Mechanical Actuation and Low Level Control
for a BMW X5 Automatic Safety System

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Final Year Project Thesis

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Submitted: June 6th, 2011

Project Summary

This project has been commissioned by the UWA Renewable Energy Vehicle (REV) team, headed by Professor Thomas Bräunl, as part of ongoing research into intelligent vehicle control and safety systems. A BMW X5, donated by BMW Germany, will be used as a research platform to advance the state of the art of intelligent vehicle control and safety systems. It will compose of an image processing system that determines whether to brake or steer to avoid collisions and assist the driver.

The aim of this project is to deliver a BMW X5 with drive by wire functionality of the steering and braking systems, and a low level controller to be integrated with either a laptop or high level controller. An electric steering motor was commissioned by Nicholas Randell in 2009, but for angular control of the vehicle a rotation sensor and motor driver are necessary. An actuator that is capable of fully actuating the brakes and a low level controller to operate these systems are required.

A brake actuator has been implemented, based on a servomotor arm mechanism which was developed using CAD modelling. A Hall Effect based sensor and bracket have been installed to detect the turning angle of the vehicle. A low level controller operates the steering and braking systems whilst communicating with a high level controller.

There is considerable scope for future projects which includes improving the functionality of the brake actuator, steering sensor or steering motor and the development of intelligent safety, innovative control or driver feedback systems.

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1.   Introduction

1.1 Background for the Project

Road traffic accidents cause over 1.2 million deaths and 20-50 million injuries worldwide each year and it is the leading cause of deaths for young people aged 15-29 (WHO 2009). It is estimated the total number of injuries and fatalities is forecast to rise by approximately 66% between 2000 and 2020 (Cropper et al 2003). Not only is there the human cost of deaths, injuries and disabilities, there is an economic cost, estimated at US $518 billion per year, which doesn't include the indirect costs associated with traffic accidents (WHO 2004). Thus there is a considerable rationale to lower the incident of traffic related accidents, which is where intelligent vehicle design can and does play a role.

Incorporating safety systems in cars has been a driving force in car manufacturing for many years. There are two main categories of the safety systems that have been widely adopted in cars. The first category is "passive safety systems", which include vehicle seatbelts, headlights, airbags, crumple zones and other structural safety elements. The second category is "active safety systems", which include anti-lock brakes, adaptive cruise control, lane departure warning, traction control, electronic stability control, pre-crash and emergency brake assist systems. Whilst there is considerable research and implementation of active safety systems, there has only been limited commercial deployment of "intelligent" systems for vehicles, often due to legal and regulation issues (OECD 2003). However, in a report produced by the Commission of the European Communities (2001), which examined the legal issues behind ADAS (Advanced Driver Assistance Systems), it was stated that "ADAS systems remain 'unproblematic' from the legal and the user's viewpoint only as long as they can be controlled and/or overruled by the driver at any time" (p. 11). This provides a motivation to produce a safety system that can be overruled by the driver, but assists in the event of an immediate accident or dangerous driving.

The project has been commissioned by Professor Thomas Bräunl of the Renewable Electric Vehicles (REV) team with the intent to produce a research platform for advancing the state of the art of intelligent vehicle control and automatic safety systems. Advanced computing algorithms which are tested in a practical environment can then be

developed at the University of Western Australia. Several technologies are applicable to this field including Mechatronics and control, image processing, computer logic and artificial intelligence systems. Thus, the project will provide significant opportunities for future final year projects.

A 2001 BMW X5 motorcar, donated by BMW Germany, is to be modified to control the steering and braking systems with the intent to implement an automatic safety and collision avoidance system. A graphical representation of the intelligent vehicle concept is below in Figure 1, showing the intended layout and components including the cameras, actuators, sensors and low level controller. The cameras will provide a video feed to a high level controller, which using image processing algorithms will decide whether to actuate the steering or braking systems to avoid an imminent collision. There is also a possibility of developing driver assistance or autopilot systems for the vehicle.
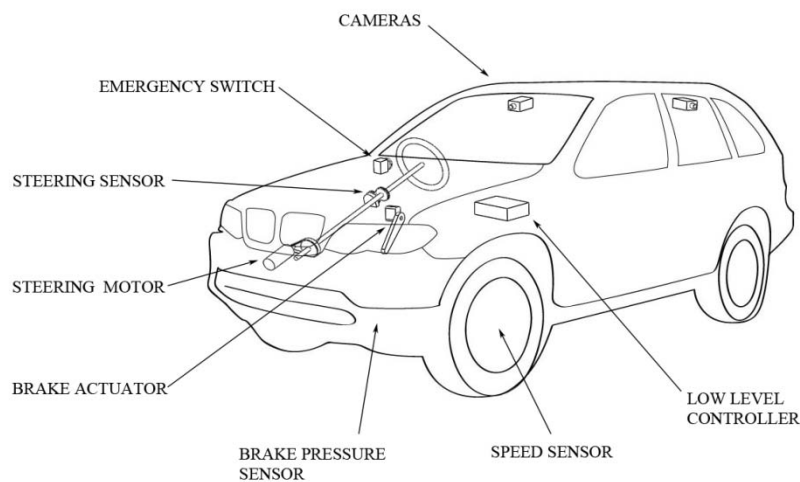
Figure 1: REV BMW X5 Intelligent Vehicle Concept.

This project deals specifically with implementing a brake actuator, steering sensor and low level controller. These three systems will be used to control the vehicle's braking and steering systems, obtain sensor feedback and facilitate control of the system by the high level controller. Various design solutions have been investigated and chosen using criteria such as safety, reliability, extensibility, ease of implementation and most importantly retaining driver control over the vehicle.

The project will document an effective, affordable and unobtrusive method to obtain control of a vehicle and will be available to interested parties such as other universities

for research. Car companies, such as BMW, may be interested in research developments using the vehicle. Finally, there is an inherent interest by society for a reduction in road traffic accidents and hopefully the vehicle can contribute to advances in this area.

<u>1.2 Project Objectives</u>

The specific aim of this project is to deliver a BMW X5 with drive by wire functionality of the steering and braking systems, and a low level controller to be integrated with either a laptop or high level controller for the automatic safety system.

An electric motor is installed, capable of actuating the steering system of the BMW X5, commissioned by Nicholas Randell in 2009. An electronically controlled motor driver, electrical wiring, fusing and emergency switch are required for this system. For accurate positional control of the steering motor, a sensor to detect the absolute rotation of the steering is necessary. This sensor is a vital component of the automatic safety system so it must be both reliable and accurate, and should obtain the steering angle without interfering with the normal operation of the vehicle.

The automatic safety system requires a safe and reliable method to actuate the brakes, whilst being unobtrusive to the driver, preserving normal functionality of the vehicle and giving the driver absolute control in the event of a malfunction.

A low level controller is required to operate the steering and brake actuators, obtain sensor feedback and communicate with a high level controller. It is desirable to have a simple interface such as a USB connection to control the vehicle using a defined and reliable communication protocol for future projects.

Throughout the project, an emphasis has been placed on retaining absolute control of the vehicle for the driver both during normal use and whilst the actuators are activated. An emergency switch must be installed to allow manual interruption of the automatic safety system.

The ultimate benefit of this project is to provide a research platform for other student projects in intelligent vehicle and safety system development, but there is also scope for adding extra features such as innovative driver feedback and control systems.

Completion of the project should allow the REV team to focus its energies on intelligent vehicle development and high level academic research, hopefully eventually leading to advances in the state of the art of intelligent vehicle control and safety systems.

2. Literature Survey and Design Selection

This chapter explores the various options that were considered for the brake actuator, steering angle sensor and low level controller for the BMW X5 automatic safety system. The relevant technologies and possible design solutions are reviewed in this chapter, and selections made based on certain design criteria.

A literature survey revealed most major car manufacturers have at some point implemented steering and brake actuation systems in their models. Lane Keeping Assist technology applies a counter-steering force in order to keep the vehicle within the lanes of the road and has been implemented by various companies, including Toyota (Toyota 2011A), Daimler (Daimler 2011), Honda (Honda 2003) and Bosch (Bosch 2011). Toyota (Toyota 2011B), Honda (Honda 2003) and interestingly the BMW X5 all have brake assistance systems which have the capability to apply the brakes (Bentley 2007, BMW 2011). Using the onboard braking capabilities of the BMW X5 was considered as a possible brake actuator solution during the selection process.

Most major car companies have already integrated steering and brake actuation systems into their products. This implies that the relatively simple solutions being considered for this project will not advance the current state of the art in vehicle control actuation methods, but instead will be a facilitator for UWA to undertake high level research into computer based algorithms and intelligent vehicle and safety system development.

2.1 Brake Actuator

A literature review was undertaken to investigate the various brake actuation options available, which included brake by wire (Shah 2009), linear actuation (Shah 2009), hydraulic pressure (HydraStar 2011) and overriding the BMW X5's onboard hydraulic brake booster (BMW 2011; Bentley 2007).

2.1.1 Brake by Wire

One solution for brake actuation, proposed by Shah, 2009 and shown in Figure 2, is to use a servomotor, positioned between the firewall and brake pedal in combination with a cable and pulley to apply a pulling force on the brake. This system was shown by Shah to be a viable solution, and relatively easy to implement.
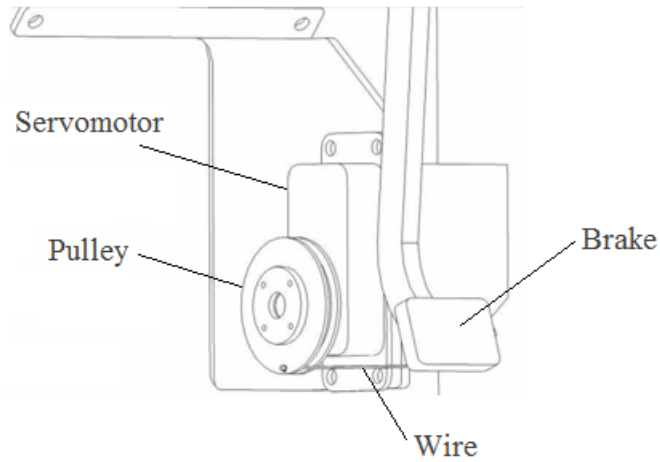
Figure 2: Brake by Wire System Rendering (Shah 2009)

Research into the servomotor-pulley actuation method led to the idea of having a servomotor directly apply a force to the brake using an actuator arm with rollers.

2.1.2 Linear Actuation

A solution for linear actuation of the brake was previously implemented by the Golem Group in the DARPA entry in 2006 (Golem 2006). A linear actuator could be placed behind the brake pedal, through the firewall of the vehicle as shown in Figure 3. Several issues are present in this design, such as the problem of mounting an actuator in the engine bay, cutting through the firewall and possible interference with normal operation of the brake.

Figure 3: Linear Brake Actuator through Firewall (Golem 2006)

An alternative linear actuation method is shown in Figure 4, proposed by Shah, 2009. A linear actuator would be placed under the seat, and a wire cable arrangement used to actuate the brake. Whilst this is a viable solution, a stroke reduction system is necessary which adds complexity to the system.
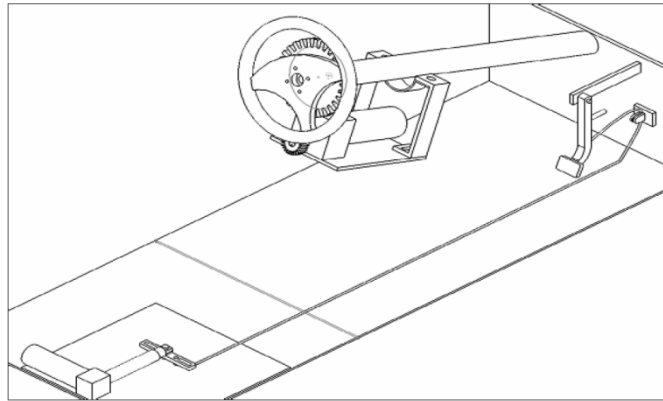
**Figure 4**: Linear Brake Actuator (Shah 2009)

2.1.3 Hydraulic Pressure

Direct control over a vehicle's hydraulic brake system was previously used by Prohaska & Devlin, 1998 to control the braking system for automatic vehicle research. An investigation found a commercially available device, the HydraStar XL, which is capable of electronically controlling a hydraulic pressure line to actuate the braking system of trailers (HydraStar 2011). This system could be installed into the brake line of the BMW X5, thereby facilitation electronic control over the brakes. Some advantages to such a system were that it would be out of sight, and fairly easy to implement.

2.1.4 Overriding the BMW X5's Onboard Hydraulic Booster

Two methods were investigated to take control of the onboard hydraulic booster of the BMW X5.

The first method was to deconstruct the hydraulic unit, shown in Figure 5, and take control of the system's valves and charge pump. This would pose some serious safety and implementation issues so this solution was not investigated further.
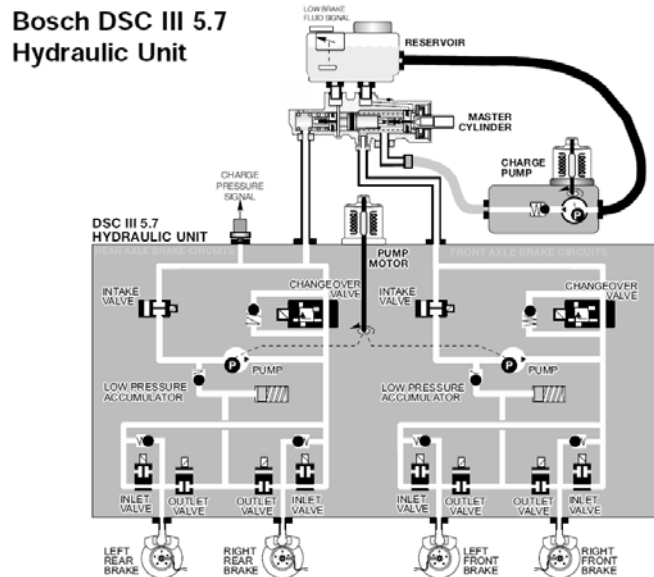
Figure 5: Bosch DSC III Hydraulic Unit (Bentley 2007)

The second method investigated was to hijack the vehicle's speed sensor and provide a modified signal in order to manipulate the onboard stability control system. The theory being that if a spike in speed is detected, the BMW's traction control system will apply the brakes to regain traction with the road. This option was discussed with the project supervisor and deemed too dangerous to implement and technically difficult.

2.1.5 Brake Actuator Selection Criteria

Selection of the brake actuator solution was based on the following criteria.

- Safety of the car and passengers
- Unobtrusive to the driver and preserves normal functionality of the vehicle
- Reliable control and actuation
- Effective brake actuation
- Relatively easy to implement
- Compatibility with an electronic controller
- Reasonable level of accuracy

2.1.6 Comparison and Selection of Brake Actuator Type

Significant time was spent researching the different options available to perform the brake actuation, but after consideration the servomotor was chosen as the best option. All the systems were able to be integrated with an electronic controller, and all were

thought to be reasonably accurate and possible to design in such a way to fully actuate the brake.

The following table is a comparison of the various systems that were considered. The comments reflect the research into the different options which led to a further investigation into the servomotor arm actuator solution.

	Safety	Unobtrusive and Retains Normal Functionality	Reliability	Effective Actuation	Easy to Implement
Servomotor Arm	Good	OK Might interfere with driver's foot. Prevents release of brake	Good	Good	Good Servomotor available, bracket easily fabricated
Servomotor Pull by Wire	Good	Good Prevents release of brake	Good	OK May be slow due to pulley	Good Servomotor available, pulley easily fabricated
Hydraulic Pressure	OK Must alter hydraulic system	Good Prevent release of brake but very unobtrusive	OK May require maintenance	Good But may have limits on activated duration	OK May be messy to implement, commercial unit may not be suitable
Linear Actuator	OK More parts & modification necessary	OK Will interfere if fixed through firewall	OK More parts, weaker actuator	OK May be slow & power issues	OK Design requires extra mounting points and parts
Override BMWs Braking System	Bad Must trick current braking safety system, dangerous	Bad Modifies normal functionality of onboard safety systems	OK If functional, probably reliable	Good If functional, will be capable of actuation	Bad Requires special circuitry & extensive testing

Table 1: Comparison of Brake Actuator Options.

Several features of the servomotor arm actuator stood out compared to the other options. It is possible to design this system so the driver is always able to push the brake further. It is a relatively easy design to implement, requiring a servomotor which was already available from previous years, a mounting bracket and an actuator arm, both of which can be fabricated with relative ease. The decision to implement the arm over the pull by wire option was due to the speed of actuation and space restrictions under the brake pedal. The servomotor can be easily integrated with a microcontroller, doesn't require significant modification to the BMW X5 and uses the car battery as a power

source. Additionally, many high torque servomotor varieties are available if a different servomotor is required for upgrade or replacement in the future.

2.2 Steering Angle Sensor

Three main steering sensor options were considered including the incremental encoder of the steering motor, the BMW's onboard steering angle sensor, or mounting a rotation sensor to the steering column.

*2.2.1 Pre-existing Steering Angle Sensor of the BMW X5*

The BMW X5 has a pre-existing steering angle sensor, shown in Figure 6, which communicates via the onboard CAN bus (controller area network) protocol, used for communication between various components of the BMW. The sensor determines the steering angle using two potentiometers and converts the information into a CAN bus signal, using its integrated microcontroller (Bentley 2007). CAN bus is a serial communications protocol, developed by Robert Bosch GmbH, widely used in modern vehicles such as BMW's. It is a standard that allows multiple devices to communicate reliably and quickly over a single twisted pair (Robert Bosch 1991).
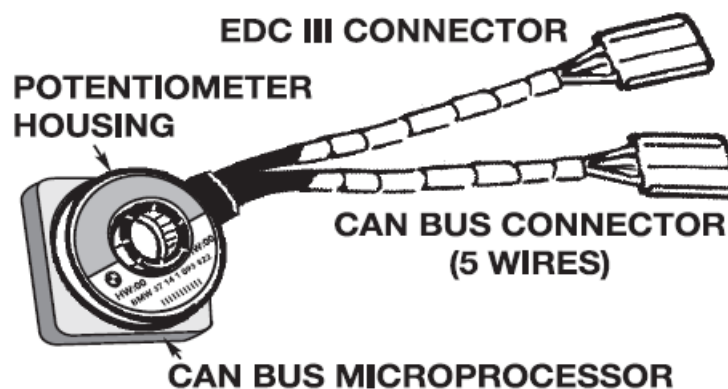
Figure 6: BMW X5 Onboard Steering Angle Sensor (Bentley 2007)

Various third party devices have been created to gain access to the CAN bus network of a vehicle, which is intended to be a mostly closed system. In particular, a CAN bus shield based on a Microchip MCP2515 CAN controller (Microchip Technology 2010), shown in Figure 7, has been developed by Sparkfun Electronics, capable of data logging automotive CAN Bus signals (Sparkfun Electronics 2011). It is intended that this device is used with an Arduino UNO (Arduino 2011) and software libraries produced by

Arduino. This poses the possibility of obtaining steering sensor data directly from the vehicle, and without any additional alterations or installations required.
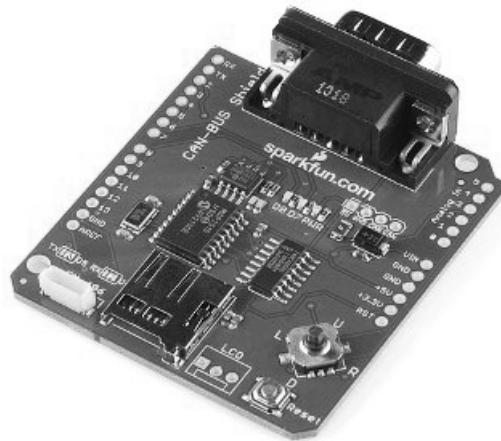
Figure 7: Sparkfun Electronics CAN Bus shield for use with the Arduino UNO embedded controller (Sparkfun Electronics 2011)

2.2.2 Steering Motor's Internal Incremental Encoder

The Pittman GM14902 DC Gear motor (Pittman 2005), shown in Figure 8, was previously installed by Nicholas Randell in 2009 and includes an integrated Avago HEDS-9140 three channel optical incremental encoder (Avago Technologies 2010). The sensor outputs two waveforms for direction and a third waveform for rotation index (speed). Two key factors that affect the decision to use this component are the possible effects of physical vibration on the interconnections and the negative effects of electrical noise on signal integrity (Keating 2008) due to its location inside the engine bay of the vehicle.
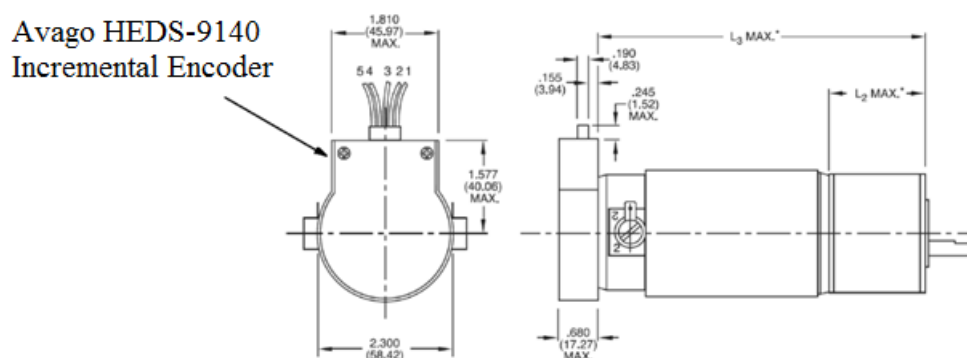

Figure 8: Pittman GM14902 DC Gear motor with Integrated Avago HEDS-9140 Incremental Encoder (Pittman 2005)

2.2.3 Installation of a New Rotational Sensor

It is possible to mount a rotational sensor to the steering column of the BMW, using a gear or belt drive. Two types of sensors were investigated for this purpose including a Hall Effect rotational smart sensor and incremental rotary encoder. The Vishay Spectrol 601HE Full 360° Hall Effect smart sensor, shown in Figure 9, provides an analogue electrical output over a full rotation, and does not require any additional electronics to condition the signal to an easily utilised form (Vishay Spectrol 2008). Incremental rotary encoders, such as the Avago HEDS-5701, utilise a disc with markings and an optical sensor to detect rotations of the shaft, outputting three waveforms which must be processed to determine direction and speed (Avago Technologies 2006). The sensor could be driven by a belt or gear drive, the advantage of a gear drive being the steering column doesn't require dismantling to install.
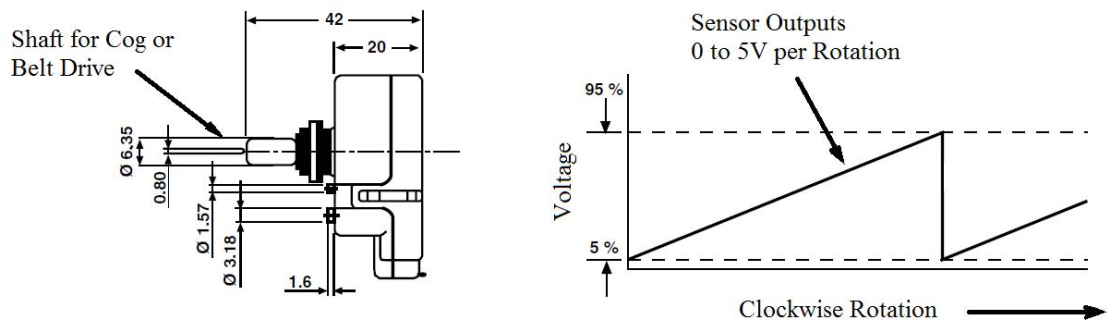
Figure 9: Vishay 601HE Hall Effect Smart Sensor (Vishay Spectrol 2008)

2.2.4 Steering Sensor Selection Criteria

Selection of the steering sensor solution was based on the following criteria.

- Reasonably accurate
- Easy to implement
- Reliable
- Not exposed to harsh environments or susceptible to electrical noise or vibration
- Compatible with an electronic controller
- Unobtrusive to normal vehicle operation

2.2.5 Comparison and Selection of Steering Sensor

A comparison was made of the various sensing options available for detecting the steering angle of the vehicle, shown in Table 2. The viability of the steering motor's internal encoder and BMW's steering sensor were investigated before resorting to mounting a sensor to the steering column.

The first two options were already present in the vehicle and if easily implemented, preferable over installing an additional device. The BMW X5's absolute encoder requires interfacing with the vehicle's CAN Bus communication system to acquire steering angle data, and was not investigated fully due to the technical difficulties involved. The steering motor's internal sensor was tested and produced no variations in the output pin, pointing to a possible failure in the device. Hence, the solution chosen was a Vishay 601HE sensor, provided by a previous student, and an appropriate mounting bracket for the device. Two options were compared for driving the sensor, using either a gear or belt drive.

	Accurate	Easy to Implement	Reliable	Electrical Noise and Vibration Exposure	Compatibility with Controller
Hall Effect Sensor: Gear Drive	Good	Excellent Very easy to implement	OK Gears can slip easier than belt drive	Good Under some mechanical stress and vibration	Excellent Easy to utilise analogue voltage
Hall Effect Sensor: Belt Drive	Good	OK Must remove steering column	Good Belt drive is reliable	Good Under some mechanical stress and vibration	Excellent Easy to utilise analogue voltage
Steering Motor Encoder	Good	OK Hard to find a suitable connector, testing showed possible failure	Bad Testing found possible failure	Bad Motor is in the engine bay area	OK Requires rotation counting, higher input lines
BMW CANBus Signal	Good	Bad CANBus is not a simple signal, BMW may use proprietary protocol	Excellent Onboard signal would be very reliable	Excellent Well placed sensor	OK The shield takes up extra pins and requires coding and analysis

**Table 2:** Comparison of Steering Sensor Options

A decision was made to use the gear driven Hall Effect sensor, primarily due to ease of installation and availability of parts, but also as it satisfied the selection criteria for the steering sensor.

2.3 Low Level Controller

Two low level controllers were considered to control the actuators, read the sensors and communicate with the high level controller. These were the EyeBot JR and an Arduino UNO, both of which are based on embedded microcontrollers. An embedded controller was desired over developing a custom microcontroller solution due to ease of implementation, future extensibility and troubleshooting.

2.3.1 EyeBot JR

The EyeBot JR shown in Figure 10 is an embedded controller, developed by the UWA Robotics and Automation Lab under guidance by Professor Thomas Bräunl. It is based on a PICAXE 40X microcontroller system, which is a standard Microchip PICmicro microcontroller, pre-programmed with PICAXE bootstrap code, enabling re-programming over a simple serial connection with BASIC code (Revolution Education 2004). The EyeBot JR has 32 input/output pins, 8 analogue input pins, a 4 MHz resonator and a RS232 serial connection (UWA Robotics and Automation Lab 2005). It is programmed in the BASIC language using a Programming Editor developed by PICAXE (PICAXE 2011).
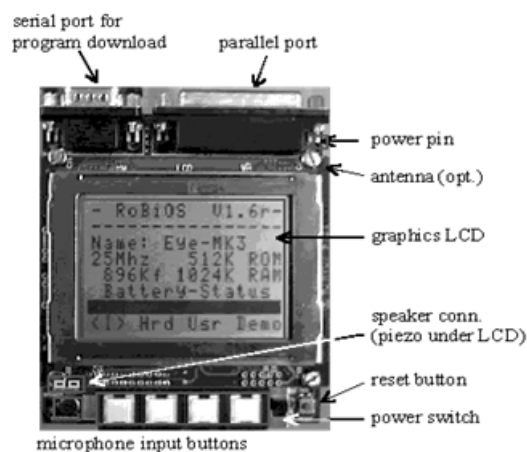
Figure 10: EyeBot JR Embedded Microcontroller (UWA Robotics and Automation Lab 2005)

2.3.2 Arduino UNO

The Arduino UNO shown in Figure 11 is an open source embedded microcontroller board based on the Atmel AVR ATMega328 (Atmel 2009). It has 14 digital input/output pins, 6 analogue input pins, a 16Mhz oscillator, USB connection (Arduino 2011) and is well supported with high levels of use amongst hobbyists and developers. It is programmed in the C language using libraries developed primarily by Arduino.
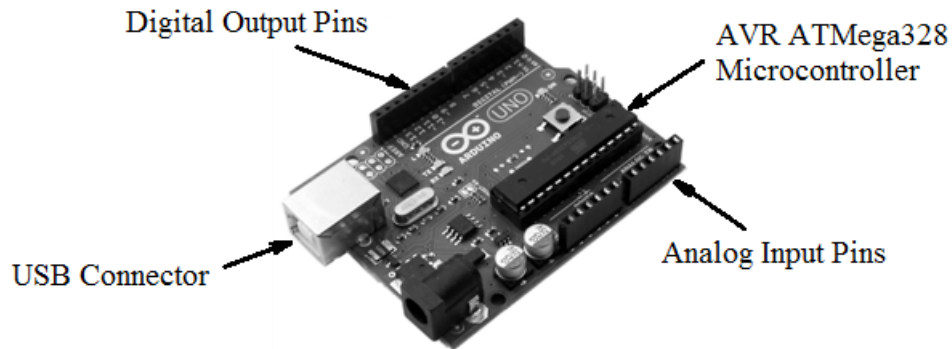
Figure 11: Arduino UNO Embedded Microcontroller (Arduino 2011)

2.3.3 Low Level Controller Selection Criteria

Selection of the low level controller was based on the following criteria.

- Easy to implement and program
- Ideal communication interface
- Sufficient IO lines and control ability
- External support and documentation

2.3.4 Comparison of Low Level Controller Options

A comparison between the Arduino UNO and EyeBot JR, based on the selection criteria is below in Table 3. Both controllers were of sufficient processing power for the desired application.

	Easy to Implement and Program	Communication Interface	Sufficient IO Lines and Control Ability	External Support and Documentation
Arduino UNO	Excellent C language, user friendly programmer tool & libraries	Good USB Connection, Serial over USB can have issues with compatibility	OK 14 Digital, 6 Analogue pins. No apparent control issues.	Excellent Many forums & documentation.
EyeBot JR	Good BASIC language, a bit less intuitive	Good Serial connection, must use USB to serial adaptor	Good 32 Digital, 8 Analogue pins. Problem with concurrent servomotor and PWM control	OK Issues harder to resolve.

Table 3: Comparison of Low Level Controller Options

After some testing of the two devices, the Arduino UNO was chosen as the low level controller for the automatic safety system. This was primarily due to ease of implementation and programming.

3.   Brake actuator

3.1 Overview

A brake actuator is necessary to control the stopping characteristics of the BMW X5 for the automatic safety system. This chapter shows the methods used to develop a working solution that satisfies the design criteria by producing a computer model, an initial prototype and a design revision.

3.2 Design

The brakes are the most important safety feature of the vehicle, thus a focus was placed on retaining normal operation of the braking system and abstaining from making dangerous alterations.

The reasons why the servomotor arm actuator was chosen are outlined in chapter 2, but in order to accurately model and build a design, further clarification of the force necessary to actuate the brake pedal was required. A measurement rig was used to produce a torque-angle graph of the brake rotation.

3.2.1 Measurement of Brake Force Generation

The rotation and torque measurements were taken using an experimental rig, shown in Figure 12. A camera was mounted to the brake pedal pivot and force applied through a mass scale. A vertical string was fixed to the body of the vehicle, through the centre point of the camera's line of site to enable calculation of the angular difference using video frames.
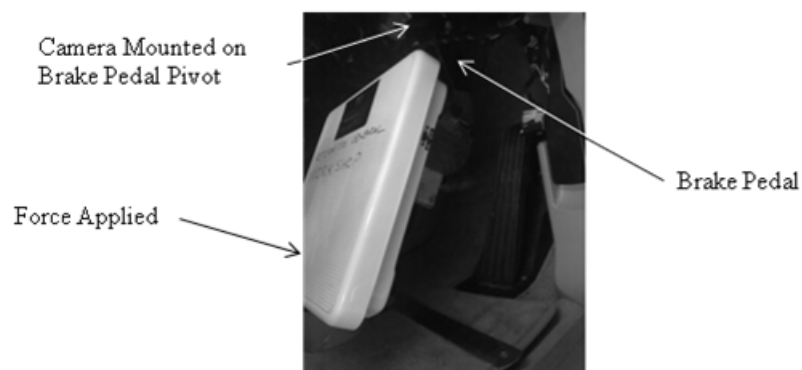

Figure 12: Measurement Rig for Measuring Torque vs. Rotation of Brake

A force reading (in kg) was read during video recording of the rotation, so that the angle could be correlated to a specific torque later. The result, shown in Graph 1, is an

exponential curve. This fits the characteristics of the brake, as the further it is pressed the harder it becomes to achieve further rotation. There is a finite rotational limit of the brake actuator which was found to be approximately 17 degrees.

Further clarification of the data was desired on the necessary brake force to bring a moving vehicle to a complete stop. It was found, using the camera mounted apparatus whilst driving the vehicle at approximately 10 km/h, the maximum brake rotation required to stop the moving vehicle was 13 degrees, correlating to a torque of 37Nm. This was confirmed with a mass scale reading of 13kg. The length of the brake pedal was measured to be 290mm; this value was used for all subsequent calculations.
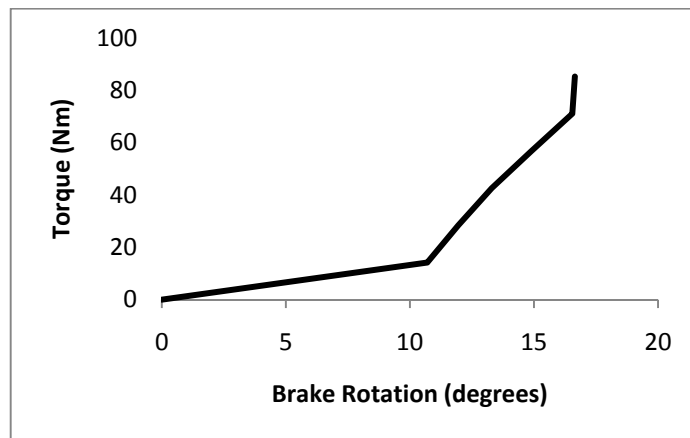
Graph 1: Experimental Readings for Brake Pedal Torque vs. Rotation

3.2.2 Design Constraints of Servomotor Arm Actuator

1. Design fits within the space restrictions of the cabin and can be mounted on the BMW X5's frame, shown in Figure 13. These mounting points have been chosen, as they appear to be sufficiently strong, don't require modification to attach a bracket and allow enough space between the cabin interior and the mounting points for the servomotor.
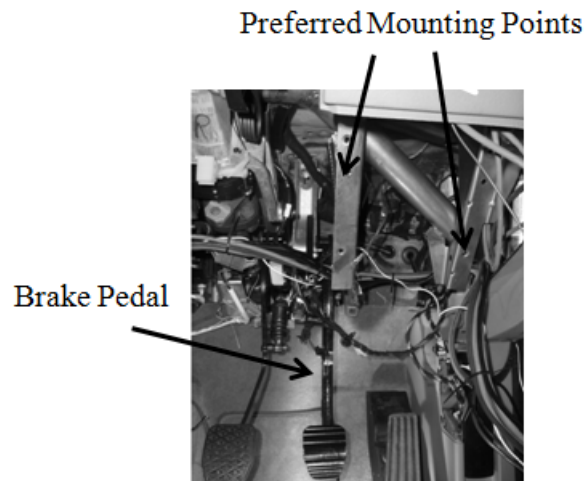
Figure 13: Preferred Mounting Area for Servomotor

2. Able to actuate the brake to the full stopping force of the vehicle. The necessary torque was found to be 37Nm, for an angular rotation of 13 degrees in section 3.2.1. The structure of the actuator arm and its components must also be designed above these force specifications.

3. Able to fully actuate the brakes within approximately 0.15 seconds. A study done by NTSEL, 2007 showed the average brake stroke speed to be 456mm/s in an emergency situation. It was desirable to have a similar or better speed than this, to be capable of controlling the brakes in a similar fashion to a human driver.

Equation 3.1 is used to calculate the approximate brake stroke length, by calculating L (arc length). Inputs into the equation are the rotational requirement (arc angle θ) for brake actuation, shown to be 13 degrees in section 3.2.1 and brake pedal length (radius r) of 290mm. This gives an arc length (L) of 66mm, which is taken as an approximation of brake stroke length.

$$L = (\theta / 360) \times (2\pi r) \qquad\qquad (3.1)$$

This means that the BMW X5's brake pedal should be able to be applied in 0.145 seconds (66mm / 456mm per second) to match an average human.

4. Easily fabricated by workshop. Parts requiring workshop fabrication include the mounting bracket, brake arm and roller. Relatively simple designs were desirable, using common materials such as aluminium or steel, in order to speed the prototyping process and facilitate faster progress in the other components of the project.

5. Must be unobtrusive of the driver's foot and allow the driver to increase the brake force regardless of the servomotor position. The servomotor, mounting brackets, and actuator arm should all be designed in such a way to minimise interference with the driver's normal foot pressing action on the brake, and preferably mounted hidden and away from view.

6. Adjustable mounting position and actuator arm. It's desired that the bracket is able to be adjusted or removed with relative ease. The actuator arm should have an adjustable length from the servomotor to the brake pedal and the rollers to be removable for changes in the design or future repairs.

3.2.3 Modelling of Servomotor Arm Actuator
A SSPS-105 servomotor (Tonegawa-Seiko 2011) was available for use with the project, from previous years. A feasibility investigation was required to determine whether this device was able to actuate the brakes effectively using an arm actuator.

Several key design constraints had to be satisfied to approve the use of the SSPS-105 servomotor.
- Strength of the servomotor and its ability to actuate the brake effectively. Must be able to apply a torque of 37Nm for an angular rotation of 13 degrees
- Speed of the servomotor. Must be able to actuate the brake to 13 degrees in approximately 0.15 seconds
- Fits within the space restrictions and can be installed on the preferred mounting points in Figure 13

The vehicle's brake was measured using cardboard, rulers and photos to produce a schematic for modelling. Solidworks was used to develop the CAD model, shown in Figure 14.
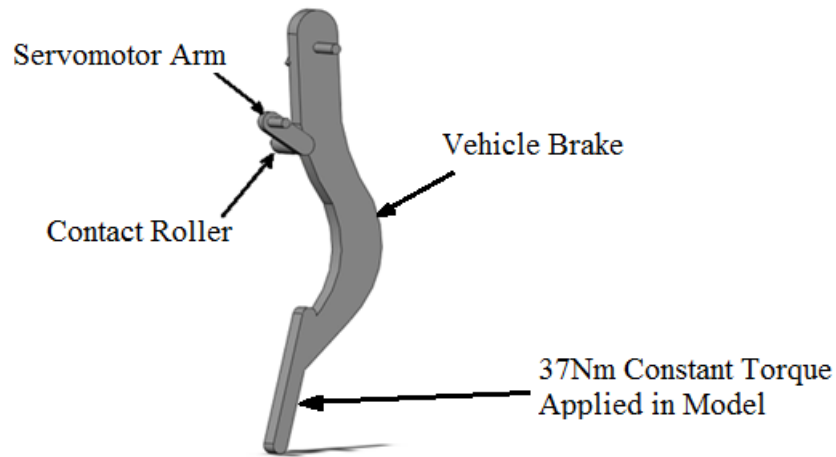
Figure 14: Preliminary Brake Actuator Design used with Solidworks™ Motion Simulation

The Solidworks Motion Analysis package was used to model the dynamic forces to ensure the design fit within the mechanical and power constraints. For the motion analysis, a constant opposing torque of 37Nm was applied to the brake to represent the maximum force necessary, and the required torque to rotate the brake pedal 13 degrees, at a constant speed over 5 seconds. A constant opposing torque was used, to ensure the design fit within the maximum force requirements and for simplicity in modelling. The result is shown in Graph 2, which shows a maximum servomotor torque requirement of 21.4Nm. This model fit the servomotor's maximum torque of 38Nm (Tonegawa-Seiko 2011) by a safety margin of approximately 60%.
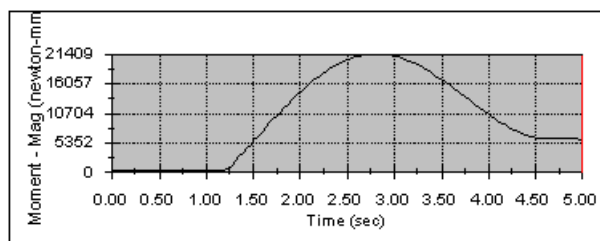
Graph 2: Solidworks™ Motion simulation of torque response for servomotor arm design.

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The SSPS-105 servomotor datasheet (Tonegawa-Seiko 2011) shows an operating speed of 0.95 seconds per 90°, which for a 13° rotation equates to a time of 0.14 seconds, according to equation 3.2. This appears to satisfy the requirement of a 0.15 second actuation time.

$$\text{Time} = 13° \times (0.95/90°) \qquad (3.2)$$

To determine if the design would fit in the preferred mounting area, the servomotor was placed and checked for adequate space between the cabin interior, suitability of mounting points for a bracket and line of sight to the brake pedal. This check showed the design would fit in this area, but further prototyping was necessary.

3.2.4 Prototype & Design Revision

In order to perform a practical test of whether the servomotor was powerful enough, the arm did not interfere with the driver and the system fit in the proposed location, a prototype was required. The design in Figure 15 was produced in Solidworks and subsequently fabricated by the workshop out of 10mm Aluminium.
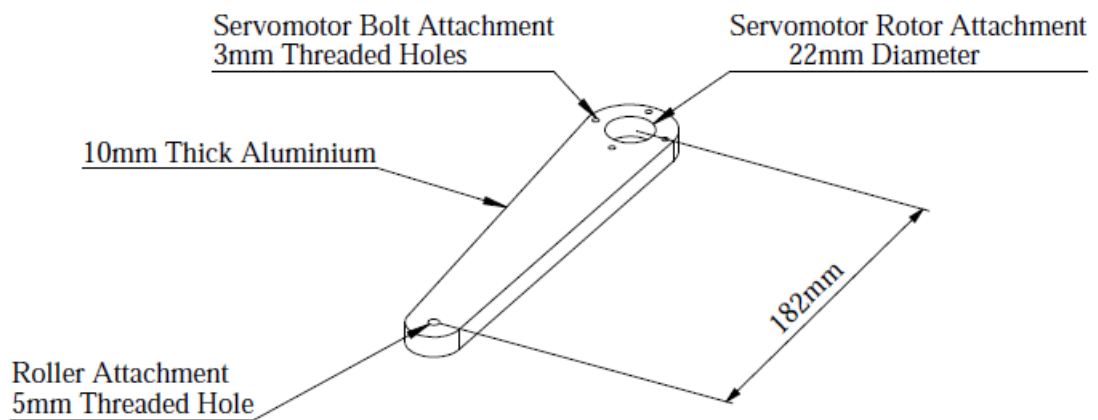
Figure 15: Prototype Brake Arm Actuator

A mounting bracket, necessary to test the strength of the servomotor and ensure the design fit in the desired area was fabricated by the workshop to the specifications in Figure 16.
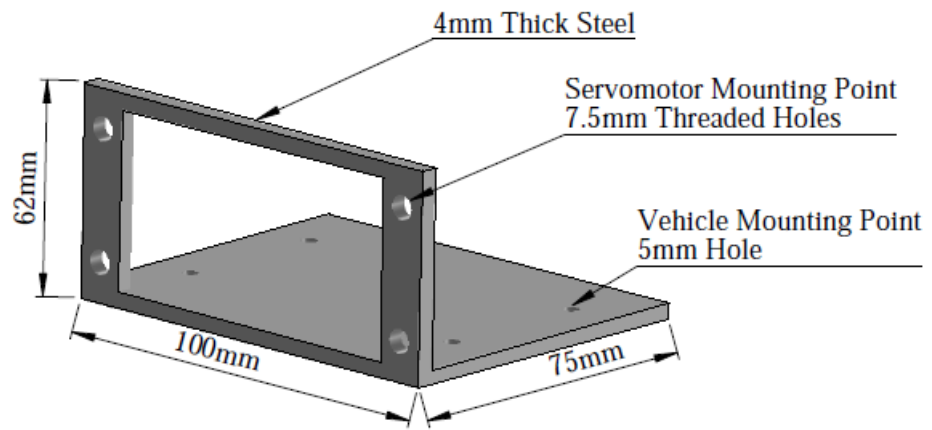
Figure 16: Servomotor Mounting Bracket

The design was tested, showing the servomotor fit within the constraints of the mounting bracket and the preferred mounting point in Figure 13. The servomotor was found to adequately press the brake pedal, although the length to the contact roller could be decreased because the required angle of 13° was being easily achieved. Testing showed the straight arm got in the way of normal foot operation, which led to a design revision.

The revised design includes an adjustable roller position along the length of the brake actuator arm and a bend which is intended to reduce intrusiveness in normal brake operation. Having an adjustable length allows modification of the torque & speed characteristics of the servomotor arm. An adjustable ball bearing roller was installed on the servomotor arm for contact with the brake pedal. The rollers use washers to ensure that sideways slip doesn't occur. The improved brake arm design is shown in Figure 17.
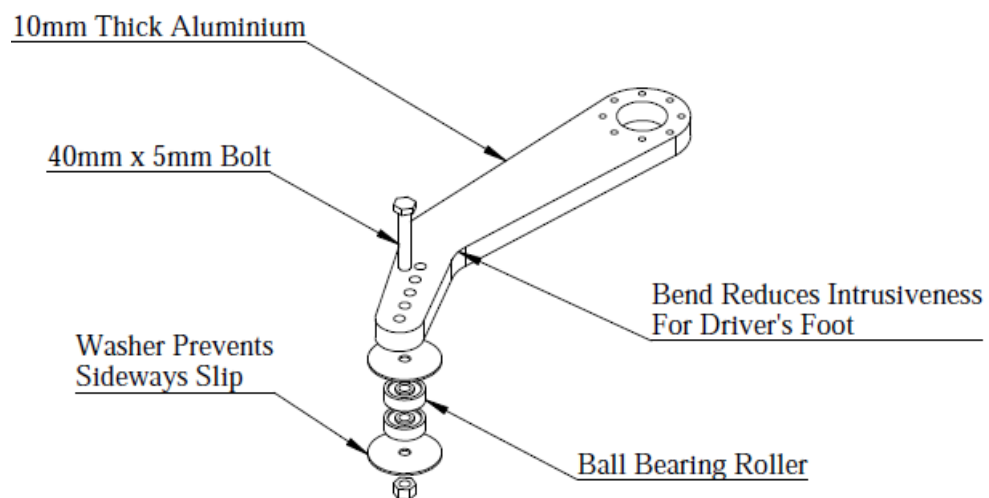
Figure 17: Servomotor actuator and improved brake arm designs.

3.2.5 Safety Considerations

There were various safety considerations when designing and implementing the servomotor arm actuator, with the key risks outlined below.

It is essential to retain driver control of the vehicle, especially the braking system which is the most fundamental safety element of a vehicle. If the servomotor were designed to be fixed to the brake pedal, and not allow forward movement, then there would be a considerable risk of damaging the vehicle and its occupants or external environment including other vehicles, structures and pedestrians. Two major factors mitigate this risk eventuating.

- The design is such that the brake is always able to be pressed further by the driver.
- To deactivate the brake actuator an emergency switch and appropriate circuitry to reset the servo position, and cut power to the device was implemented, described in chapter 5.

<u>Risk1:</u> Brake actuator interferes with driver's control of braking system, causing damage to the vehicle, occupants or external environment.

	Consequence	Likelihood	Risk
Before Mitigation	Disaster	Unusual	High
After Mitigation	Disaster	Conceivable	Low

Table 4: Risk 1 Matrix

It is important when testing and running the brake actuator, to do so in a safe environment, and be aware of the possible impairments of the braking system and the possibility of it functioning abnormally. There is a risk of damage to the vehicle, occupants or external structures, pedestrians or other vehicles on the road.

The following factors were used to mitigate this risk eventuating.

- The car was driven in safe and quiet areas, where the risk of a sudden braking incident is not an issue.
- An emergency switch was implemented to ensure the braking system can be deactivated in the event of a malfunction.
- Ensured driver awareness of the system and how to override the brake actuator.

Risk 2: Brake actuator is used in an unsafe environment and causes damage to the vehicle, occupants or external environment.

	Consequence	Likelihood	Risk
Before Mitigation	Very Serious	Likely	High
After Mitigation	Very Serious	Conceivable	Low

Table 5: Risk 2 Matrix

There is the risk that a failure of the brake actuator could occur, restricting use of the brake or the driver's ability to press the brake pedal. This would be quite a serious situation, possibly causing damage to the vehicle, occupants or external structures, pedestrians or other vehicles on the road. The brake actuator was fabricated out of relatively thick aluminium and steel that would be extremely difficult to damage to the point of malfunction. This leaves two key points of failure of the device. First, is the risk the arm becomes dislodged over time, falls off and gets caught within the pedals, preventing normal brake operation by the driver. Second, is the risk that the servomotor may dislodge from the mounting bracket. To lower the likelihood of both these risks eventuating, locking washers were used for all connections to reduce the possibility of any loosening occurring over time. The design was also implemented with many bolt connections for both the brake arm and servomotor bracket, increasing the reliability of connections between components.

Risk 3: Brake actuator arm or servomotor dislodges, preventing normal use of the brakes and causing damage the vehicle, occupants or external environment.

	Consequence	Likelihood	Risk
Before Mitigation	Disaster	Remotely Possible	Medium
After Mitigation	Disaster	Conceivable	Low

Table 6: Risk 2 Matrix

3.3 Results and Discussion

A high powered SSPS-105 servomotor in conjunction with an aluminium arm and ball bearing roller have been installed and are being used to actuate the brake pedal directly. The final design is shown in Figure 18. Detailed CAD drawings of the mounting bracket and brake arm are listed in appendix B and A respectively.
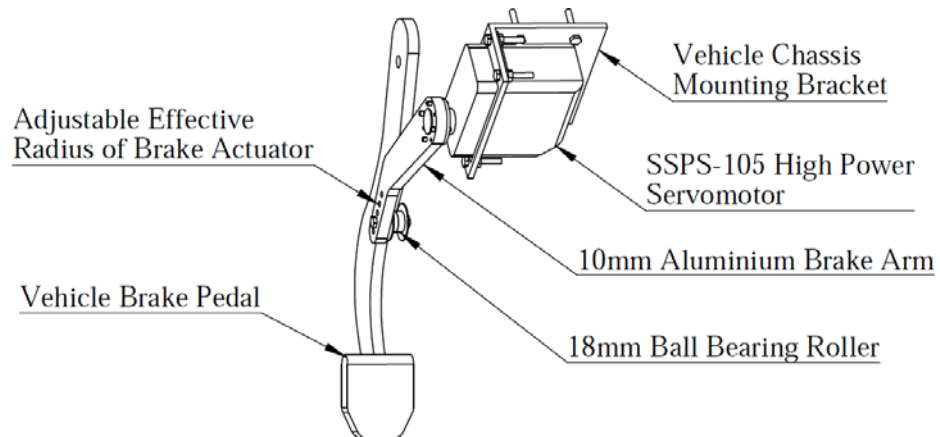
Figure 18: Final Brake Actuator Installation

The actuator arm's orientation allows the driver to always increase the brake force, whilst the shape limits the obtrusiveness of the design. For added safety, an emergency switch has been implemented which deactivates the servomotor by resetting its position off the brake and subsequently cuts its power supply. The prototype bracket was found to be ideal and not in need of any alterations. It has been installed in the car to allow for various height configurations of the servomotor, and the roller can be positioned at various radii on the actuator arm. The servomotor arm configuration was chosen primarily due to the ease of installation, simplicity in the design, effective actuation force and speed, availability of components and its basic control interface.

An arbitrary decision was made with the design to use two standard ball bearing rollers and several large washers to form the contact roller for the brake actuator. Whilst this is a practical and easy solution, it may cause cosmetic damage to the vehicles brake pedal. The roller may be improved in the future by having a smaller diameter, thus decreasing distance to pedal arm and reducing the chance of the driver hitting the roller. A rubber or plastic contact material on the brake pedal may also reduce the chance of cosmetic damage occurring. The decision to use aluminium for the arm actuator and steel for the

mounting bracket was not due to a technical investigation, but due to availability of the materials and ease of manufacture by the workshop. An assumption has been made that the strength of these materials is sufficient for this application.

Testing was carried out by passing commands to the Arduino UNO controller over the USB connection, with a reply a time in milliseconds of the various sensors, including the brake pressure sensor. The key test data are listed in appendix F.

The following is a critical analysis and discussion of the success of the implemented brake actuator. The discussion analyses the final solution with respect to each of the selection criteria in section 2.1.5.

Safety of the car and passengers
The design is relatively safe, allowing for increased brake pressure by the driver in any situation, and deactivation of the brake servomotor using an emergency switch.

Unobtrusive to the driver and preserves normal functionality of the vehicle
The servomotor arm was designed with a bend, for less intrusiveness of the driver's use of the brake pedal. The contact roller has side guards in the form of large washers that prevent the driver from contacting the ball bearings. The overall design ensures that an average human driver's foot won't contact the servomotor brake actuator system. The system can be easily removed and no major modifications to the vehicle chassis were required to install it. The cabin's inner panel sits between the servomotor and driver, effectively hiding the servomotor from view and contact.

Reliable in its control and actuation
Practical testing has shown that the system is reliable in stopping the vehicle and applying the brakes. However, there is some oscillation in the holding force of the brake, shown in Graph 3. Multiple tests were carried out, all showing signs of oscillation. This may be an issue for future work, but at this stage the system brings the car to a halt very effectively, which is satisfactory for initial research into the automatic safety system.

Full Brake Actuation Test 5

*Brake Pressure Sensor (Voltage Level)* vs *Time (ms)*
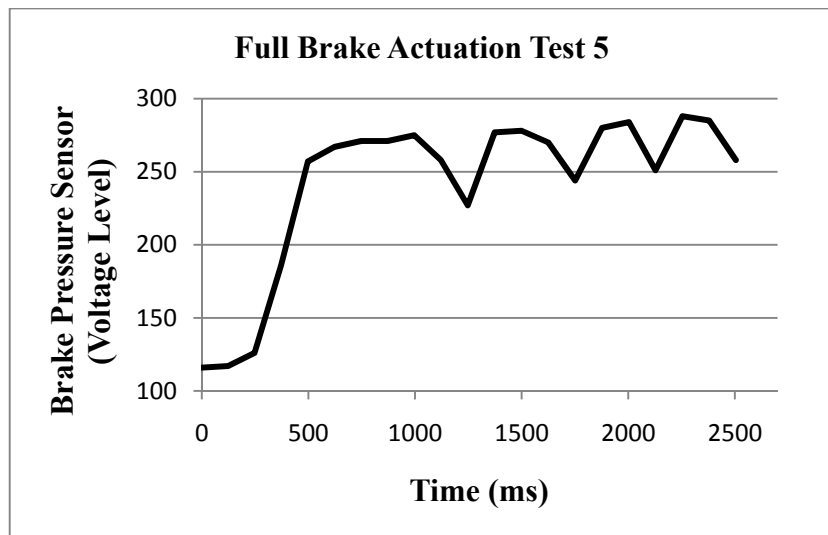
Graph 3: Brake Pressure Graph for Full Brake Actuation Test (oscillation visible)

Effective in actuating the brakes

Testing was undertaken to determine the response time to fully actuate the brakes, the average of 5 tests shown in Graph 4. The average response time of approximately 500ms is about 3 times slower than the preliminary modelling showed, due to an assumption made during the design process that the speed of the servomotor is a constant 0.95 seconds per 90° (Tonegawa-Seiko 2011). This is the speed listed in the datasheet, and is probably the no load speed, which explains the increased actuation time compared to the initial model.

Full Brake Actuation Average Response

Brake Pressure Sensor (Voltage Level) vs *Time (ms)*
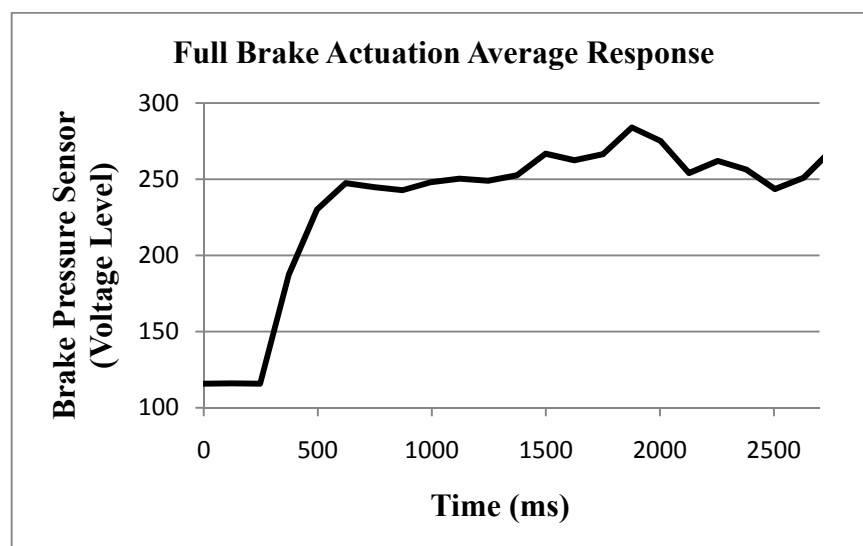
Graph 4: Average Brake Pressure Response for Full Brake Actuation

However, the servomotor is able to completely actuate the brake and bring the vehicle to a stop within a very reasonable time. The main goal of facilitating research into the

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automatic safety system is still possible, although the design may be improved in the future to increase the speed of actuation.

It may be suitable to test various brake actuator lengths in order to decrease the response time. This would not necessarily mean increasing the actuator length as whilst this will decrease the rotation angle of the servomotor, it would increase the required torque. By decreasing the actuator length, the necessary rotation angle will increase but torque requirement will decrease. So a balancing must occur to fit the characteristics of the servomotor and find a suitable actuator arm length. Decreasing the torque requirement by reducing the length of the arm may be desirable as it will reduce the oscillations and produce less strain on the servomotor over time.

Relative ease of implementation

The design was one of the easiest to implement of those reviewed, as it used available components and did not require significant changes to the vehicle to install. It took advantage of the preferred mounting points in Figure 13 which were already present in the vehicle and the SSPS105 servomotor was available from previous years. Once the design was produced, the workshop was able to fabricate the design in several days.

Compatibility with an electronic controller

The servomotor is powered by a 12V line, tested and shown in Table 7 to require a maximum current of 3.7 Amps for full brake actuation. This is well within the controller's capability, as a 30 Amp relay (Jaycar 2011) was used for the emergency switch's circuit to cut the servomotor power.

Brake Actuation Level (%)	Current Draw (Amps)
25%	0.9
50%	1.1
75%	2.0
100%	3.7

Table 7: Brake Servomotor Current Test

The SSPS105 servomotor uses a standard 20ms control signal, over a 3 wire connector which includes a 5V Signal, 5V supply and ground. This configuration is compatible and easily interfaced with the Arduino UNO embedded controller and its libraries.

Reasonable level of accuracy

The brake actuator achieves a practical level of accuracy, during testing the brake was actuated to the levels listed in Table 7, able to effectively partially press the brake pedal. However, the fine accuracy of the system could be improved, the oscillations visible in Graph 3 shows problems in the holding accuracy and stability.

Despite the shortcomings in accuracy and speed, during testing the system was proven to actuate the brake pedal of the vehicle and bring the BMW X5 to a complete or gradual stop very effectively.
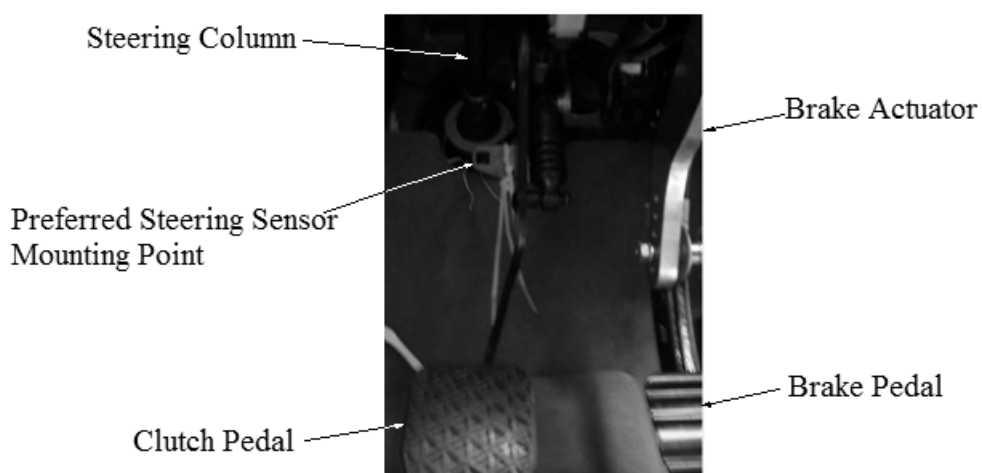
4. Steering Sensor

4.1 Overview

A steering sensor is necessary for integration with the steering motor, previously commissioned by Randal in 2009. The sensor is required to enable closed loop positional control of the vehicle's steering angle, and to provide steering angle feedback to the high level controller.

4.2 Design

The gear driven Hall Effect sensor design was chosen in chapter 2 as it is an easy to implement, reasonably accurate and flexible solution. The design consists of a bracket to hold the Vishay 601-HE Hall Effect sensor in place, a gear that is attached to the rotor of the sensor and a split gear that is attached to the steering column. The split gear allows the installation of the steering column cog without removal of the steering column itself. The following design constraints were used when developing the cog designs and mounting bracket for the steering sensor.

4.2.1 Design Constraints of Steering Sensor

1. Must be placed in a location that won't interfere with the driver or the vehicle pedals. It is preferable to use the existing mounting point in Figure 19 for ease of implementation.

Figure 19: Preferred Steering Sensor Mounting Point

2. The design should be easy to install and adjust. In particular, it was desired that the steering column needn't be removed. Parts requiring workshop fabrication include the mounting bracket, steering column gear and steering sensor gear.

3. The mounting bracket must be sufficiently stiff and must be attached in a way as to prevent slippage of the gear drive.

4. The system must transmit all angular changes of the steering column reliably and accurately. The amount of turns must remain constant over multiple cycles.

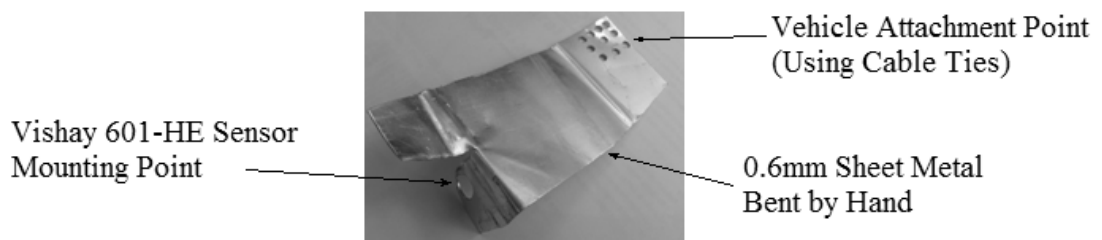*4.2.2 Prototype Steering Sensor Bracket*

The first step of the design process was to find the necessary gears to be used with the system, one for the steering sensor and the other for the steering column. The steering column was measured to be 17mm diameter, and the sensor rotor ¼ inches (or 6.35mm). Workshop donated several brass cogs which had suitable dimensions. Both cogs are made of brass, whilst the steering column cog has 48 teeth and the sensor cog has 40 teeth, a 6:5 ratio.

It was necessary to produce a functional prototype bracket due to the complexity of obtaining the required measurements accurately, so the gears were prepared for installation. The sensor cog was already suitable for mounting onto the sensor rotor, using a grub screw. A split cog design was proposed for the steering column, shown in Figure 20, which allows the gear drive to be easily installed without removal or alteration of the steering column. This design was fabricated by the workshop, and installed on the steering column of the vehicle.
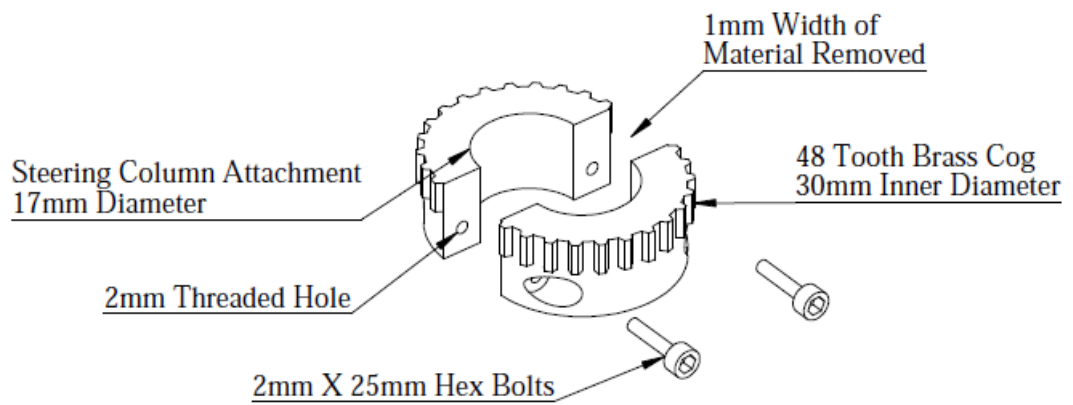
Figure 20: Steering Column Split Cog Design

With the gears installed on the sensor and steering column, a prototype bracket could be produced. Sheet metal (0.6mm thick) was used to produce a prototype, shown below in Figure 21.

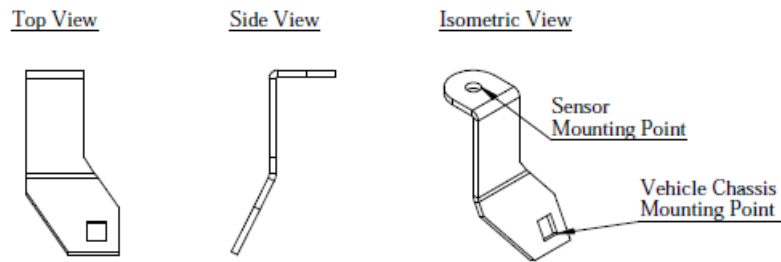**Figure 21:** Prototype Steering Sensor Mounting Bracket

The prototype bracket, shown in Figure 22, was installed and bent to fit but had to be held in place by wire due to a lack of stiffness. The sensor was tested using the Arduino UNO and found to accurately give a correct signal over several rotations. The gear connection was inspected to ensure no slippage was occurring, and none was found.
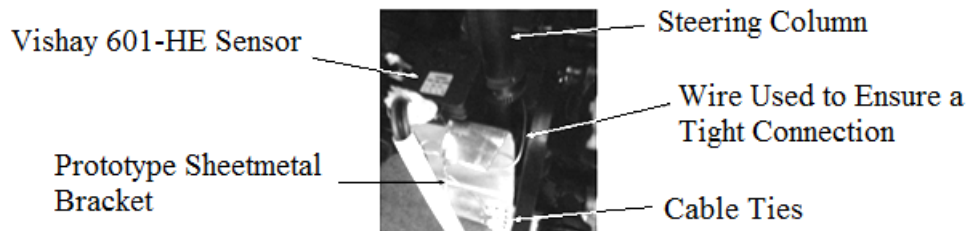
Figure 22: Installed Prototype Bracket and Sensor

4.2.3 Sheet Metal Schematic and Sensor Bracket Fabrication

The next step of the process was to produce a schematic of the final bracket for workshop fabrication. The Solidworks Sheetmetal package was used because the bracket was to be made of 3mm aluminium sheet metal and bent into shape. The model was produced based on measurements taken of the prototype, but it was intended that the fabrication process would allow for slight adjustment in the design in the last bend to ensure a proper fit and allow for a tolerance in the measurements. The schematic is shown in Figure 23, for a detailed and dimensioned drawing refer to appendix D.

Figure 23: Steering Sensor Mounting Bracket
Solidworks Sheetmetal Schematic (Simplified)

The sheet metal schematic was used by workshop to fabricate the bracket, using 3mm aluminium sheet metal. The final bend was performed in gradual steps and with careful adjustment to ensure the sensor mounting point was perpendicular to the steering column.

4.2.4 Design Safety

Several safety considerations were taken into account when designing and implementing this system, the key risks outlined below.

It is essential the steering sensor and bracket doesn't interfere with normal operation of the clutch pedal or steering column. If the bracket came loose or got in the way of normal clutch operation, it could cause an accident and possible damage to the vehicle, occupants or external environment. A method used to mitigate this risk was to use a conical locking washer for the vehicle attachment point, to ensure a tight fit and so the mounting bracket shouldn't come loose over time. The design was produced with a bend to the left, illustrated in the top view of Figure 23, which keeps the sensor and

bracket relatively far from the clutch and predisposes the bracket to fall to the left, away from the clutch and brake pedals of the vehicle.

Risk1: Steering sensor loosens, blocking control of the clutch and causing damage to the vehicle, occupants or external environment.

	Consequence	Likelihood	Risk
Before Mitigation	Very Serious	Unusual	Medium
After Mitigation	Very Serious	Conceivable	Low

Table 8: Risk 1 Matrix

There is the risk of slippage in the gear drive, and an incorrect rotation value being read by the sensor. This will produce an incorrect angular value in the control system and if a heavy reliance is placed on the steering sensors reliability it may cause an accident when using the automatic safety system. The risk has been somewhat mitigated by using a conical locking washer to ensure a tight fit, and ensuring the bends fit the application well. A length of wire is still being used with the sensor mount, to maintain a tension between the steering column and bracket. An awareness of this issue is necessary, and testing must occur in a safe environment.

Risk2: Steering sensor gear slips over time, causing inaccurate readings of the steering angle and incorrect steering by the automatic safety system. This may cause damage to the vehicle, occupants or external environment.

|	Consequence	Likelihood	Risk
Before Mitigation	Very Serious	Likely	Very High
After Mitigation	Very Serious	Conceivable	Medium

Table 9: Risk 2 Matrix

4.3 Results and Discussion

A Vishay 601HE Hall Effect based rotational sensor (Vishay Spectrol 2008), mounted on the steering column and shown in Figure 24, is being used to detect the steering angle of the vehicle. Detailed and dimensioned CAD drawings of the mounting bracket and split gear are provided in the appendix D and C respectively. The steering column

cog is split in half and can be easily mounted using two 2mm hex screws. The sensor bracket has been mounted onto an existing component of the car's chassis using a bolt and conical locking washer for rotational stability.
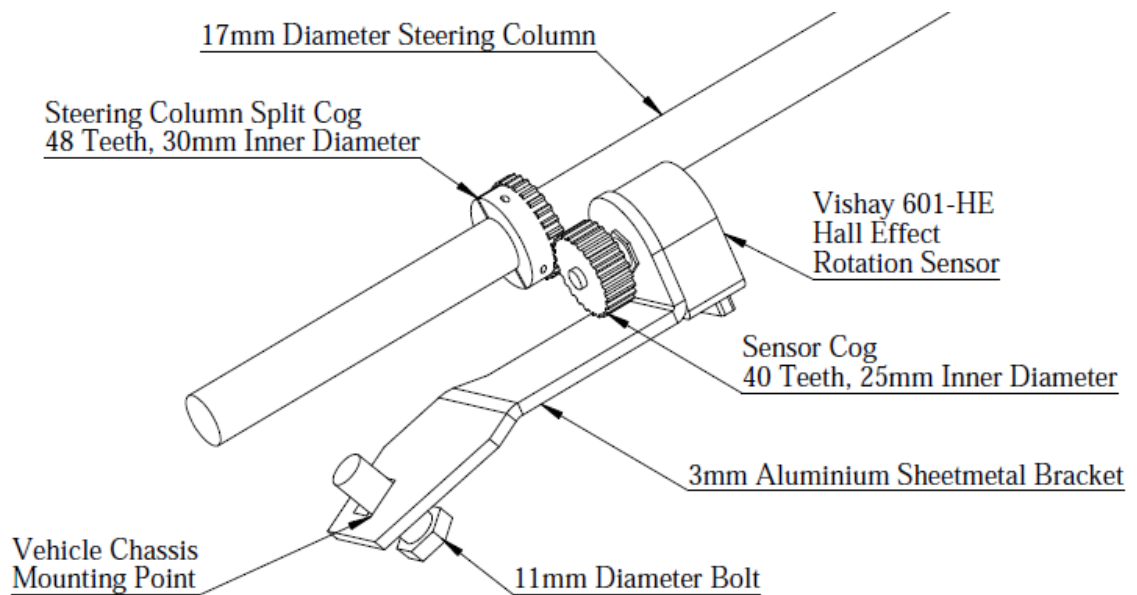
Figure 24: Steering Sensor Installation

A rotation counter has been implemented in software, as the sensor rotates 4 times from full left to full right. When the controller is activated, the vehicle's steering angle must be close to the centre for the counter to be initialized properly. Otherwise, the counter may be reset by turning either from full right to full left or full left to full right. The code used for the rotation counter is listed in appendix E. The location of the sensor inside the driver's cabin reduces vibration, electrical noise, and exposure to harsh environments.

The primary reason for using a gear driven design over a typical belt drive is to eliminate the need for a split belt system or removal of the steering column for belt installation. It has the advantage of being easily adjustable. A lower gear ratio (1:6) could provide a reduction sufficient to enable a single rotation over the entire range of the vehicle's steering, eliminating the need for a rotation counter.

The steering sensor is used in conjunction with the steering motor for positional control of the vehicle's steering angle, using a PID control algorithm. It has been successful in obtaining the steering angle accurately over many steering cycles. The centre value for

steering angle in the software is 127; this value was tested to ensure the centre point of the steering sensor corresponds to the straight steering angle of the vehicle. The steering wheel was held in place, and the steering motor instructed to maintain the vehicle at 127 whilst driving approximately 50 meters. No noticeable drift from the centreline occurred, confirming this value is very close to the actual steering centre point of the vehicle.

An arbitrary decision was made to use 3mm sheet aluminium as the material of choice, after discussing the design with the workshop. It is assumed this material is stiff enough for this application and won't degrade significantly over time. An assumption has been made that the conical locking washer will provide enough opposing force on the connection so that it is very unlikely the mount will come loose over time. The decision to use a 6:5 gear ratio was an arbitrary choice, based on the availability of the gears at the workshop. This ratio may be changed in the future to correlate a single rotation of the sensor to a complete rotation of the vehicle's steering angle.

The following is a critical analysis of the implemented steering angle sensor. The discussion compares the final solution with each of the selection criteria in section 4.2.1 and analyses the success of the design.

Reasonably accurate

Preliminary testing has shown the steering sensor to be quite accurate, able to sense 4400 different rotation levels for a rotation in the steering wheel from full left to right. This equates to a potential accuracy of approximately 0.05°, assuming the steering range of the vehicle is 180°. The proposal to change the gear ratio to 1:6 to enable a single rotation for the steering sensor will still provide an accuracy of approximately 0.3 degrees which still is an acceptable level of accuracy for this application.

Easy to implement

The design was very easy to implement, once prototyping was complete the workshop had it fabricated in a matter of hours. There was a strong and ideal mounting point for the sensor bracket already present in the vehicle. The split cog design can be easily installed and adjusted with the use of a hex key.

Reliable

The steering sensor has been tested by turning the vehicle's steering from full left to full right repeatedly, and ensuring the steering value remains 0 for full left and 255 for full right. It has passed this test, and thus far has enabled accurate positional control of the steering motor. However, there is a worry the bracket may come slightly loose, enabling the gear drive to slip. This would be a serious safety issue if the car is being used in a live environment, for example the sensor may think it is centre aligned, but in fact the car is turning off centre leading to an accident. Currently, a loop of wire is being used to ensure the bracket and column maintain a tight connection, ensuring no slip of the gear drive, but this may need to be improved in the future, especially if the automatic safety system is used in a practical environment, or with an unaware operator.

Not exposed to harsh environments, susceptible to electrical noise or vibration

The location of the sensor and mounting bracket inside the cabin ensures that it isn't exposed to a harsh environment, excessive electrical noise or vibration. However, the bracket is close to the clutch pedal and there is a possibility it may be hit by the driver's foot. If the sensor is not producing accurate readings this should be investigated. Overall, the location is ideal for the sensor as it is mounted on a very strong chassis connection and inside the driver's cabin.

Compatibility with an electronic controller

The sensor is ideally interfaced with the Arduino UNO microcontroller. It requires a simple 3 line connection to the controller, consisting of a 5 volt power supply, Ground and 5 volt analogue voltage signal.

Unobtrusive to normal vehicle operation

For normal operation of the vehicle, no noticeable opposing torque is applied to the steering wheel rotation, and the location of the bracket and sensor is out of the way of an average driver's foot. The clutch pedal does not contact the bracket mounting point.

5.   Low Level Controller and Emergency Switch

5.1 Overview

A low level controller is required to enable control of the steering motor and servomotor brake actuator and to read the steering, brake and any additional sensors. This controller must be integrated with a high level controller, potentially a laptop or EyeBot M6 (UWA Robotics and Automation Lab 2009).

5.2 Low Level Controller

5.2.1 Implementation

A low level controller has been implemented using an Arduino UNO based on the Atmel AVR ATMega328 microcontroller (Arduino 2011). A custom pin shield was constructed out of circuit prototype board, to ensure a reliable connection to the IO lines of the Arduino, shown in Figure 25.
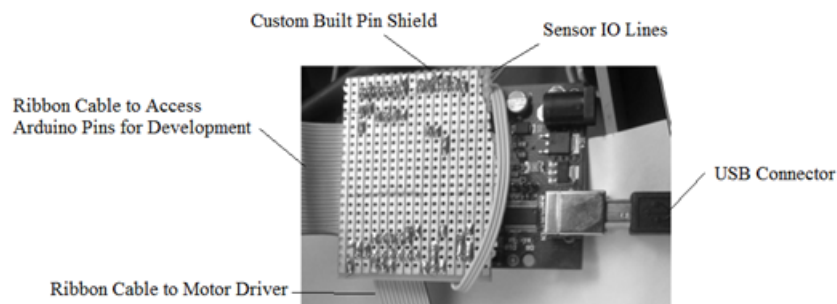
Figure 25: Arduino UNO Controller and Custom Built Pin Shield

The low level controller will communicate with the high level controller using a serial over USB or TTL connection. A 3 byte communication protocol has been proposed. The first byte signals the control type (B for brake, S for steer, O for off or error). The second byte indicates the value of the control signal (0-255 for brake force, 0 for full left and 255 for full right steering). The third byte is a CRC (cyclic redundancy check) byte to reduce the possibility of receiving a corrupt signal due to transmission errors. The communication protocol has been tested to be functional using a C++ windows program and will be used for development of the automatic safety system in the future.

For testing, a program was produced which communicates over the serial line using string commands. All sensor data is constantly uploaded to the serial line by the Arduino UNO. The code is listed in appendix E.

5.2.2 Discussion

The Arduino UNO is an ideal embedded controller for this application as it is very easy to program and intuitive to use. The USB connection proved to have compatibility issues with the EyeBot M6 because the Arduino uses a special driver designed for common operating systems such as Windows, and does not have native support for the Linux distribution used on the EyeBot M6. Testing data showed the sampling rate was not very high (approximately 300ms) but this is due to the overuse of strings over the serial line.

5.3 Electrical System and Emergency Switch

The electrical system was implemented using mostly arbitrary design decisions. The following sections explain the decisions made whilst implementing the electrical system throughout the project, which includes;

- A motor driver, used to electronically control direction and power of the steering motor
- An emergency switch which has 2 associated circuits for providing an "Off" signal to the brake servomotor and then cutting its power supply after a delay
- Fusing and wiring of all electrical interconnections

5.3.1 Motor Driver

A steering motor has been installed in the engine bay that rotates the steering column directly using a timing belt drive, previously commissioned by Nicholas Randell in 2009. This system takes advantage of the onboard power steering, whilst still allowing the driver to overpower the steering motor.

The motor driver was required to have an electronically controllable direction and speed, preferably using the Arduino's digital 5 volt pins for direction and a 5 volt PWM (pulse width modulation) pin for speed. After searching various electronics suppliers an arbitrary decision was made to use the VNH2SP30 full H-Bridge motor driver

(STMicroelectronics 2008), with a maximum continuous current rating of 30 Amps, as it met the design requirements. It is easily interfaced with the Arduino UNO, has 2 digital pins for direction, 1 pin for PWM and 1 analogue pin for current sensing. It is a small modular unit, easy to install into a project box and purchase over the internet. Current sensing is currently being performed by the controller, and will be used to limit the amount of power consumed by the motor and possibly sense if the human driver is resisting the steering motor rotation.

A software based PID control algorithm, used in conjunction with the steering sensor allows for positional control of the vehicle's turning angle. The PID still requires fine tuning, as the response is a bit jerky and may be optimised. There is also a change in steering resistance with speed of the vehicle, which may need to be taken into account into the PID control algorithm. The steering motor is not intended to be driven whilst the car is stationary as this draws excessive current, so a current limit is set in software. A future project may include installing a speed sensor to disable steering motor activation whilst not in motion.

It was desirable to have sensor feedback of the brake actuator. An investigation of the service manual (Bentley 2007) showed there is presently a brake pressure sensor in the vehicle. The line was spliced into, and a voltage of 0.58V to 2.96V measured according to brake actuation level. The limit of 2.96V was found by pressing the brake pedal to its absolute limit. Table 10 shows the wiring diagram of the brake pressure sensor, determined by testing the connections with a multimeter.

Brake Pressure Sensor Wiring Colours		
White	Black	Blue
Ground	5V Supply	0.58V to 2.96V Pressure Level

Table 10: Brake Pressure Sensor Wiring Diagram

5.3.2 Emergency switch and associated circuits

An emergency switch was required to give the driver complete control of the safety system by providing a method to cut power to the low level controller, steering motor, and brake servomotor. To deactivate the brake servomotor, a signal is required to reset it to an inactive position and then cut the power after several seconds.

The location of the emergency switch was required to be in an easily accessible and visible location for the driver. This led to the decision to have it placed next to the steering wheel, shown in Figure 26, which is an easily accessible location next to the right hand of the driver, in a similar location as the headlight switch of the vehicle.
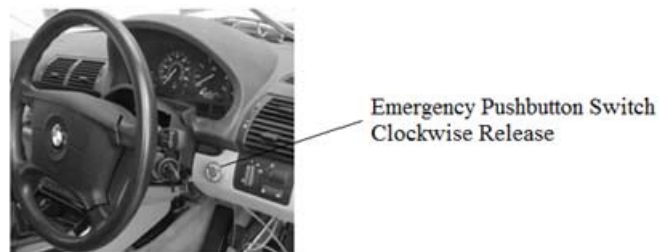
**Figure 26:** Emergency Switch Location

A DPST (double pole single throw) pushbutton emergency switch was chosen with a twist action release mechanism. Each pole of the DPST switch has a separate configuration; one is a N.C. (normally closed) and the other a N.O. (normally open) type switch. This was desired as the power to the Arduino UNO and motor driver can be cut through the N.C. pole and the brake servomotor reset action energised by the N.O. pole.

In order to reset the servomotor position and subsequently cut its power supply, two circuits were required, a signal generator and a power delay circuit. It was desired these both be adjustable, but stable and independent of the Arduino microcontroller. The emergency circuit functional block diagram is shown in Figure 27.
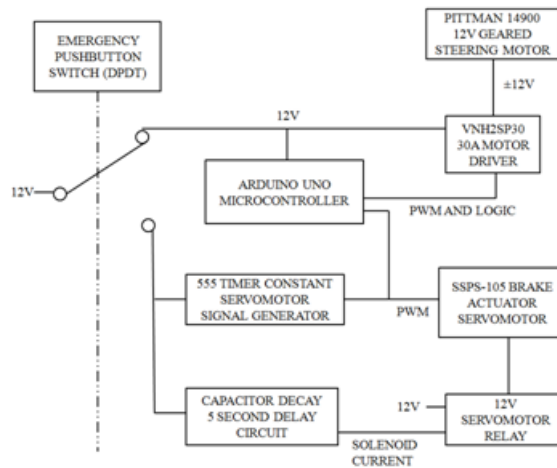
**Figure 27:** High level circuit functional block diagram

A signal generator, able to send out a 20ms PWM signal to control the servomotor was required to reset the position of the servomotor. Research was undertaken to find options to perform this task, and a choice was made to use a circuit based on the 555 timer (National Semiconductor 2006) integrated component in an astable configuration. The circuit design, shown in Figure 28, was sourced from a hobbyist website (Shenton RC Speedway 2011), prototyped and tested to be functional with the SSPS-105 servomotor. The servomotor angle is adjustable using a potentiometer on the circuit.
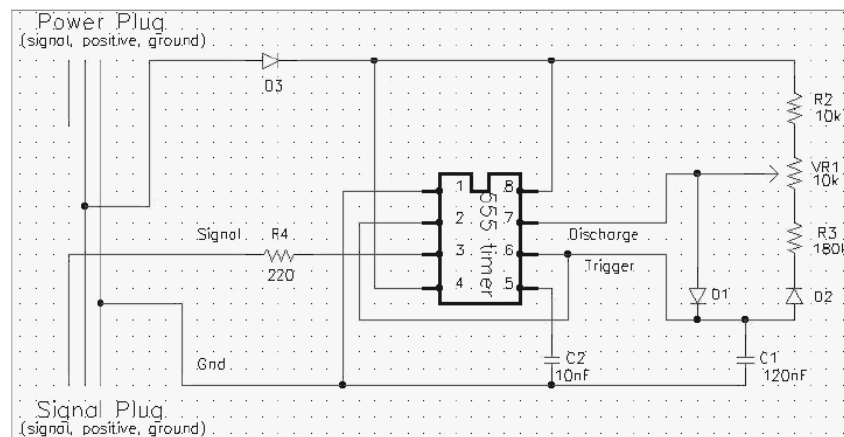
Figure 28: Servomotor PWM Signal Generator (Shenton RC Speedway 2011)

A power-off time delay circuit to disable a relay after several seconds was required. Research was conducted and a circuit found on a hobby website, shown in Figure 29, that uses the voltage decay of an electrolytic capacitor to energise a relay through a 2N2222 transistor (Phillips Semiconductors 1997) for approximately 2 seconds, before dissipating its charge (Bowden's Hobby Circuits 2011). This circuit was prototyped, the resistor and capacitor chosen to obtain a delay time of approximately 1 second and then implemented. The delay time may be adjusted by changing a capacitor or resistor.

49
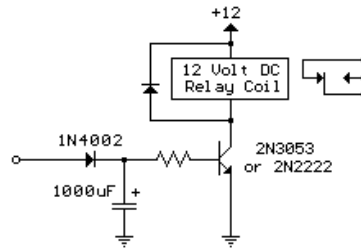
Figure 29: Power-Off Time Delay Circuit (Bowden's Hobby Circuits 2011)

5.3.3 Electrical Wiring

Electrical safety and short circuits were an important consideration during construction of the control box and wiring of the components. Fuses were used on all active lines to mitigate the risk of a short circuit or overloaded actuator.

The wire gauge was matched with the maximum current requirements of the steering motor, which is 26.4 Amps (Pittman 2005) and the VNH2SP30 motor driver, which is approximately 30A (STMicroelectronics 2008). 8 AWG wire was selected as it has a maximum current rating of 73Amps, giving a 62% buffer in the maximum current draw. A 30A inline blade fuse was used to protect the motor driver and steering motor, as the steering motor is susceptible to over current if driving the steering against full lock or idle wheels.

The SSPS-105 servomotor has a maximum current draw of 9Amps, so 8 AWG wire was more than sufficient. A 10Amp inline blade fuse was used to protect the servomotor and the event of a short circuit.

A 45Amp fuse was used on the ground line, as a master fuse for the whole box. The reason for placing it on the ground line is because it is the only common line shared by the controller, as there are three 12V input lines to the box; a constant 12V, 12V Arduino, servomotor and steering motor and 12V emergency lines.

Crimp connectors were used for the power lines and ribbon cables for the interconnections between the electronic components. The control box is shown in Figure 30, with the control signals to the motor driver using a ground alternating ribbon cable to reduce effects of noise on signal clarity. A ribbon cable can be used to access all the Arduino pins, shown in Figure 25.
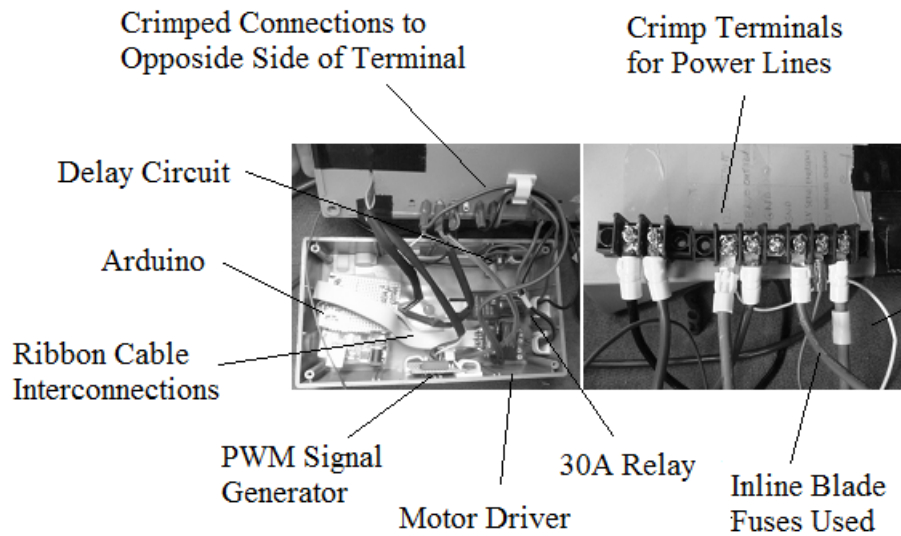
Figure 30: Low Level Controller Box

5.3.4 Safety Considerations

The electrical system has various safety considerations, a summary is listed below.

Someone may drive the car, unaware of the operations of the safety system and have an accident. The use of a large red emergency pushbutton for the emergency switch was chosen to enable intuitive disabling of the system by any user to mitigate this risk.

The Arduino might fail due to a short circuit or otherwise. This is the reason why separate circuitry has been used for the servomotor reset and power delay operations. These are analogue circuits and are integrated with the emergency switch, independent of the Arduino.

Short circuits are a considerable risk for the low level controller, which is why an effort has been made to use neat interconnections, crimped connections where possible and for final protection, the controller has been fused in various locations including a master fuse on the ground line.

6. Conclusions and Future Work

The project has been successful in implementing the required systems for control over the steering and braking of the BMW X5. The progress of this project should significantly contribute to the development of a practical automatic safety system. A method to implement a simple and reliable actuation system for control of a vehicle in a relatively unobtrusive manner and at a low cost has been demonstrated.
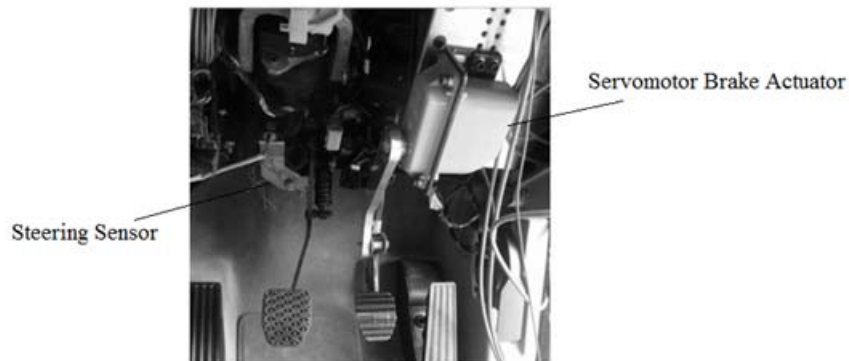
Figure 31: Implemented Servomotor Brake Actuator and Steering Sensor

Possible future improvement work for this project may include upgrading the steering motor or conversion to a stepper motor, using a different brake actuator or brake arm design for faster, less intrusive or a more accurate response. There is an oscillation issue with the servomotor and the accuracy of the brake pressure sensor may be improved.

The steering sensor may be improved for extra reliability, especially to prevent potential slip in the gear drive. A higher gear ratio on the steering sensor may be desirable to limit the rotation of the sensor to one revolution. The PID controller requires optimisation for smooth steering actuation and an analysis of the steering response depending on different vehicle speeds may be desirable.

Future potential projects using the vehicle's autonomous capabilities may include intelligent image recognition and control logic development, driver assistance systems for people with disabilities or limited motor function, alternative vehicle control mechanisms such as joystick or eye control or a driver training system.

Work in the area of intelligent vehicles with the BMW X5 may include innovative driver feedback systems such as a translucent windscreen display, colour based speedometer, audio feedback of proximity to other cars and the possibility of conversion to electric vehicle, hydrogen power or some other alternative fuel source. Extra sensory information may be desired, such as a sweeping laser, radar, speed or distance sensors.

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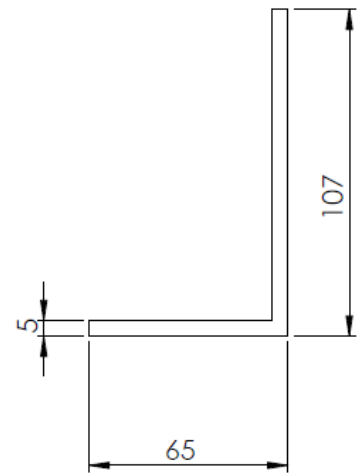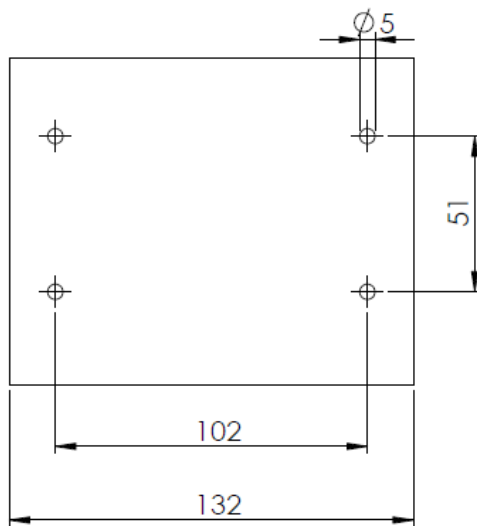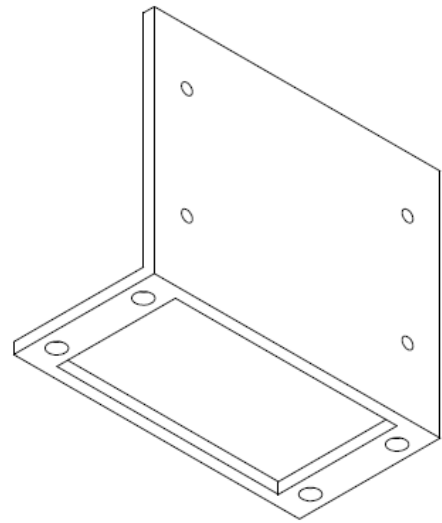WHO – see World Health Organisation

Appendices
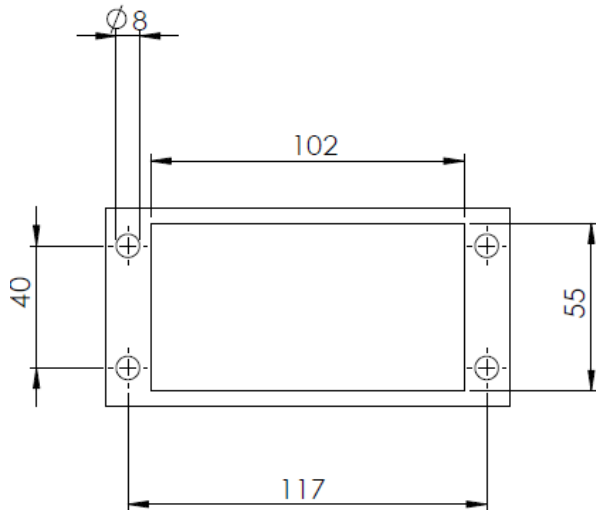

Appendix A – Brake Actuator Arm CAD
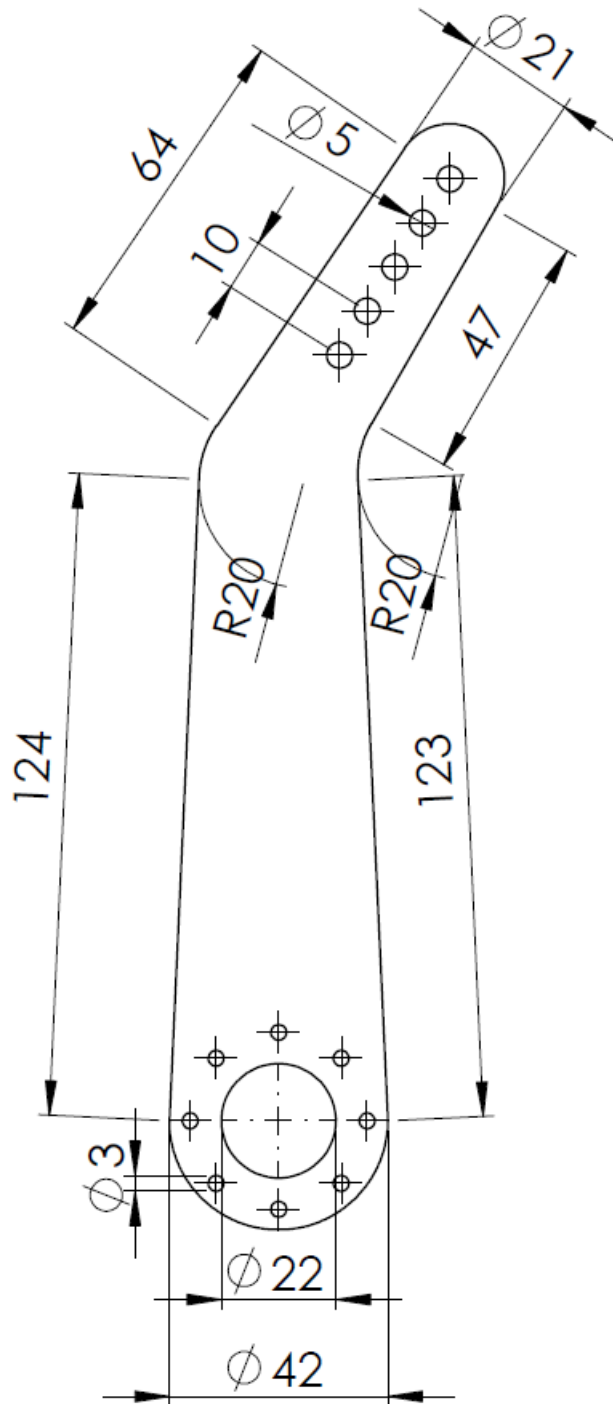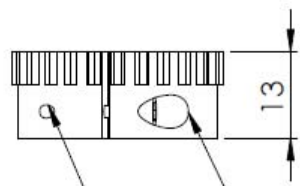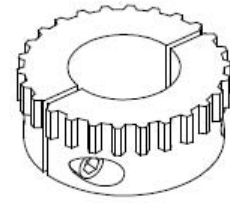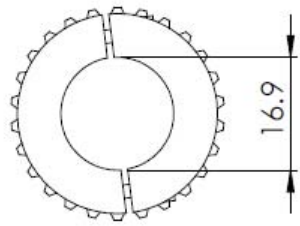

Note: all dimensions are in mm

Appendix B – Brake Actuator Bracket CAD

Note: all dimensions are in mm

Appendix C – Steering Sensor Split Cog CAD
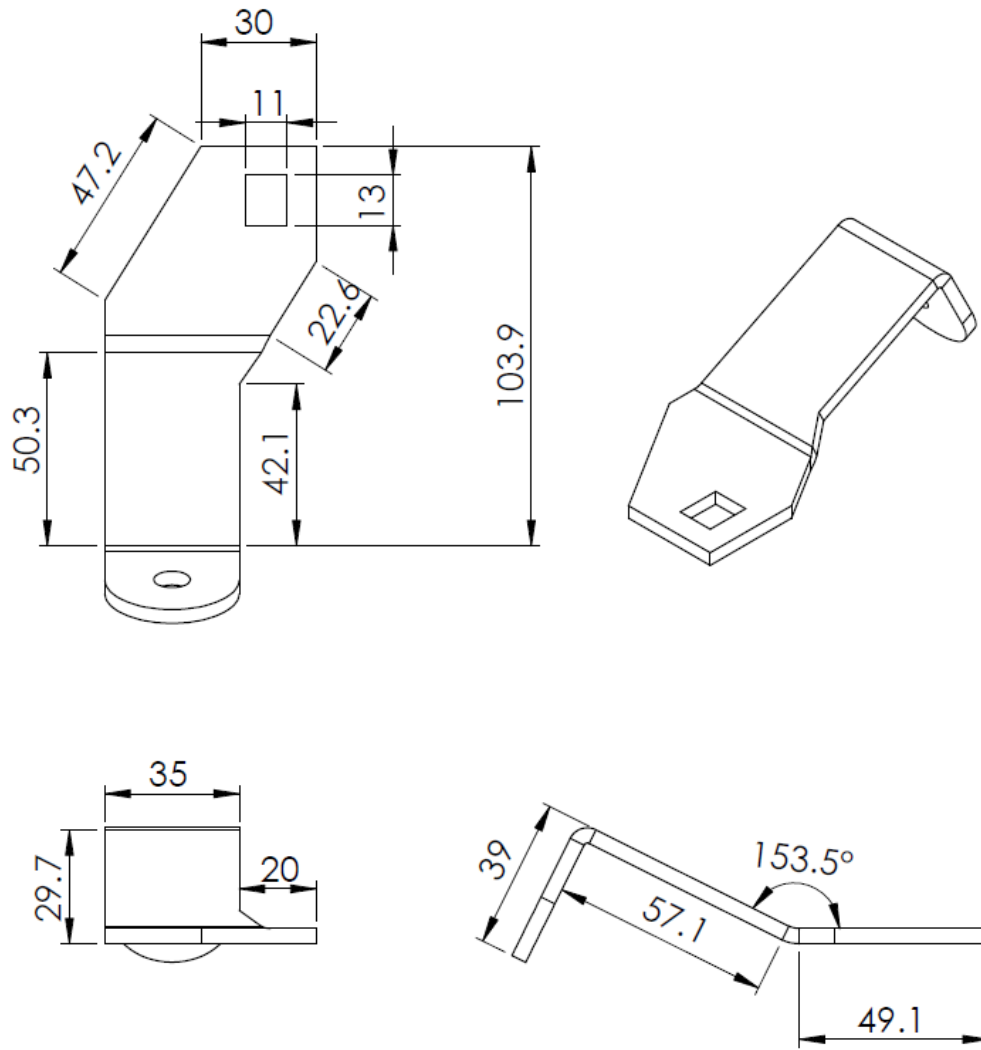

16.9

13

29.8

4mm Drilled out section
for Hex Bolt Head

2mm Threaded Hole

Note: all dimensions are in mm

Appendix D – Steering Sensor Sheet Metal Bracket CAD

Note: all dimensions are in mm

Appendix E – Arduino Test Code

```
#include <EEPROM.h>

#define SERIALINPUTLENGTH 3
#define SERIALINTERMINATOR 13
char inString[SERIALINPUTLENGTH+1];
String lastCommand;

int inCount;

#include <Servo.h>

const int SETPTCENTER = 2;
const int SERVOMIN = 1390;
const int SERVOMAX = 1320;
const int steerSensorPin = A0;
const int brakeSensorPin = A4;
const int motorCurrentSensorPin = A5;
const int steerSensorThreshold = 300;
const int servoPin = 6;
const int motorPwmPin = 3;
const int motorRightPin = 2;
const int motorLeftPin = 4;
const int maxLeftAngle = 500;

Servo myservo;

int steerSensor = 0;
int oldSteerSensor = steerSensor;
int setPt;
int desiredStAngle = 500;
int stAngle = 127;
int stTarget = -1;
int motorSpeed = 0;
double motorCurrent = 0;
int servoAngle = SERVOMIN;
int brakeSensor = 0;
boolean dontSteer = true;

int inValue = 500;
long lastTime = millis();

double KP =16;

double KI = 0.05;
double KD = 0.5;
int lastStError = 0;
int sumStError = 0;
int iMax = 100;
int iMin = 0;

void setup()
{
  Serial.begin(9600);
  myservo.attach(servoPin);
  pinMode(motorPwmPin, OUTPUT);
  pinMode(motorRightPin, OUTPUT);
  pinMode(motorLeftPin, OUTPUT);
  pinMode(servoPin, OUTPUT);
  pinMode(brakeSensorPin, INPUT);
  pinMode(steerSensorPin, INPUT);
  pinMode(motorCurrentSensorPin, INPUT);
  EEPROM.write(0, SETPTCENTER); //reset setPt to cnr
  setPt = EEPROM.read(0);
}

void loop()
{
//INPUT CHAR COMMAND - CONVERT TO INTEGER VALUE
  char c1 = Serial.read();
  if (c1 == 'S' || c1 == 'B') {
    inCount = 0;
    do {
      while (!Serial.available());          // wait for input
      inString[inCount] = Serial.read();     // get it
```

```
    if (inString [inCount] == '\n') break;
    } while (++inCount < SERIALINPUTLENGTH);
  inString[inCount] = 0;                 // null terminate the string
  inValue =atoi(inString);
  if (c1 == 'B') { servoAngle = map(inValue,0,255,SERVOMIN,SERVOMAX); dontSteer = true; lastTime = millis();}
  else if (c1 == 'S') {desiredStAngle = inValue; dontSteer = false; lastTime = millis();}
  lastCommand = c1;
  Serial.println();
  Serial.println();
  }
Serial.print(lastCommand);
Serial.print(inValue);
Serial.print("  ");

//STEERING SENSOR & COUNTER
  steerSensor = analogRead(steerSensorPin);
  if (steerSensor > (1020-steerSensorThreshold) && oldSteerSensor < steerSensorThreshold) {
    if (setPt >0) { EEPROM.write(0, setPt-1); }
  }
  if (steerSensor < steerSensorThreshold && oldSteerSensor > (1020-steerSensorThreshold)) {
    if (setPt <4) { EEPROM.write(0, setPt+1); }
  }
  oldSteerSensor = steerSensor;
  setPt = EEPROM.read(0);
  if (setPt == 0) {
    stAngle = steerSensor-maxLeftAngle;
  } else if (setPt >= 1 && setPt <= 4) {
    stAngle = steerSensor+(1020-maxLeftAngle)+(setPt-1)*1020;
  }
  if (stAngle < 0){ stAngle = 0; }
  if (stAngle > 4400){ stAngle = 4400; }
  stAngle = map(stAngle,0,4400,0,255);

//PID CONTROL
  int stTarget = desiredStAngle; //map(desiredStAngle, 0, 255, 0, 4400);
  int stError = stAngle - stTarget;
  int motorSpeed = KP * stError;
  motorSpeed += KD * (stError - lastStError);
  motorSpeed += KI * (sumStError);
  lastStError = stError;
  sumStError += stError;
  if(sumStError > iMax){ sumStError = iMax; }
  if(sumStError < iMin){ sumStError = iMin; }

//To cancel motor turning try brake command
if (dontSteer == true) {
  motorSpeed = 0;
}

//SET BRAKE AND MOTOR LEVELS
  if (motorSpeed > 0){
    Serial.print("  mot-1 ");
    digitalWrite(motorRightPin, LOW);
//   digitalWrite(motorLeftPin, LOW);
    digitalWrite(motorLeftPin, HIGH);
    if (motorSpeed > 255) { motorSpeed = 255; }  //max pwm speed
    analogWrite(motorPwmPin, motorSpeed);
  }
  if (motorSpeed < 0) {
    Serial.print("  mot+1 ");
    digitalWrite(motorRightPin, HIGH);
    //digitalWrite(motorRightPin, LOW);
    digitalWrite(motorLeftPin, LOW);
    motorSpeed = -1 * motorSpeed;  //correct the -ve
    if (motorSpeed > 255) { motorSpeed = 255; }  //max pwm speed
    analogWrite(motorPwmPin, motorSpeed);
  }
  if (motorSpeed == 0) {
    Serial.print("  mot00 ");
    digitalWrite(motorRightPin, LOW);
    digitalWrite(motorLeftPin, LOW);
    analogWrite(motorPwmPin, motorSpeed);
  }

  myservo.writeMicroseconds(servoAngle);
  brakeSensor = analogRead(brakeSensorPin);       //read brake sensor
  motorCurrent = analogRead(motorCurrentSensorPin); //0.13 V/A : 26.624 = 1A
```

```
motorCurrent = ( (motorCurrent / 1024)*5) / 0.13;

//PRINT STEERING ANGLE, STEERING TARGET AND SERVO ANGLE
Serial.print(" stSENS ");
Serial.print(steerSensor);
Serial.print(" stABSVAL ");
Serial.print(stAngle);
Serial.print(" stTARG ");
Serial.print(stTarget);
Serial.print(" PWM ");
Serial.print(motorSpeed);
Serial.print(" motorCURR ");
Serial.print(motorCurrent);
Serial.print(" Servo ");
Serial.print(servoAngle);
Serial.print(" Brake ");
Serial.print(brakeSensor);
Serial.print(" tTotal ");
Serial.print(millis());
Serial.print(" tLastCMD ");
Serial.println(millis() - lastTime);

  //delay(33);
}
```

B255 - Full Brake Command
Values are Brake Pressure Readings

Time	0	123	247	372	497	622	747	872	996	1121	1247	1373	1499	1625	1751	1877	2003	2128	2254	2379	2505	2631	2757	2884	3000
Test 1	117	115	111	197	249	262	266	229	230	233	274	232	273	258	272	275	240	252	239	233	236	273	280		
Test 2	114	115	115	184	220	229	231	247	265	276	239	243	235	237	269	338	286	283	274	253	246	244	286	288	
Test 3	115	116	113	163	201	251	223	223	225	228	229	231	270	270	270	275	292	248	275	235	234	236	243	277	280
Test 4	117	116	114	205	224	228	233	245	245	257	276	280	278	277	277	252	274	236	234	276					
Test 5	116	117	126	186	257	267	271	271	275	258	227	277	278	270	244	280	284	251	288	285	258				
Average	15.8	16	15.8	187	230.2	247.4	244.8	242.8	248	250.4	249	252.6	266.8	262.4	266.4	284	275.2	254	262	256.4	243.5	251	269.7	282.5	280