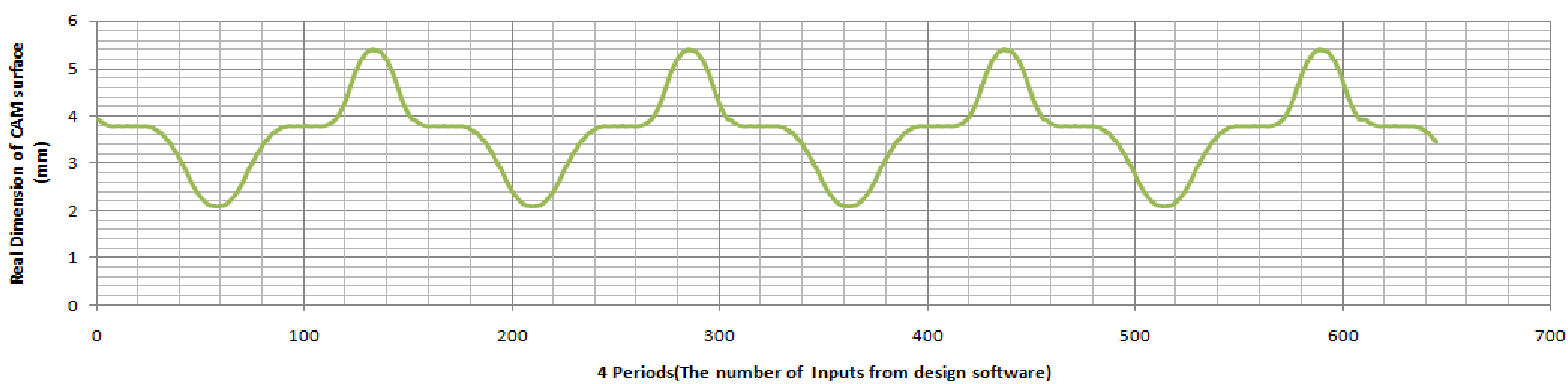


Figure15. Real dimension of Cam surface in four periods of cam rotation (data from design software).

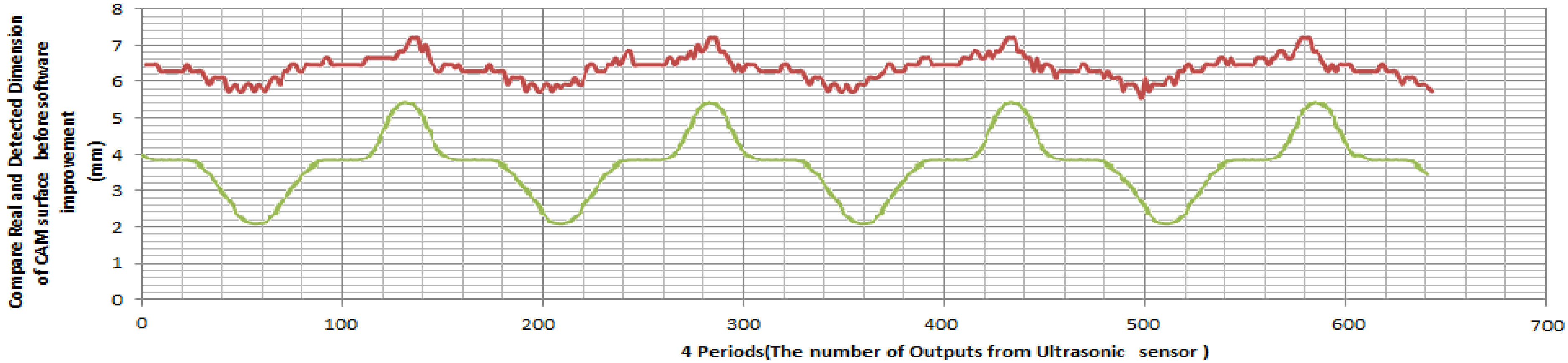


Figure16. Compare real and detected dimension of CAM surface before software improvement.

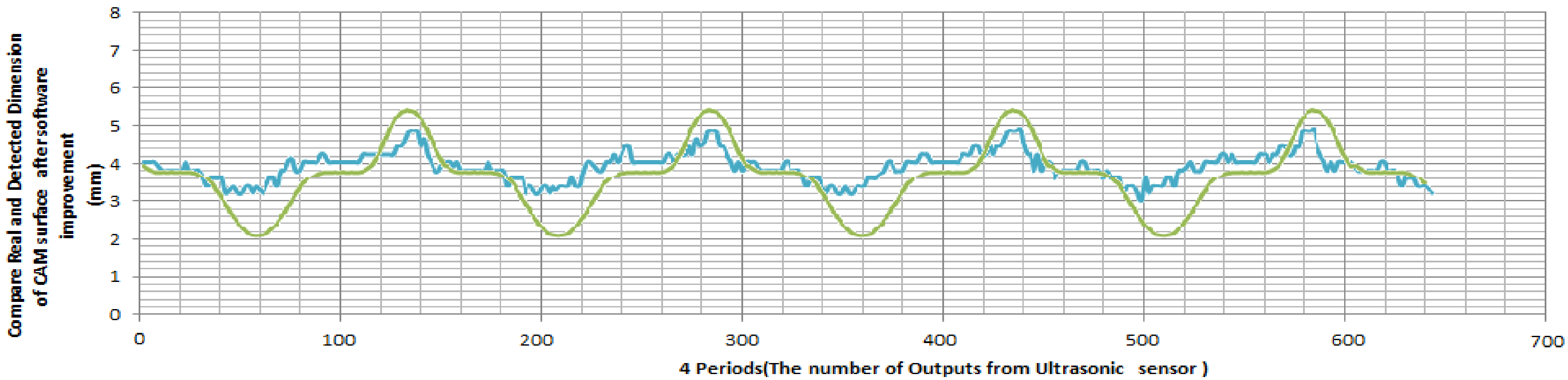


Figure 17. Compare real and detected dimension of CAM surface after software improvement.

there is no reaction to the road profile surface. In this way, the system is able to collect direct data of the road profile surface from the Optical encoder. The results include clear information of arm movement and calculate the minimum and maximum angle $\alpha 2, \beta 2$ in Figure 25 while the system is not under the control by controller.

According to the design information, real minimum and maximum amounts of $\alpha 2$ and $\beta 2$

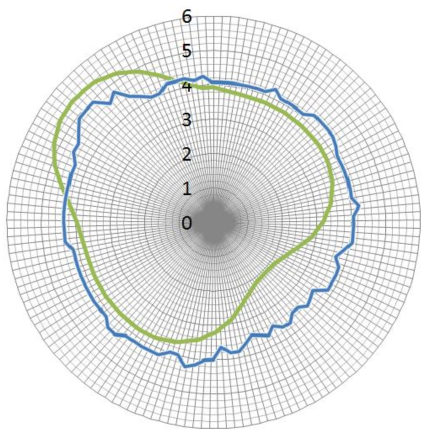


Figure 18. Compare real and detected dimension of CAM surface in one period.

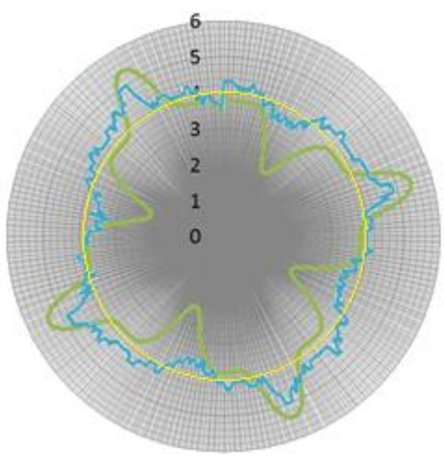


Figure 19. Compare real and detected dimension of CAM surface in 4 periods.

are presented as Figure 26.

Figure 27 shows the start position, minimum $\beta 2$ and maximum $\alpha 2$ on surface cam. Figure 28 is showing the optical encoder outputs while the system is not under the control by the controller. The data from optical sensor can show the angle fluctuation during the 4 periods of cam rotation while the linear motion mechanism and stepper motor are locked by controller; therefore the output results include the angle of arm and $\alpha 2, \beta 2$ in Figures 29 and 30 without controlling linear motion mechanism by controller.

Comparing angles $\alpha 1, \beta 1$ and $\alpha 2, \beta 2$ shows the reduction of angle fluctuation in maximum and minimum of Cam dimensions. This procedure will repeat continuously in other points on Cam as shown in Figure 31 thereby decreasing the effect of vertical motion and acceleration on passengers of vehicle.

Conclusion

Comparison and analysis of the information from design software (Solid works) and the data from three different programs in controller prove the efficiency and advantages of using the Ultrasonic sensor to scan the road profile (Cam) and linear motion mechanism to control suspension system. By application of a complicated controller which can support more sensors, the system will be able to adapt to new situations as well as handle complex functions. These functions include different programming structure which command mechanical parts of suspension system under the controller.

RECOMMENDATIONS

Application of new functions can increase the efficiency of system to improve drive quality with regards to handling, passenger comfort and safety. It means vehicle is intelligent to react in emergency situations such as sudden snag, reaction during the accident, rotation and imbalance.

In order to reduce the damage to vehicle and injuries to passengers, the recommended program is to level up the front of car and help in exact contact between bumpers of two vehicles during the accident as shown in Figure 32. Bad contact between bumpers in Figure 33 provides worse damage in both cars. An automobile's bumper is the front-most or rear-most part apparently designed to let the vehicle sustain an impact without damage to the vehicle's safety systems. They are not capable of reducing injury to vehicle occupants in high-speed impacts, but are increasingly being designed to mitigate injury to pedestrians struck by cars. In most jurisdictions, bumpers are legally required on all vehicles. The height and placement of bumpers may be legally specified as well, to ensure that when vehicles of different heights are in an accident, the smaller vehicle will not slide under the larger vehicle. But the problem is that during the accident, the use of break system results in change to the standard height in vehicle. This will make the bumper unable to meet its functions as configured. By application of Gyro sensor in suspension system, accelerations can be measured so that in strong braking during an accident the system will adjust the vehicle height automatically.

The second subject is to change vehicle height automatically according to the car speed. In high speed driving the car needs to be more stable as shown in Figure 34. Reduction of distance between ground and car body causes more stability. On the other hand, reduction of Z distance between the center of gravity (car body) and ground has an effect on the aerodynamic properties of the car. Figure 35 shows longer distance between the center of gravity (car body) and ground in high speed results in less stability (Schofield et al., 2006).

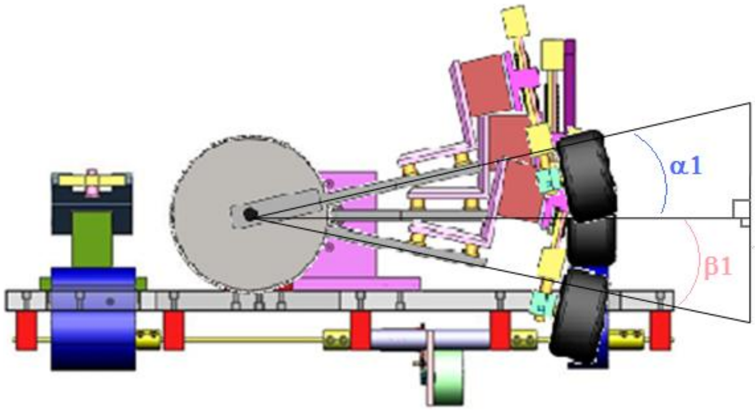


Figure 20. Maximum down and up movement of arm (Maximum $\alpha 1$, $\beta 1$).

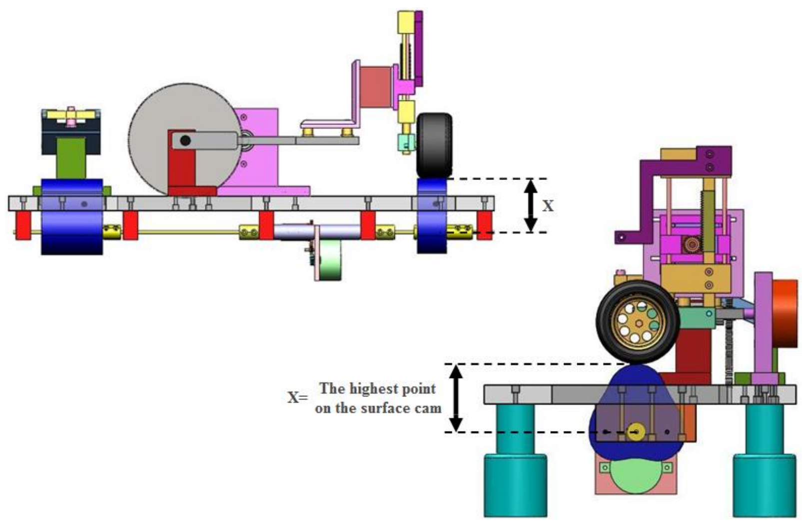


Figure 21. The achievement of less $\alpha 1$ (close to zero degree) in the highest point on the cam surface.

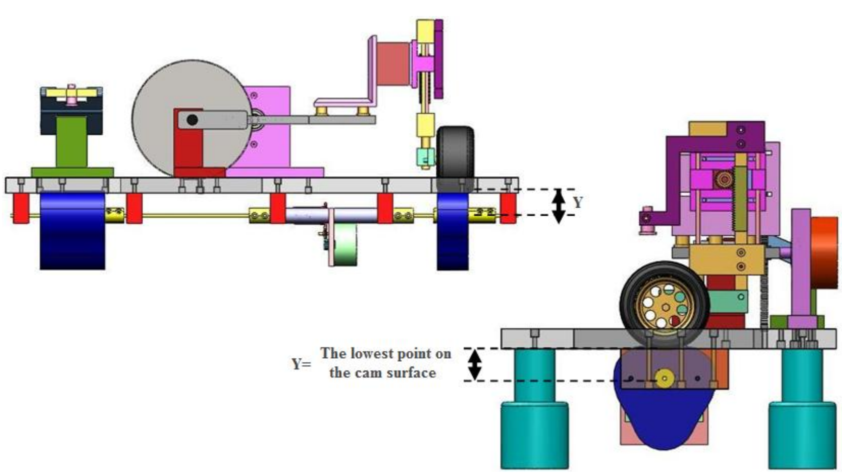


Figure 22. The achievement of less $\beta 1$ (close to zero degree) in the lowest point on the cam surface.

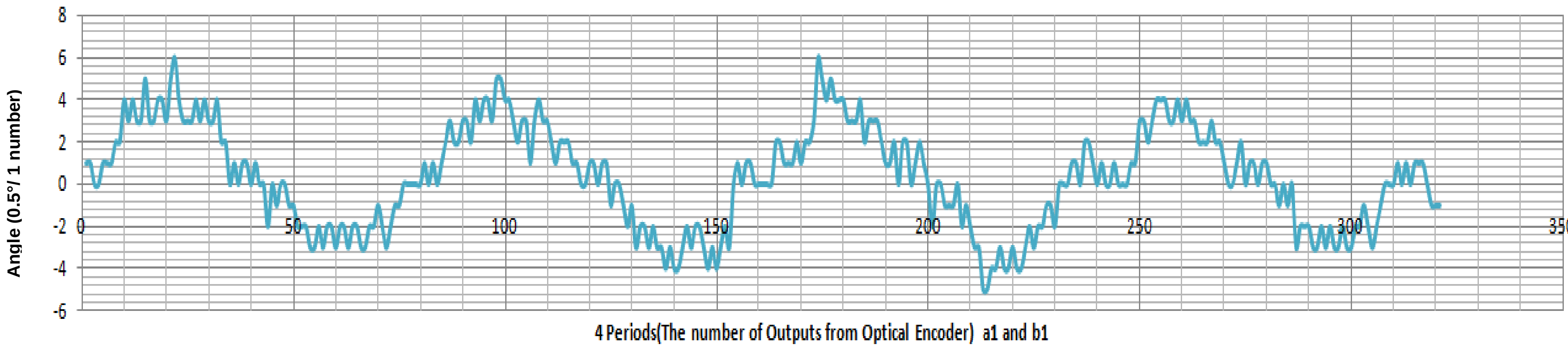


Figure 23. Analyzing of data in second program while the system is under the control by controller (Outputs from Optical Encoder).

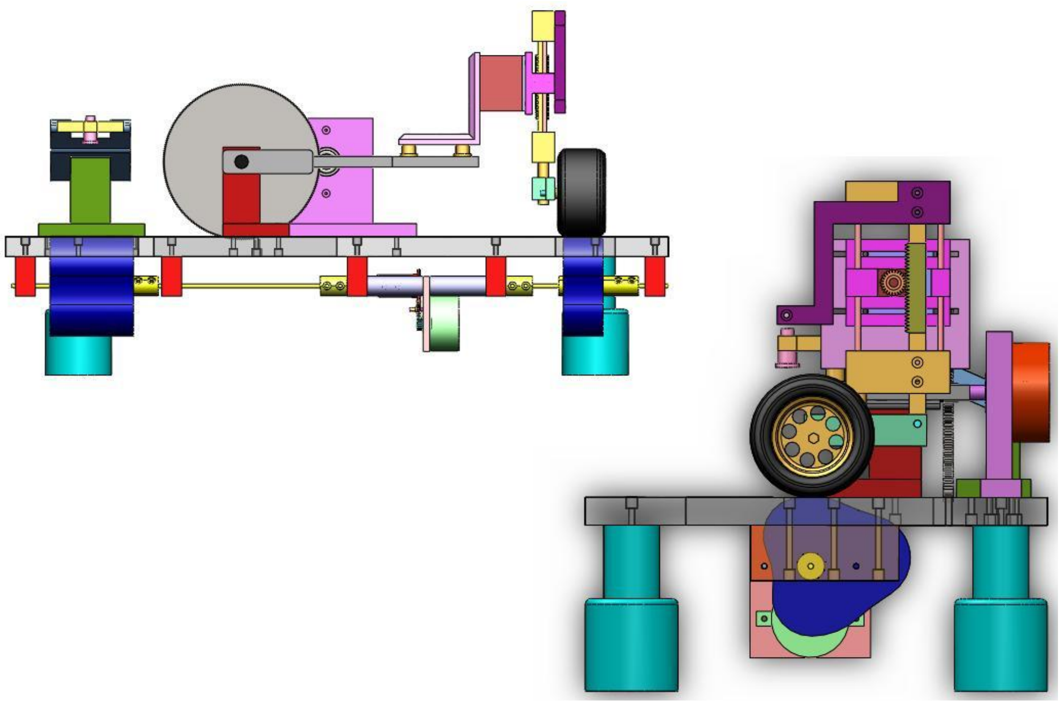


Figure 24. Stable situation for model ($\alpha 1=0,\beta 1=0$).

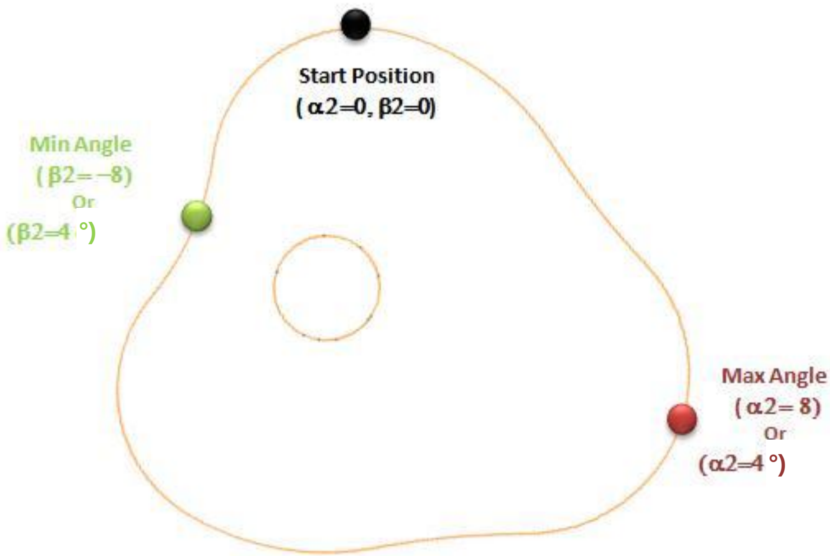
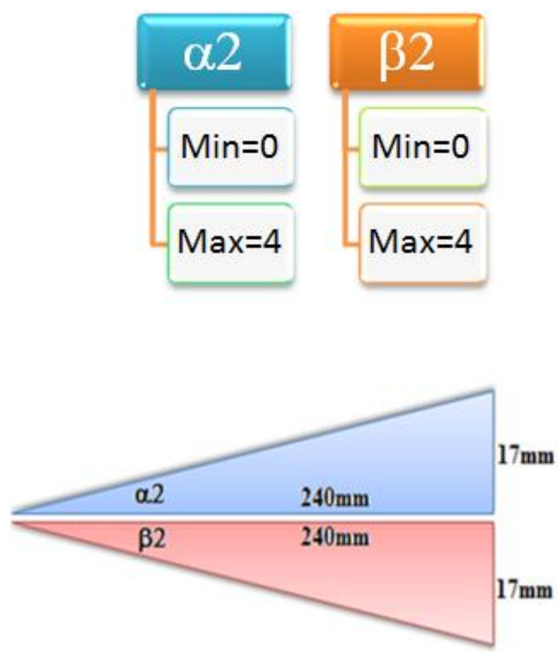


Figure 25. Start position, maximum α2 and β2 on cam surface.



$$\sin\alpha 2 = \frac{17}{\sqrt{(240^2+17^2)}}$$

$$\sin\beta 2 = \frac{17}{\sqrt{(240^2+17^2)}}$$

$$\rightarrow \alpha 2_{Max} = \beta 2_{Max} = 4° \quad = 8 \text{ Values in controller}$$

Figure 26. The minimum and maximum amount of α2 and β2 (data from design software).

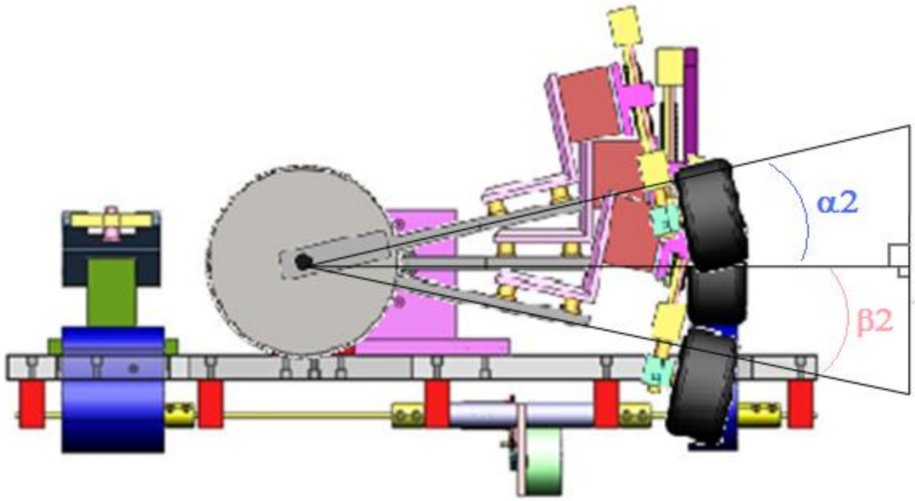


Figure 27. Maximum down and up movement of arm (maximum α2, β2).

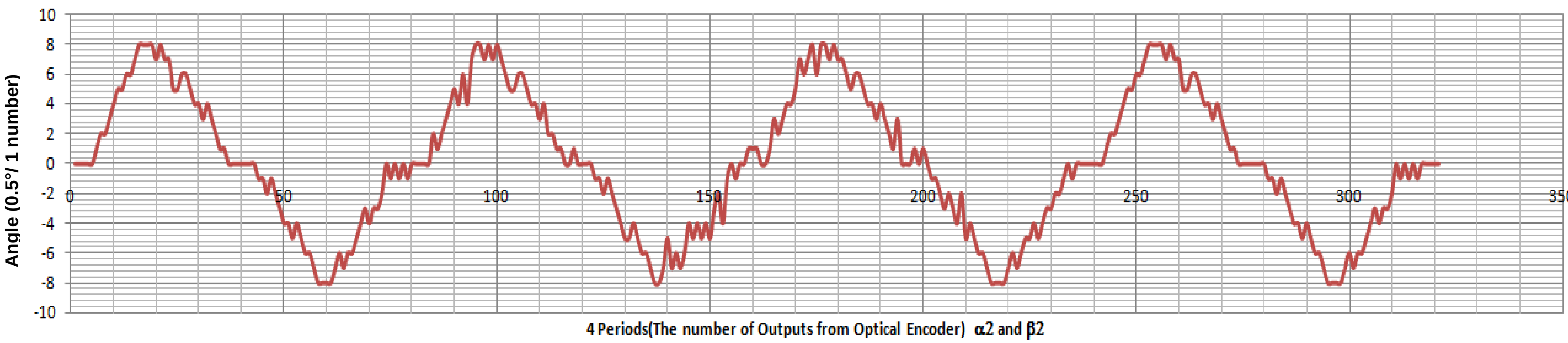


Figure 28. Analyzing of data in third program while the system is not under the control by controller (Outputs from Optical Encoder).

Independent adjustable ride height of each corner of the car prevents roll over, rotation and imbalance which is shown in Figure 36. This adjustable ride height allows manipulation of the center of gravity of the car. In particular, by manipulating the front to back or side to side location of the center of gravity, weight transfer can be controlled to influence specific tires on the car. If the car is predisposed to distribute weight

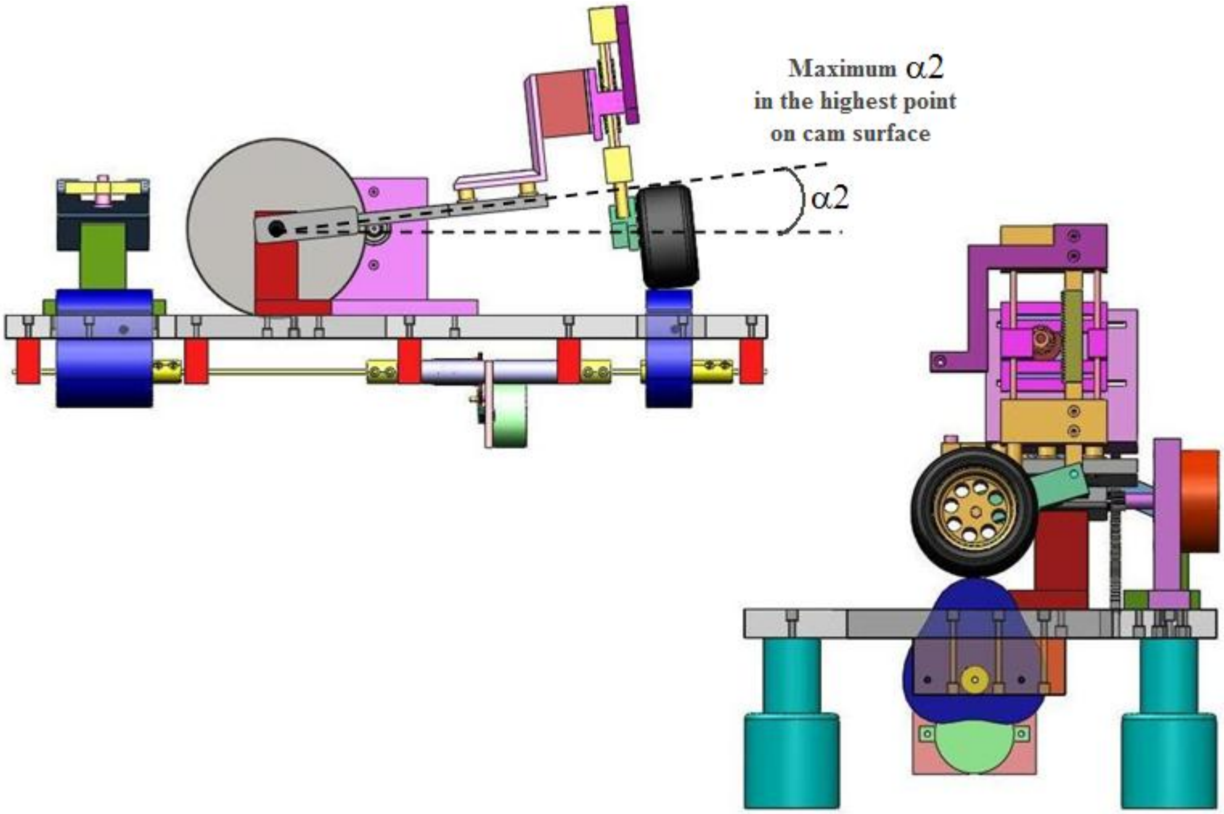


Figure 29. The achievement of maximum $\alpha 2$ in the highest point on the cam surface.

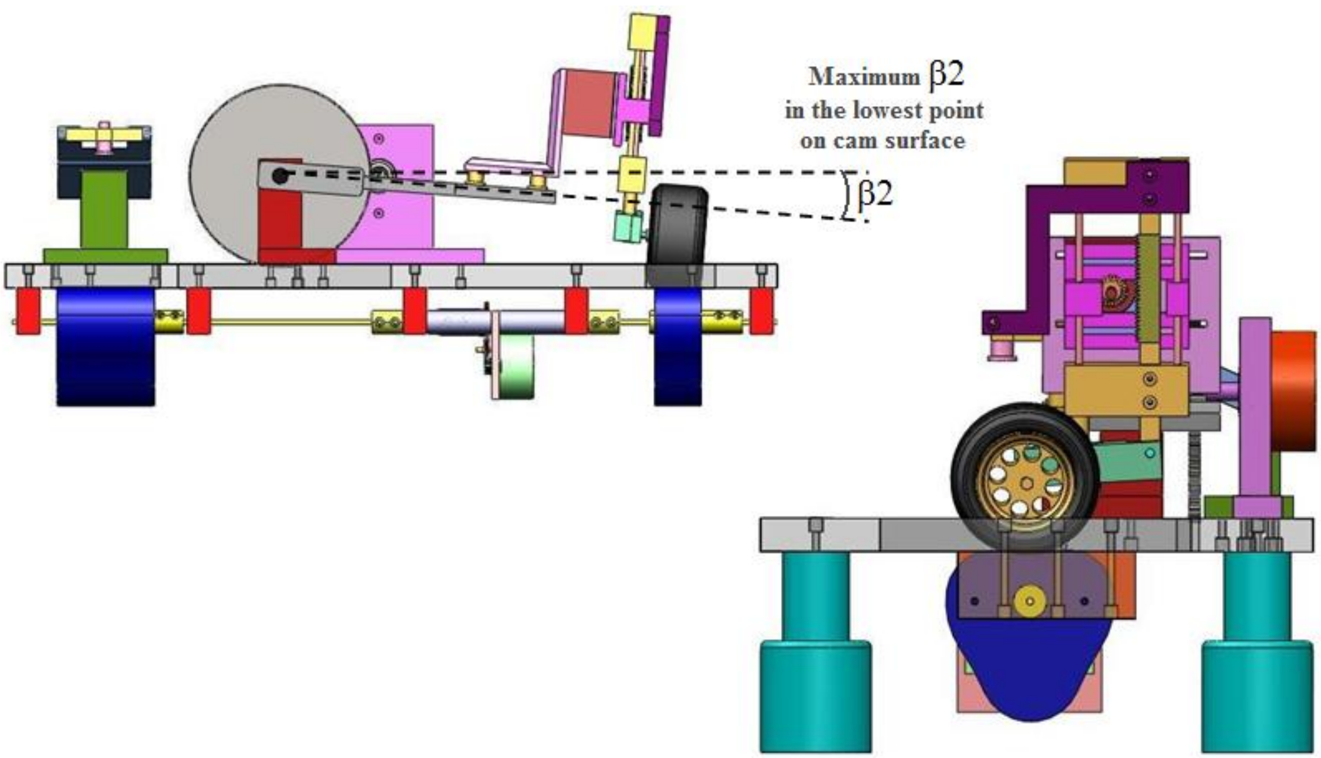


Figure 30. The achievement of maximum $\beta 2$ in the lowest point on the cam surface.

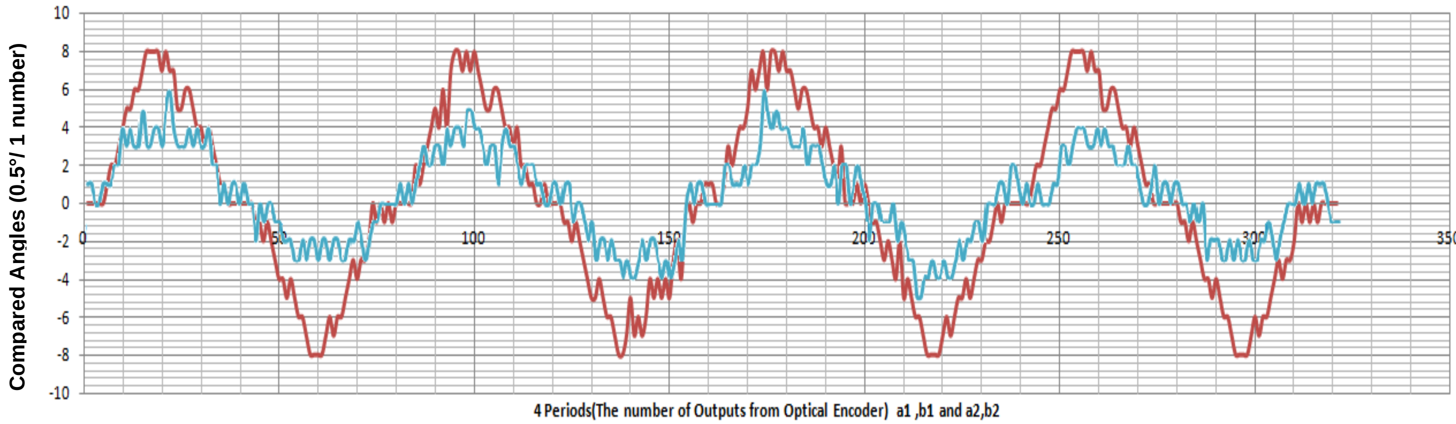


Figure 31. Compare angles $\alpha 1$, $\beta 1$ and $\alpha 2$, $\beta 2$.

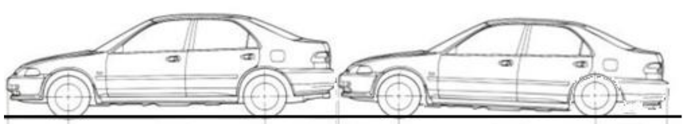


Figure 32. Good contact between bumpers during the accident (Less damage).

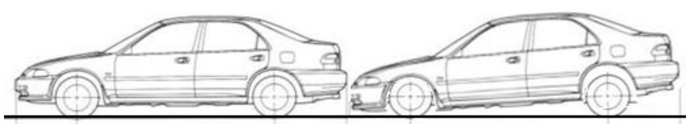


Figure 33. Bad contact between bumpers during the accident (Serious damage).

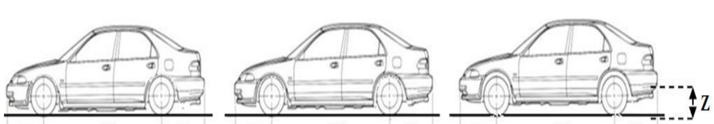


Figure 34. Shorter distance between the center of gravity (car body) and ground in high speed results in more stability.

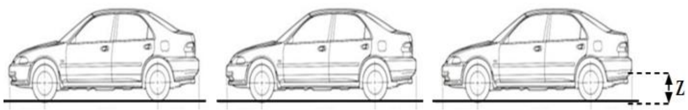


Figure 35. Longer distance between the center of gravity (car body) and ground in high speed results in less stability

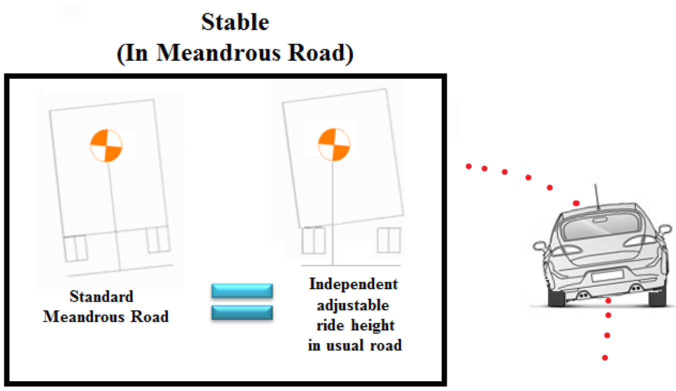


Figure 36. Vehicle with independent adjustable ride height prevents of rollover.

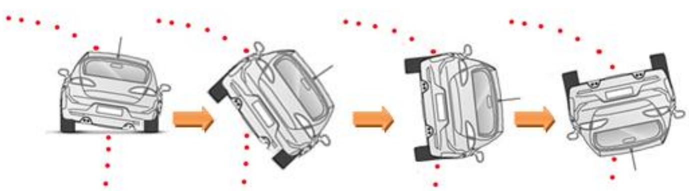


Figure 37. Vehicle without independent adjustable ride height can result in rollover

transfer to a certain way, then the grip of certain tires and the overall speed of the car through corners can be optimized significantly.

This operation can apply in system by programming and the use of accelerometer to measure acceleration in front to back or side to side location. Figure 37 shows probable rollover in vehicle without independent adjustable ride height (Nijmeijer et al., 2007).

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