Drive-by-wire

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Synopsis

Drive-by-wire systems consist of sensors, computers, and actuators, which replace mechanical link or hydraulic controls in a motor vehicle resulting in a decrease in vehicle weight, improved handling, and facilitating the implementation of active safety systems. Elements of a drive-by-wire system are examined and the feasibility of implementing a road-legal (as per Australian Design Rules) system into a Lotus Elise is investigated. Research indicates that a drive-by-wire system cannot be implemented into the Lotus Elise whilst retaining road legality in Western Australia. However, the potential benefits of drive-by-wire systems warrants further research, particularly on the topics of system redundancy, system packaging, multiple actuator interaction, control system architecture, vehicle electrical systems, and force feedback mechanisms.

To further investigate the implications of by-wire safety systems, a design project was initiated to interface a collision avoidance vision system with the steering, brakes and throttle control of a vehicle. Performance requirements for various components were established, and preliminary system designs were considered. Components meeting the optimal requirements were considerably expensive and cheaper alternatives were investigated. An initial system design based on these alternative components is presented.

Letter of Transmission

150 Cook Avenue,

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28/05/2009

Professor David Smith,

Dean of the Faculty of Engineering, Computing and Mathematics

University of Western Australia

35 Stirling Highway

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Dear Professor Smith,

I am pleased to present this thesis, entitled "Drive-by-wire" as part of the requirement for the degree of Bachelor of Engineering.

Yours sincerely,

Amar Shah

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1 Introduction

The Australian Bureau of Statistics (2008) reported 1456 fatal crashes in 2006, with single vehicle, multiple vehicle, and pedestrians contributing to 47%, 37% and 15% of these fatalities respectively. The European Road Safety Charter (2001) aims to halve the number of fatalities due to road accidents by 2010 and the global automotive industry is continually striving to improve vehicle safety by implementing various passive and active safety features (ATSB 2008; NHTSA 2008; ETSC 2008). Drive-by-wire systems consist of sensors, computers and actuators, which replace mechanical or hydraulic link controls in a motor vehicle resulting in a decrease in vehicle weight, improved handling, and facilitating the implementation of active safety systems (Wilwert et al. 2007).

The University of Western Australia Renewable Energy Vehicle (REV) project aims to replace the petrol engine in a 2002 Lotus Elise with a high performance electric motor. In conjunction with the REV project, this project aims to study the feasibility of implementing road-legal (as per the Australian Design Rules) brake, steer, and throttle, by-wire systems in the Lotus Elise.

Modern farm machinery, industrial vehicles, trains and boats commonly feature by-wire systems (Bertoluzzo et al. 2004). However, the most illustrious application of by-wire systems can be found in modern aircraft. The F-16 jet fighter employed the first fly-by-wire system without mechanical back-up in 1974 (Askue 2003) and Airbus A320 utilised the first commercial fly-by-wire system in 1988 (Balas 2003). These systems are now found in most modern aircrafts and have been developed to become highly reliable systems (Askue 2003). Aircraft such as the Eurofighter Typhoon capitalize on the high performance control afforded by these systems by being achieving high levels of manoeuvrability despite being inherently unstable (Fielding 2000).

A review of this time proven technology serves as a basis for the development of drive-by-wire systems. A study of current brake, steer, and throttle technology is followed by a review of force feedback systems and control system architecture. The implications of the Australian Design Rules on implementing a drive-by-wire system are investigated next, concluding with a discussion of the overall research outcomes.

2 By-Wire Technology

2.1 Fly-by-wire

The most significant development in fly-by-wire technology was the "development of the failure survival technologies to enable a high-integrity system to be implemented economically with the required safety levels, reliability and availability" (Collinson 1999). Vehicles employing solely by-wire systems in safety critical applications such as braking and steering would require similar control system development to ensure the driver remains in control of the vehicle even if one or more parts of the control system fail. The initial development of fly-by-wire control systems employed mechanical fail-safe controls (Askue 2003), and this approach may also be used to initially develop drive-by-wire systems. However, to maximise the advantages of drive-by-wire systems, systems with multiple level redundancy can be used to ensure safe operation (Collinson 1999). Figure 1 shows one possible configuration for the control system data bus. Three levels of system redundancy ensure control is maintained under partial system failure.

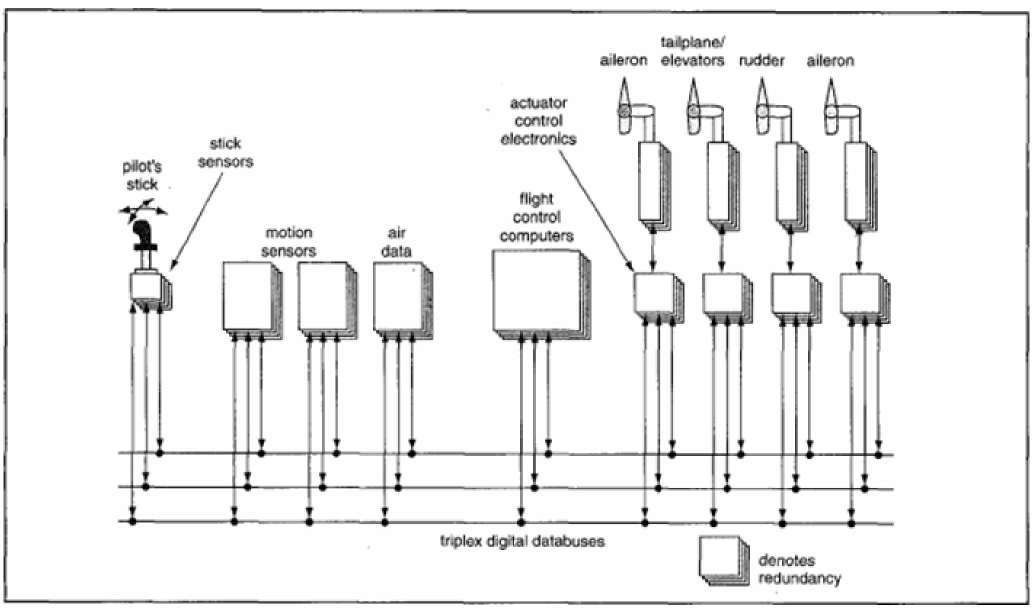

Figure 1: Flight control system bus configuration (Collinson 1999)

Figure 2 shows how a quadruplex actuation system utilises four independent actuators to collectively drive the control surfaces. The system detects a failure by comparing the output of each actuator with the output of the other three actuators. If significant differences are detected, the faulty actuator is bypassed leaving three correctly functioning actuators (Askue 2003; Briere 2001; Collinson 1999; Dennis 1990).

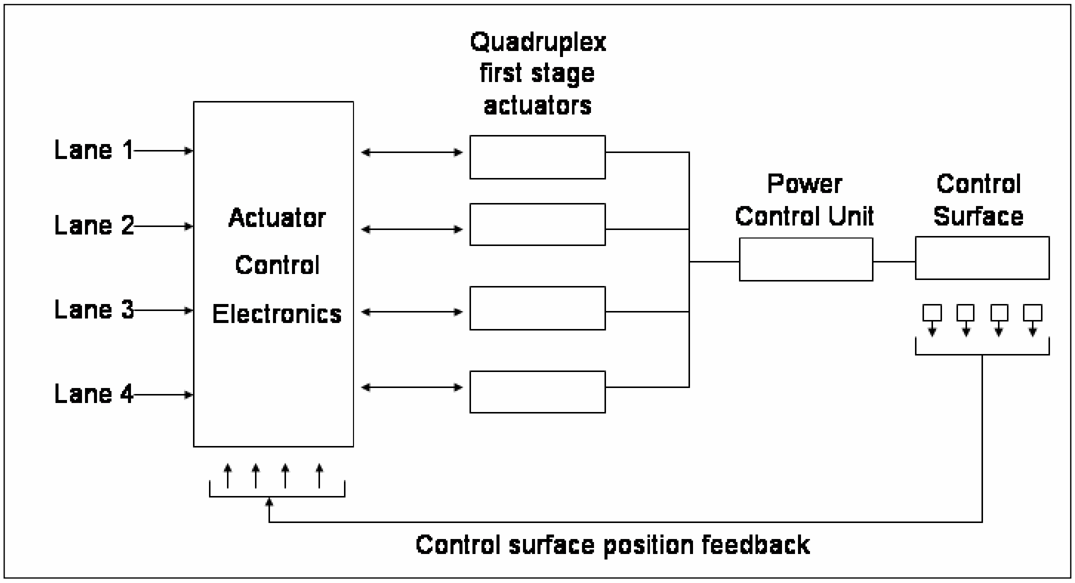

Figure 2: Quadruplex actuation system (Collinson 1999)

In order to implement a safe drive-by-wire system, multiple levels of redundancy such as those shown in Figure 1 and Figure 2 above are required. This would ensure that the driver retains full control of the vehicle under partial system failure. A review of current drive-by-wire technology is presented next.

2.2 Brake-by-wire

Automotive brakes provide the means to slow down or stop a vehicle, by using friction to convert the kinetic energy of a moving vehicle into heat. Whilst numerous braking systems are available on modern vehicles, passenger vehicles commonly employ hydraulic braking systems (Duffy et al. 2001).

The braking system for the Lotus Elise (Figure 3) is actuated when the driver pushes the brake pedal, which leverages a push rod into the tandem master cylinder. The master cylinder operates brake callipers using a front/rear split hydraulic circuit. The hydraulic force acts on pistons within the calliper housing, which in turn cause the brake pads to come in contact with the brake disks. The friction between the brake pads and the brake disks, transforms the kinetic energy of the vehicle into heat energy, and hence reduces the speed of, or stops, the vehicle (Massey 2001; Duffy et al. 2001). The handbrake is a secondary braking device that acts independently upon the rear callipers and is required as part of the Australian Design Rules (ADR 31/01 2005).

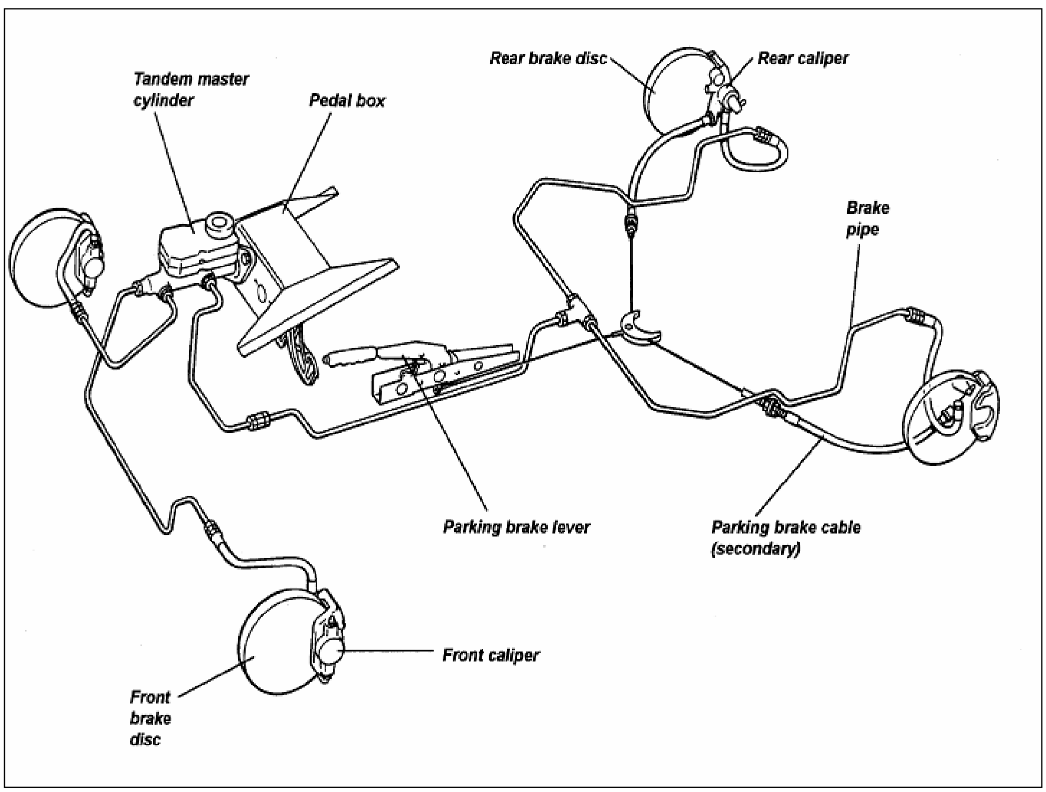

Figure 3: Lotus Elise Brake System Layout (Massey 2001)

Hydraulic brakes such as the ones found in the Lotus are commonly found in passenger vehicles. However, most modern vehicles also include a brake booster, which reduces the pedal force required to actuate the brakes, as well as safety systems such as anti-skid braking, and brake-force distributions (Duffy et al. 2001). Although electric braking systems are yet to be implemented on a production vehicle, various forms of 'hybrid' systems have been implemented on passenger vehicles (Wilwert et al. 2007).

In 2001 Mercedes Benz, in conjunction with Bosch, released the SL models of vehicles with an electro-hydraulic braking system called "Sensotronic Brake Control" (Kuhlgatz 2005). This system (Figure 4) uses a sensor to determine the driver's brake input; a microcomputer processes this signal, along with various other sensor signals, and, depending on the particular driving situation, calculates the optimum brake pressure for each wheel. As in conventional brake systems, the brake calliper is hydraulically actuated. A hydraulic back-up system becomes operational if the system detects a failure (Kuhlgatz 2005). This system partly resembles a brake-by-wire system, however, still requires various hydraulic components, and as such is not entirely an electronic braking system.

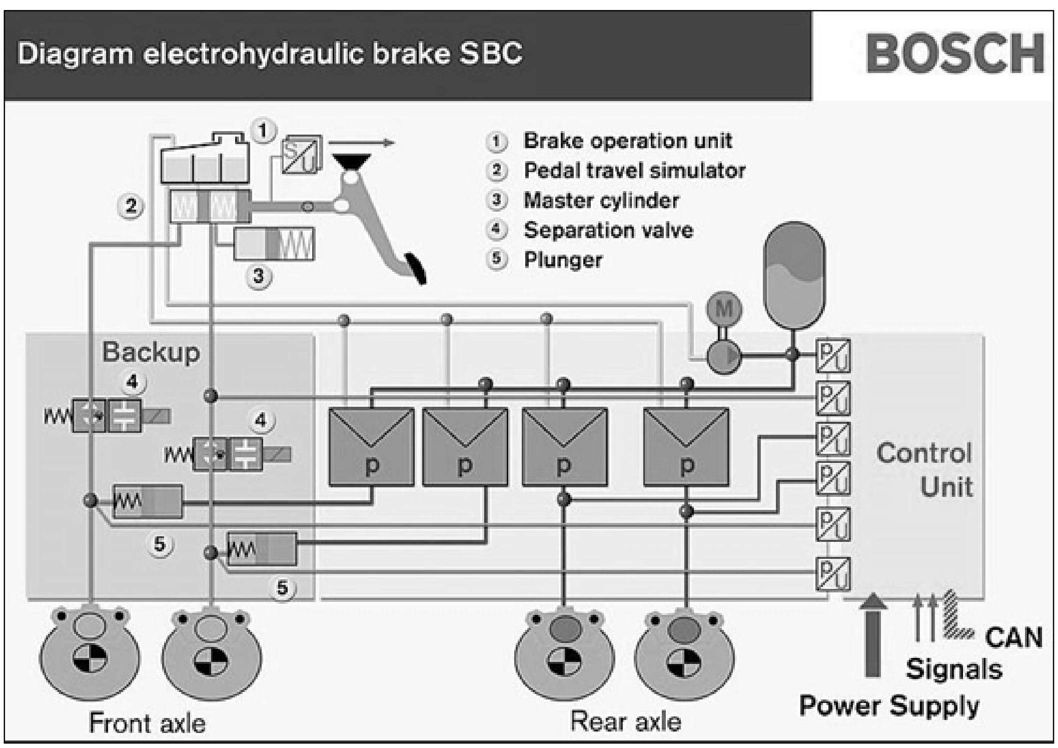

Figure 4: "Sensotronic" Brake Control (Kuhlgatz 2005)

Automotive suppliers such as Bosch, Continental and SiemensVDO are in the process of developing electro-mechanical brakes which use electric motors, instead of a hydraulic system, to force the brake pads against the brake discs (Kuhlgatz 2005; Continental 2006; TTTech 2006, SiemensVDO 2007). Proposed designs for the electro-mechanical brake callipers developed by Continental and SiemensVDO are shown in Figure 5 and Figure 6 respectively.

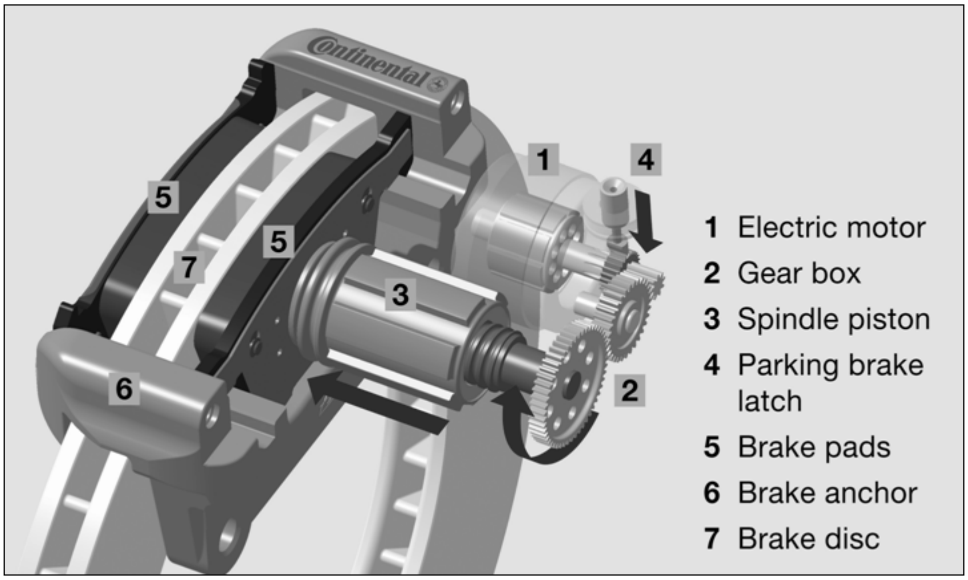

Figure 5: Continental Electro-mechanic Brake (Continental 2006)

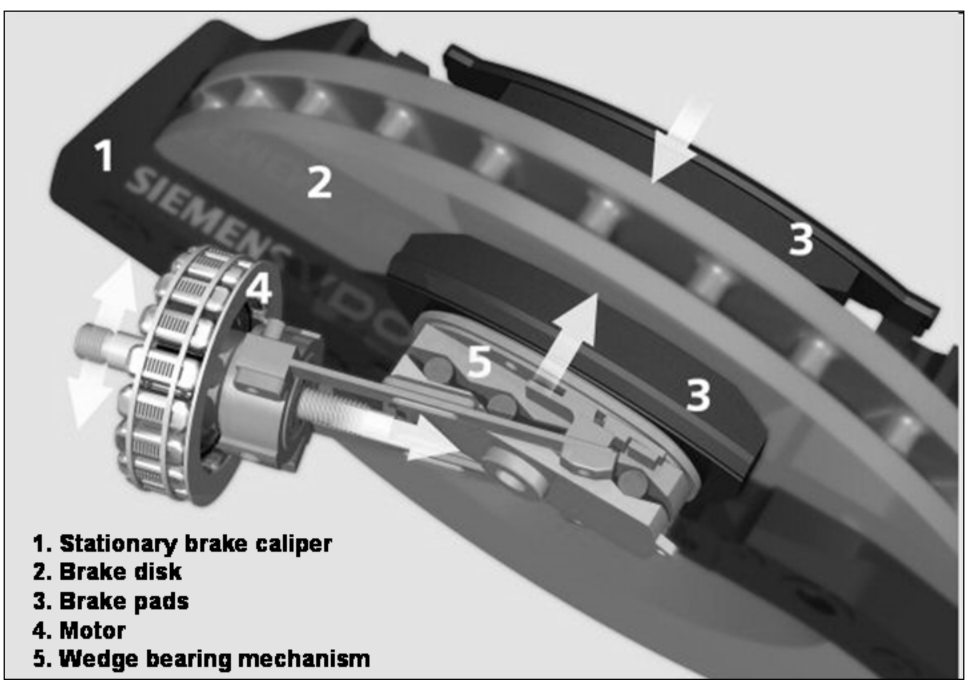

Figure 6: Electronic Wedge Brake (SiemensVDO 2007)

It is important to consider that neither of these systems incorporates multiple levels of redundancy, with both systems relying on a single actuator to apply braking force. Each system uses a similar gear and ball-screw assembly to convert rotational displacement into linear displacement (Continental 2006; SiemensVDO 2007).

The torque required to stop a modern vehicle necessitates the use of powerful motors and electronics, which are limited by the conventional 12V systems used in automobiles (Bingham 2001). However, SiemensVDO (2007) claims the Electronic Wedge Brake (Figure 6) "exploits the self-energizing effect of a brake wedge to generate the needed stopping force from the kinetic energy of the vehicle's motion", and hence operates with the existing 12V electrical systems found in vehicles today.

The implementation of a 42V automotive electrical system has been the topic of significant interest by the global automotive industry and a consortium has been formed to oversee its implementation (MIT Consortium on Advanced Automotive Electrical and Electronic Components and Systems 1999). Many automotive suppliers consider that a shift to this high voltage architecture is necessary to implement efficient and reliable by-wire systems (Bingham 2001). In any case, highly reliable control systems will be necessary to ensure the safe operation of these devices. To this extent, it is interesting to note that Mercedes Benz discontinued the use of the "Sensotronic" brake system due to the reliability issues with control system electronics and the ensuing low public confidence in the system (Meiners 2005).

An all-electric brake system may conceptually use an electric motor to provide the necessary torque to decelerate or stop a vehicle. However, the large motor torque requirements, reliable control systems, high power electronics, and reliable power sources required make the previously mentioned electro-mechanical systems a more feasible alternative in the near future (Bingham 2001). Further investigation is required to determine the optimal method for incorporating multiple levels of system redundancy into such systems.

2.3 Steer-by-wire

The steering system refers to the collection of components and linkages in a vehicle that allow the driver to dictate the path that the vehicle follows. The system provides precise control over the direction of the front wheels, moderates the correct amount of effort required to turn the front wheels, transmits feedback to the driver and absorbs intrusive shocks and bumps (Stockel 2001).

The Lotus Elise employs a rack-and-pinion steering system (Figure 7), without power assistance (Massey 2001). Steering wheel rotation is transferred to the upper column via a spline attachment. This rotation is transferred through the upper and lower columns to a pinion gear. The rotation of the pinion gear is transferred into a linear displacement of the rack, which in turn moves the track end rods. These rods are connected to the steering arms, and suspension up-rights allow the wheels to turn in the required direction (Stockel 2001).

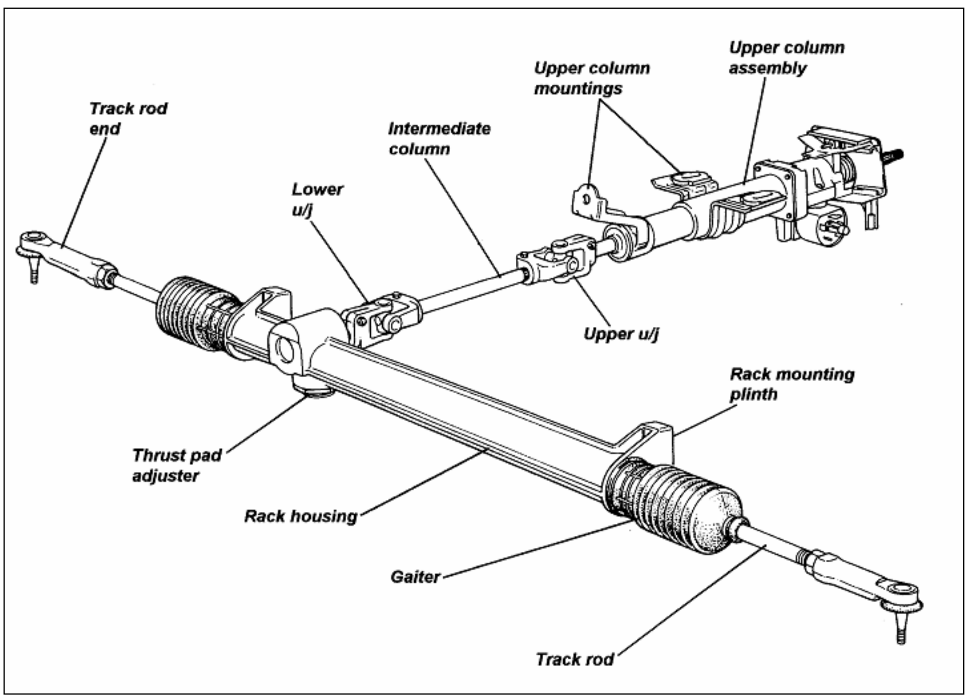

Figure 7: Lotus Elise steering components (Massey 2001)

In addition to the steering components shown in Figure 7, many modern vehicles also include power steering systems. These systems normally use an engine driven pump and hydraulic system to reduce the driver effort required to steer the vehicle (Stockel 2001).

Electro-hydraulic power steering systems use an electrically driven and electronically controlled power steering pump, and allow for varying levels of steering assistance, for example, speed-sensitive steering (Kokotovic et al. 1999). Improvements in automotive electronics technology have led to the implementation of electric power-assisted steering systems (Figure 8) which eliminate the need for hydraulic systems. These systems could potentially be modified for use in a purely by-wire system (Delphi 2005).

Figure 8: Electric power-assist steering (Delphi 2005)

Steer-by-wire systems are yet to be implemented into production vehicle. However, a large number of manufacturers have released by-wire concept vehicles. A concept by FHI (Tech-on 2005) is show in Figure 9. Similarly, GM uses a Visteon steer-by-wire system in the Chevy Sequel concept car (AutoSpectator 2006).

The Visteon system consists of front and rear electromechanical actuators, a torque feedback emulator for the steering wheel, and a distributed electronic control system. Redundant sensors, actuators, controllers and power provide a back-up structure that allows the system to be fault-tolerant. Control is provided by multiple electronic control units that are linked by a fault-tolerant FlexRay communication system (AutoSpectator 2006).

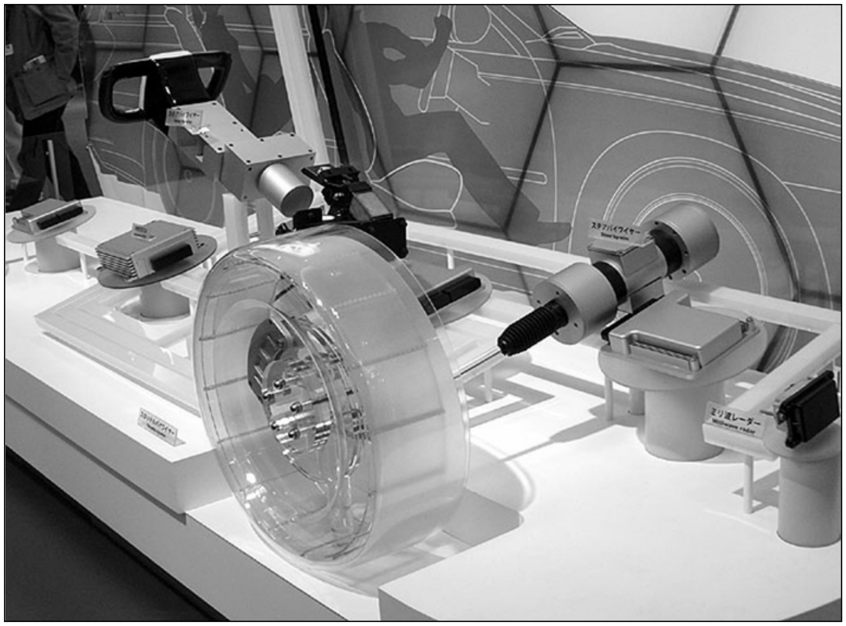

Figure 9: FHI Steer-by-wire Model (Tech-on 2005)

Steer-by-wire systems eliminate the mechanical linkage between the steering wheel and the front wheels, and replace them with electronic sensors, control systems, and actuators. In addition to reducing the mass of the vehicle, the risk of injury to the driver due to the steering column entering the cockpit in the event of a frontal crash is reduced. Variable steering ratios can be implemented dependant on driving conditions, and if each wheel is individually actuated, variable relative steering angles may improve vehicle dynamics and stability (Wilwert et al. 2007).

As with brake-by-wire, control system reliability is a high priority, and adequate redundancy is necessary to ensure that single component failures do not lead to the loss of control of a vehicle. Similar to brake-by-wire systems, the introduction of a 42V automotive electrical system may also be necessary to enable reliable and cost effective implementation of steering actuators (Wilwert et al. 2007).

2.4 Throttle-by-wire

Conventional automotive throttle systems transfer the driver input on the foot pedal via a cable to the throttle body. A rotary movement in the throttle body butterfly valve controls the air flow into the engine, and thus the engine response. Electronic throttle control replaces the mechanical link with electronic sensors, and an electrically actuated butterfly valve is controlled via the engine control module (Stockel 2001).

Unlike brake and steer by-wire systems, throttle-by-wire systems are already found in many modern cars, with Chevrolet introducing the first production throttle by wire system in the Corvette in 1980 (Wilwert 2007). Figure 10 below shows the various components of a typical electronic throttle control system.

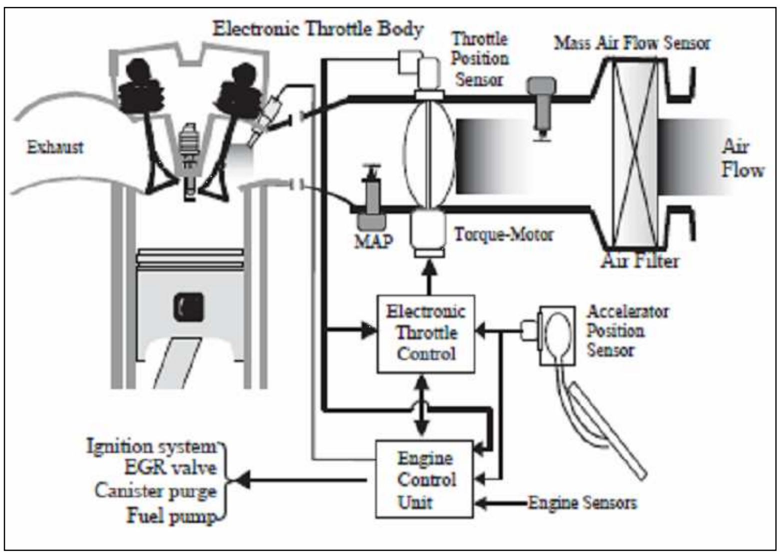

Figure 10: Electronic Throttle Control (Conaster et al. 2002)

A simple version of a throttle-by-wire system is used in the REV Hyundai Getz project (Figure 11); the throttle pedal position is measured by a potentiometer, which sends a voltage signal to the motor controller, which in turn drives the motor. A similar system may also be used in the Lotus. However, this system does not incorporate multiple levels of system redundancy.

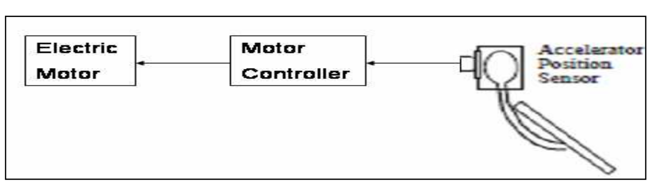

Figure 11: Electronic throttle control

2.5 Control system and communication architecture

A significant time delay between the application of a control input and the execution of the required action, for example, steering and braking, can have significant safety implications. As such, the performance of control systems implemented for the by-wire control of a vehicle can be considered time-critical.

Current automotive digital communication architecture is based on Controller Area Network (CAN) technology (Cena 2005). Arguably, this technology may not be adequate for the demands of by-wire systems, and technologies such as Time-triggered CAN (TTCAN), Byteflight, and FlexRay may be more suitable (Cena 2005).

CAN was developed by Bosch and was first deployed in automotive applications in 1986. The communication in the CAN network is event triggered and peak loads may occur when the transmission of several messages is requested at the same time. CAN's non-destructive arbitration mechanism guarantees the sequential transmission of all messages according to their identifier priority, however message latency may occur. TTCAN was introduced as an extension to the well known CAN protocol. It introduces time triggered communication and a system-wide global network time with high precision (Bosch 2008).

FlexRay is a Time Division Multiple Access (TDMA) protocol developed by a consortium of automotive companies to meet the drive-by-wire requirements of determinism, fault tolerance and reliability. With TDMA the nodes of a network engage the bus in fixed time instants and occupy it for fixed time intervals. In this way the protocol exhibits a deterministic time behaviour that eliminates the collisions among the messages and the consequential delays in their transmission (Temple 2004).

The Byteflight protocol was developed by BMW for safety-critical applications in automotive vehicles and exhibits the following features; high data integrity, collision-free bus access, message oriented addressing via identifiers, guaranteed latency high-priority messages, high flexibility, easy system extension, dynamic use of bandwidth and low system cost (Byteflight 2009).

Further research is required to determine the most suitable protocol for drive-by-wire systems.

2.6 Force Feedback

The mechanical linkages in steering and braking systems provide a means for the driver to "feel" reactive forces such as steering torque and brake pressure. Without the traditional mechanical steering link, the loss of tactile feedback often results in a degradation of control via over or under steer, thus compromising safety (LeRoy 2007).

To provide this "feel", by-wire systems employ force-feedback systems such as actuators connected to the steering wheel and brake pedal (Gualino 2006). An example of a steer-by-wire system architecture incorporating redundancy and feedback is shown in Figure 12.

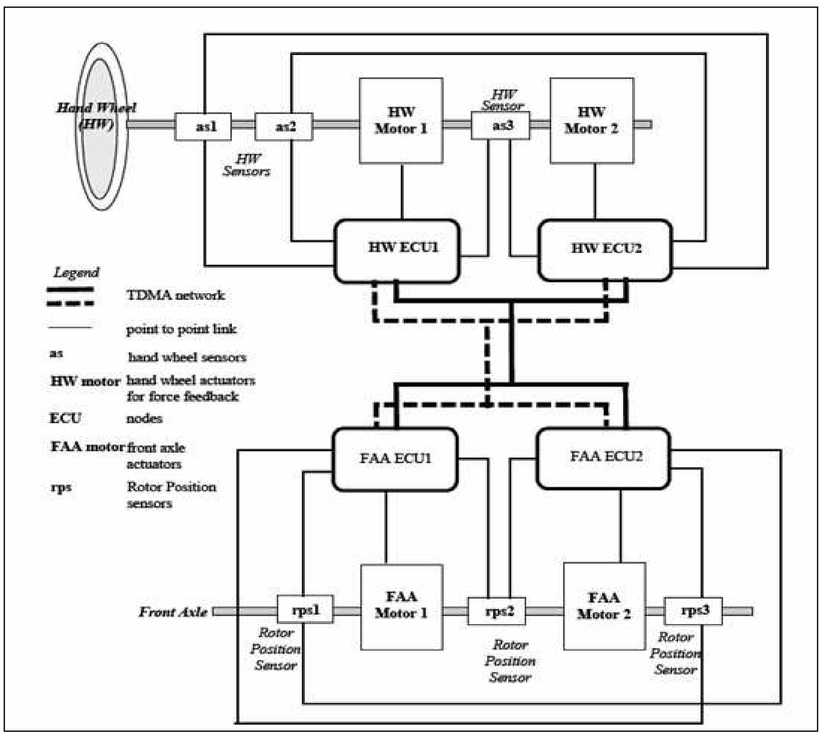

Figure 12: Steer-by-wire system architecture (Wilwert et al. 2007)

Gualino (2006) concludes that although the results gained using optimised torque feedback architecture (Figure 13 and Equation 1) suitable for a steer-by-wire vehicle were promising, there is "still much work to do to allow the mass production of such a system".

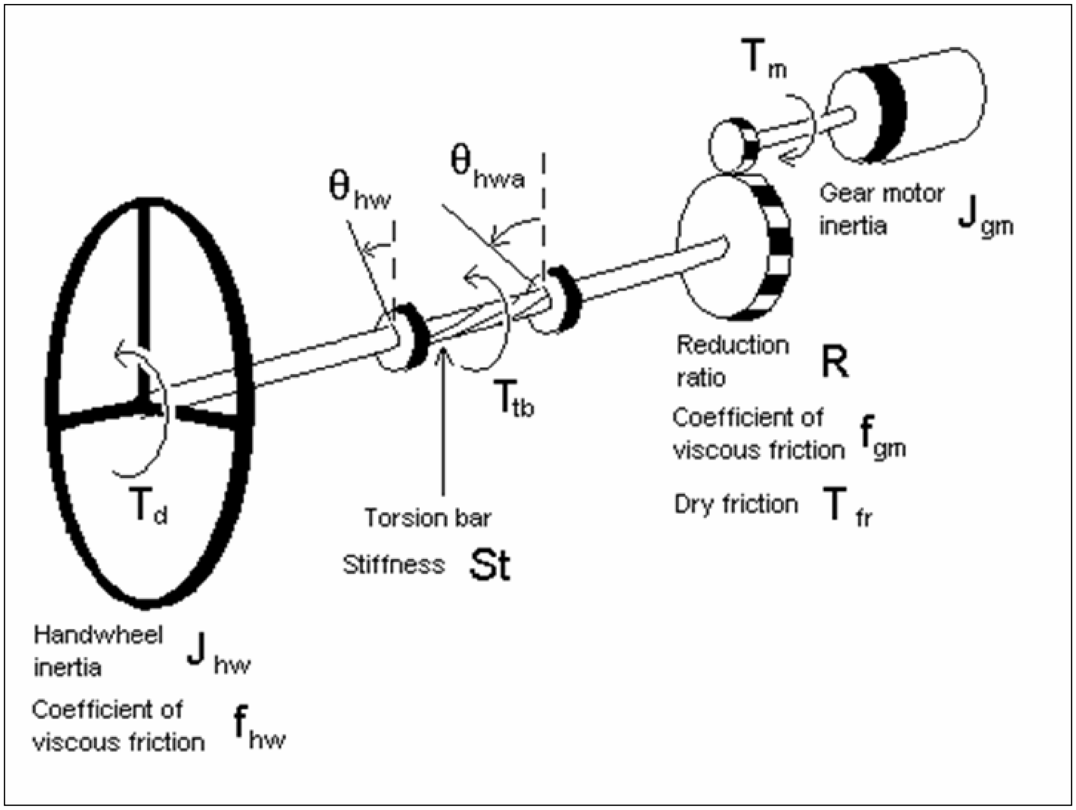

Figure 13: Steering Feedback Model (Gaulino 2006)

$$
\begin{aligned}
\dot{q} &= \overline{\theta} - \overline{\theta}_{ref} \\
T_m &= J_{gm} R \Bigg\{ -\frac{F_{fr}}{J_{gm} R} \tanh\left(n\,\dot{\theta}_{hwa}\right) \\
&\quad + \left(\frac{f_{hw}}{J_{hw}} - \frac{f_{gm}}{J_{gm}}\right)\dot{\theta}_{hwa} - \frac{T_d}{J_{hw}} \\
&\quad + S_t \left(\frac{1}{J_{hw}} + \frac{1}{J_{gm} R^2}\right)\overline{\theta} \\
&\quad + \frac{f_{hw}}{J_{hw}}\dot{\overline{\theta}} - 2\xi w_c \overline{\theta} - w_c^2 q \Bigg\}
\end{aligned}
$$

Equation 1: Steering feedback control law (Gaulino 2006)

Further research is required to establish the optimal feedback mechanism for steering and braking systems before these systems can be implemented safely into passenger vehicles.

3 Australian Design Rules

All modifications made to the Lotus Elise must comply with relevant Australian Design Rules. The braking system is covered by 'Australian Design Rule 31/01 – Brake Systems for Passenger Cars' and the steering system is covered by 'Australian Design Rule 42/04 – General Safety Requirements' (Australian Design Rules 2008). These regulations are based on the transport division regulations of the United Nations Economic Commission for Europe (UNECE) in particular Regulation 13 for brake systems and Regulation 79 for steering systems (UNECE 2008).

The implementation of a brake-by-wire system will be affected by the following regulations in particular:

- "The service braking system must make it possible to control the movement of the vehicle and to halt it safely, speedily and effectively, whatever its speed and load, on any up or down gradient. It must be possible to graduate this braking action. The driver must be able to achieve this braking action from his driving seat without removing his hands from the steering control." (ADR 31/01- Section 5.1.2.1 2005)

- "The secondary braking system must make it possible by application of the service brake control to halt the vehicle within a reasonable distance in the event of failure of the service braking system. It must be possible to graduate this braking action. The driver must be able to obtain this braking action from his driving seat without removing his hands from the steering control. For the purposes of these provisions it is assumed that not more than one failure of the service braking system can occur at one time." (ADR 31/01- Section 5.1.2.2 2005)

- "With the parking brake released, the service braking system shall be able to generate a static total braking force at least equivalent to that produced during the Type-0 test, even when the ignition/start switch has been switched off and/or the key has been removed. It should be understood that sufficient energy is available in the energy transmission of the service braking system. (ADR 31/01- Section 5.2.20.1 2005)

The implementation of a steer-by-wire system requires the removal of the mechanical linkages between the steering wheel and the road wheels. To allow for such changes, the UNECE regulations have been amended accordingly.

"Advancing technology, coupled with the wish to improve occupant safety by elimination of the mechanical steering column, and the production advantages associated with easier transfer of the steering control between left and right hand drive vehicles, has led to a review of the traditional approach and the Regulation is now amended to take account of the new technologies. Accordingly it will now be possible to have steering systems in which there is not any positive mechanical connection between the steering control and the road wheels." (UNECE Regulation 79 2005)

The following ADR and UNECE regulations apply to steering systems in particular:

- "In the case where the braking system of the vehicle shares the same energy supply as the steering system and there is a failure in the energy supply, the steering system shall have priority" (UNECE R 79- Section 5.3.1.5 2005)

- "The reaction of "The System" shall, at the discretion of the type approval authority, be checked under the influence of a failure in any individual unit by applying corresponding output signals to electrical units or mechanical elements in order to simulate the effects of internal faults within the unit." (UNECE R 79-Annex 6, Section 4.1.2 2005)

- The regulations concerning the implementation of electronic control systems for steering and braking have the common aspect of ensuring that the driver retains the ability to control the vehicle, within defined performance standards, even under partial system failure (ADR 2005; UNECE 2005).

- "A component of the steering system of a motor vehicle that is essential for effective steering of the vehicle must be built to transmit energy by mechanical means only." (WA Vehicle Standards Regulation 21 2002)

4 Results and Discussion

This section presents a discussion on the feasibility of implementing a drive-by-wire system into the Lotus Elise, and a general discussion on the implications of the information presented in the preceding sections 2 and 3.

4.1 Australian Design Rules

The current West Australian legislation for vehicle standards requires steering components to "transmit energy by mechanical means only" (WA Vehicle Standards Regulation 21 2002). As such, a vehicle with a steer-by-wire system cannot be road-registered in Western Australia.

It is noteworthy that the UNECE regulations have been amended to specifically allow for steer-by-wire systems. It is plausible that the WA legislation will be amended to allow for steer-by-wire systems in the near future as the WA Vehicle Standards are based on ADR which are based on UNECE regulations.

Based on the requirement that the implementation of by-wire systems in the Lotus was to adhere to local Vehicle Standard legislations, it is not feasible to implement a steer-by-wire system into the Lotus Elise. However, the potential benefits of a drive-by-wire system and the high probability that a change in legislations will allow for the implementation of such systems in the near future, warrants further research and discussion on the topic.

The requirement that "the driver retains the ability to control the vehicle, within defined performance standards, even under partial system failure" (ADR 2005; UNECE 2005) implies that multiple level system redundancy is required to allow for the normal operation of the vehicle even though one or more components fail.

4.2 System Redundancy

The fly-by-wire system design discussed in section 2.1 indicated the necessity of implementing redundancy into by-wire systems. A basic non-exhaustive Failure Modes and Effects Analysis (FMEA) is presented in Appendix A. The purpose of the FMEA is to provide a general overview of the effect of having redundancy built into drive- by-wire system. It is not an exhaustive list of every possible failure mode for a drive-by-wire system.

From the consequence severity columns of the FMEA, it is clearly evident that system redundancy is crucial in implementing a safe and reliable drive-by-wire system. In particular, the consequence of failure of a control, brake or steering system component can be disastrous and it is therefore essential for redundancy to be built into these systems.

4.3 System Packaging

The implementation of system redundancy generates additional complexity. Fly-by-wire systems utilise multiple sensors, actuators, control system components and processors to implement system redundancy. To achieve a similar level of redundancy in drive-by-wire systems, additional components have to be installed within the stringent space constraints in a vehicle.

System packaging strategies have to be investigated to ensure that additional components do not adversely affect the overall dynamics of the vehicle. As such, the implementation of a drive-by-wire system may benefit from a dedicated drive-by-wire concept front end engineering design (FEED) review as opposed to the modification of a conventional vehicle to accept a drive-by-wire system

4.4 Multiple Actuators

Methods by which multiple actuators interact under normal operational and partial failure modes have to be investigated. In addition to the packaging constraints discussed in section 4.3 above, a failure mode strategy is required for each sub-system to determine the way each actuator contributes to the overall actuation application.

Two brief overviews of possible strategies are presented below to demonstrate the type of options available;

- One actuator provides all the necessary force under normal operation. The system switches to a secondary actuator if a failure is detected.
- Multiple actuators collectively provide the necessary force under normal operation. The system monitors the total force output and increases or decreases individual actuator output if a failure is detected.

There may be many other strategic options, and further investigation is required into which strategy permits the most reliable and robust control for each particular application. The optimal packaging of the system, as discussed in section 4.3 above, is also dependant on the strategy selected and the physical implications of implementing each strategy requires consideration.

It is interesting to note that both the Continental and SiemensVDO brake-by-wire systems presented in section 2.2 are dependant on single actuators. As such, these components cannot be implemented into a vehicle without modification. The challenge of packaging additional actuators to provide component redundancy also extends to these systems.

4.5 Vehicle Electrical Systems

To maintain the weight saving advantage of drive-by-wire systems, the mass of all additional components should be lower than the traditional system components that they replace. The multiple actuators required in drive-by-wire systems may be particularly susceptible to a large increase in the weight of vehicle.

Actuators that are capable of producing the required power whilst functioning on the traditional 12V systems in vehicles are physically larger, and heavier, than those that are capable of producing similar power whilst functioning on a higher voltage system The implementation of a drive-by-wire system on an electric vehicle such as the Lotus may benefit from using a higher voltage source than the traditional 12V system. This also has the added benefit of reducing the current requirements by the by-wire system, and improving the reliability of the components used.

Further research is required to determine the optimal operating voltage for the electrical systems in an electric vehicle and the effect that this has on the components required for a by-wire system. The implementation of a standard 42V system as discussed in section 2.3 may also facilitate the development of suitable components within the automotive industry.

4.6 Multiple Processors and Communication Architecture

The implementation of redundancy through the use of multiple processors requires further research into the communication architecture used and overall control system design. As with system packaging, the control system design may benefit from a dedicated drive-by-wire concept front end engineering design (FEED).

Current automotive communication systems use CAN technology that may not be suitable for time critical communication such as that required in a by-wire system. Further investigation is required to determine the type of communication system that is most suited to by-wire systems with multiple redundancy layers, including systems such as TTCAN, Byteflight and FlexRay discussed in section 2.5.

The implementation of a drive-by-wire system in the Lotus benefits from the lack of existing electronic driving aids in the Lotus; the brakes, steering and throttle are all direct acting, without systems such as ABS, traction control and stability control. This implies that the existing control system does not monitor the performance of the brakes and steering. As such, the control system for the drive-by-wire system can run independently of the existing control system. The installation of an electric motor to provide drive in the Lotus also implies that a drive-by-wire system control system may be integrated into the motor controller. Further research is required to investigate the feasibility of such a system, and to determine the optimal communications architecture and overall system design.

4.7 Force Feedback

The replacement of mechanical and hydraulic linkages in the steering and brake systems of a vehicle with by-wire systems requires the application of force feedback systems to allow the driver to receive tactile feedback based on the performance of these particular systems. The direct acting brakes and steering in the Lotus provides direct feedback to the driver. Such feedback is important in high performance driving and the replication of this feedback in a drive-by-wire system is essential.

The implementation of a motor to generate steering feedback based on the angle of the wheels and the instantaneous current requirement for the steering actuator is a possible solution to provide steering feedback. Similarly, brake pedal feedback may be replicated by monitoring the current requirement for the brake actuators and applying feedback via an actuator at the brake pedal, based on the measured current requirement. Steering and braking “feel” is dependant on the driver and is therefore subjective in nature. An objective method to assess the performance of steering feedback systems in relation to traditional steering and brake “feel” is required to determine the optimal solution for the application of force feedback.

5 Model Development

The research above indicates that by-wire systems are highly complex and the implementation of a safe and road legal by-wire system would require a thorough understanding of the various components within the system. It was also evident that the Western Australian road regulations prevent the implementation of a steer-by-wire system into a road legal vehicle. However, the potential safety benefits of by-wire systems warrants further examination of the topic.

5.1 Introduction

The Centre for Intelligent Information Processing Systems (CIIPS) at the School of Electrical, Electronic and Computer Engineering, University of Western Australia, is currently involved in the development of vision-based driver assistance systems such as lane recognition, vehicle detection and tracking for collision avoidance, and brake assistance for collision mitigation (CIIPS 2009). The addition of a drive-by-wire system in a vehicle, steering and brake by-wire in particular, would allow the vision based system to control the vehicle as required.

The aim of this project was to design and implement a system to electronically control the application of steering, brakes, and throttle, in a 2001 BMW X5. The project's primary focus was on the implementation of the actuation systems i.e. steering, brakes, and throttle actuation (Figure 14).

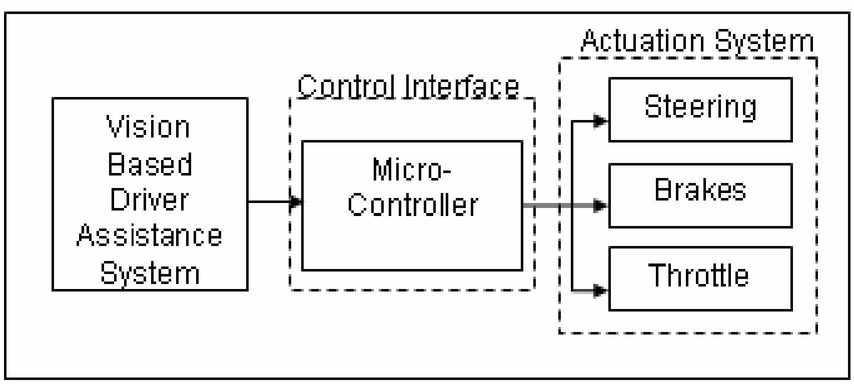

Figure 14: System Overview

5.2 Preliminary Design Requirements

The drive-by-wire system was designed to be implemented into a 2001 BMW X5 (Figure 15).

Figure 15: 2001 BMW X5

The design requirements were such that minimal modifications were made to the existing vehicle, in order to allow the vehicle to operate as per normal when the system is not in use. When in use, the system is required to disengage immediately if a user input is detected, or an emergency safety switch is engaged.

An overview of possible solutions including previously implemented solutions, and the initial design proposal is presented next.

5.3 Steering

The by-wire steering system can be implemented in a variety of ways. A non-exhaustive range of options include using an actuator to turn the steering wheel, drive the steering shaft, or actuate the steering arms.

5.3.1 Previous Solutions

Previously implemented solutions for similar tasks include:

- VEHICO GmbH (2008): Motor drive and steering gear attachment (Figure 16)

Figure 16: VEHICO Steering

- Stanford University DARPA challenge Volkswagen Touareg (Sebastian et al. 2006): Steering column mounted chain and sprocket drive.

- Anthony Best Dynamics (2007): Steering spline mounted direct drive motor (Figure 17)

Figure 17: ABD Steering (2007)

5.3.2 Initial Design Consideration

The area around the steering wheel in the X5 is shown in Figure 18 below. Initial considerations of a system similar to the VEHICO system (Figure 16) were dismissed due to the lack of space above the steering wheel, and difficulty in mounting the motor without obstructing the driver's view.

Figure 18: BMW X5 Steering Wheel

Mounting a sprocket onto the steering column, away from the drivers view, was also considered. However, this would require major modifications to the steering column. Furthermore, the packaging of the steering column in the X5 is such that there is not enough space within the driver's foot well to install a motor, sprocket and chain drive, without obstructing the driver's leg movements, and as such this option was dismissed.

The next option considered was to mount a motor under the steering column, and drive a sprocket which is attached to the steering wheel. Although this solution is not optimal (the motor and sprocket are in plain view of the driver), it is the solution that requires the least modification to the existing steering system. Furthermore, it allows for easy access for system installation or for future modifications.

The initial steering system design (Figure 21 in Section 5.4.2 below) is as follows: a sprocket attached to the steering wheel (which has an existing attachment to the steering shaft spline) is driven using a chain and a smaller sprocket, which is actuated by a motor mounted under the steering column. The optimal way to mount the sprocket, motor and associated components will require further consideration.

5.4 Braking

The braking system design should allow for the normal operation of the vehicle. As for the steering system, the brake actuator would be placed inside the cabin to avoid any major modifications to the braking system in the engine bay.

5.4.1 Previous Solutions

Previously implemented solutions for similar tasks include:

- Anthony Best Dynamics (2007); Braking Robot

Figure 19: ABD Braking Robot (2007)

- Golem Group DARPA entry (2006); Direct brake actuation through firewall

Figure 20: Brake Actuator (Golem 2006)

5.4.2 Initial Design Consideration

The normal operation of the braking system, whilst the by-wire system is not operational, is the major constraint in the placement of the braking actuator. Furthermore, to ensure occupant and pedestrian safety, it is required that the brake pedal can be further depressed whilst the system is operational.

Placement of a linear actuator under the steering column, acting directly onto the brake pedal was considered initially. However, to obtain the correct actuation angle, the actuator would have to be placed such that it would interfere with the ability to operate the vehicle under normal conditions.

To overcome this issue, the actuator could be placed in between the firewall and the brake pedal. An initial consideration of linear actuator dimensions highlighted the unlikelihood of placing an actuator within the space available behind the brake pedal.

This led to the concept of placing a linear actuator under the seat, and using a wire cable to actuate the brake pedal. This would not interfere with the normal operation of the vehicle, and also had the added benefit of mounting the actuator out-of-view of the vehicle's occupants. The cable can be routed along the floor, under the carpet, to minimise the risk of injury to the driver.

An initial rendering of the steering and brake system is shown in Figure 21 below.

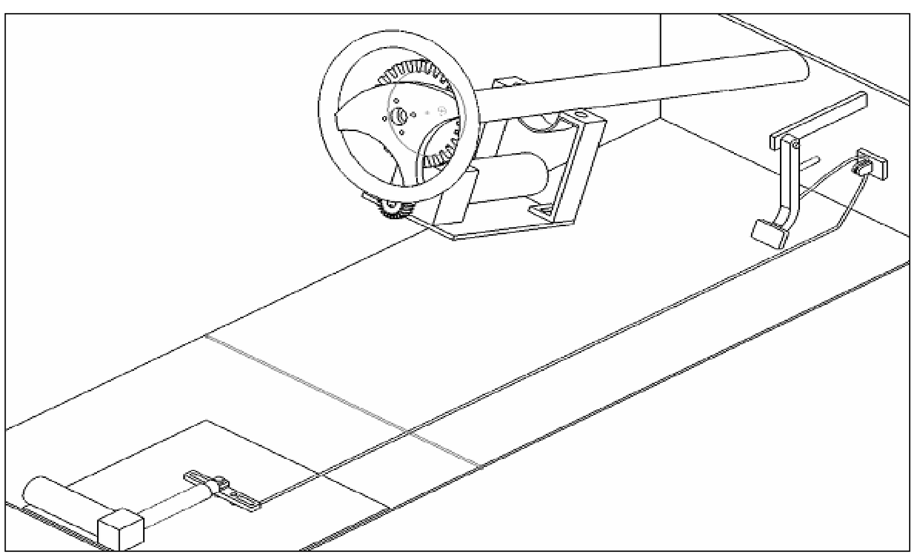

Figure 21: Initial System Rendering

5.5 Throttle

The BMW X5 is equipped with Electronic Throttle Control. This unit detects driver input on the accelerator pedal using two sensors and controls the throttle valve based on this input (BMW 2000).

The presence of this system greatly reduces the potential complexity in implementing a throttle-by-wire control for the X5. A mechanical interface such as that used for the steering and brakes is not required. Control can be achieved using electronics; a micro-controller provides a signal which can then be conditioned to match the two signals that are expected from the sensors, allowing the existing BMW throttle control architecture to carry out the throttle function.

5.6 Safety

An Emergency Stop switch that terminates power to all actuators and controls is necessary to allow a driver to take control of the car if required.

In addition to the E-stop switch, the control system reverts to normal user control whilst the by-wire system is running. The following requirements for the subsystems should be met;

- Steering: The steering will revert to user control if the steering wheel is grasped suddenly
- Brakes: The brake pedal can be depressed at any stage
- Throttle: The by-wire system will revert to user control if the accelerator pedal is depressed

These features can be implemented using controller software in addition to required electronics and hardware.

5.7 Design Proposal

An overview of the initial design proposal is presented below (Figure 22):

- The steering system would consist of a DC motor and a chain drive to a sprocket mounted onto the steering wheel. The steering wheel is mated to the steering shaft using the existing spline.
- The brake system would consist of a linear actuator and cable system that pulls the brake pedal to actuate the brakes.
- The throttle system uses a controller and associated signal conditioning electronics to replicate the accelerator pedal position signal.

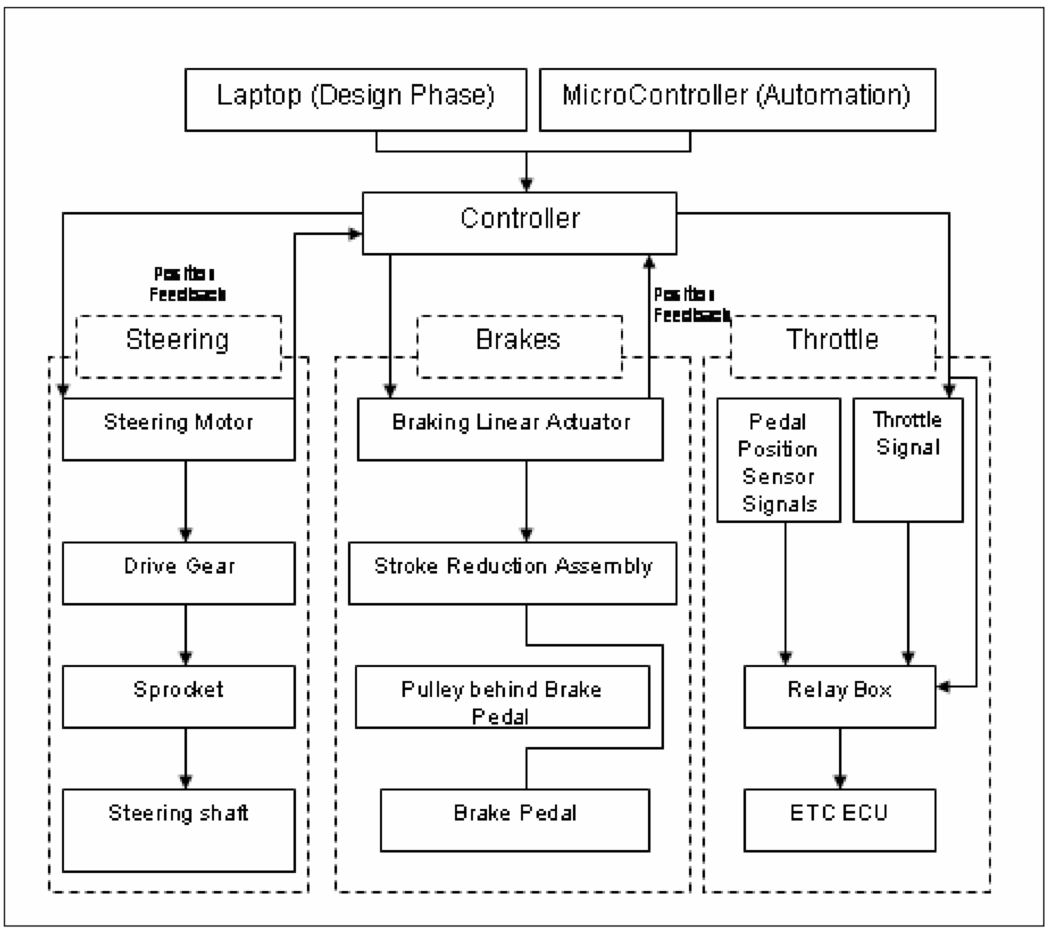

Figure 22: Design Proposal Overview

5.8 Component Requirements

The following section presents calculations and data to identify major component requirements for the by-wire systems, based on the preliminary design proposal outlined above.

5.8.1 Steering

5.8.1.1 Steering Torque

The first step in designing the steering mechanism was to calculate the torque required to turn the steering shaft. A force gauge was used to measure the force required to turn the steering when the car was stationary (this will be the instance at which maximum torque is required to turn the steering shaft (Stockel 2001)). The results are presented in Table 1 below.

Table 1: Steering Force

Trial	Measurements (Kg)	Force (N)
Clockwise		
1	4.5	44
2	4	39
3	5	49
4	4.2	41
5	4	39
6	4.2	41
7	4.4	43
8	4.5	44
Counter clockwise		
1	4.6	45
2	4.3	42
3	4.2	41
4	4	39
5	4	39
6	4.2	41
7	4.4	43
8	4.6	45

The average force required in both cases was approximately 42 N with a maximum force of 49N.

The following calculations define the torque requirements for the motor;

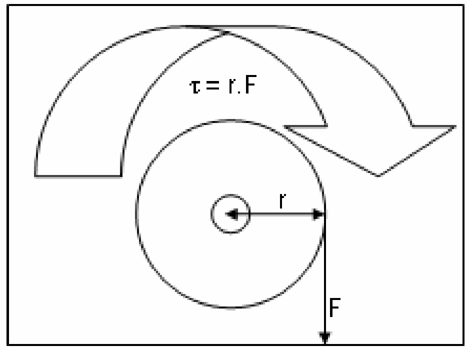

Figure 23: Steering Torque

Force required (F): 49 N

Distance (r): 0.155m

Torque on steering shaft:

$$\tau = r.F \tag{2.1}$$

τ =7.6 Nm

$\tau_{\text{(With safety factor)}}$= 10 Nm

A safety factor of 0.7 was included to accommodate for the wide range of factors that can influence the torque required to steer the wheels. Additionally, it attempts to compensate for variances and errors in measurement.

The calculations above indicate that a motor with a torque output of 10 Nm would be required if it were to directly turn the steering shaft. However, gearing can be used to reduce the torque requirements on the motor.

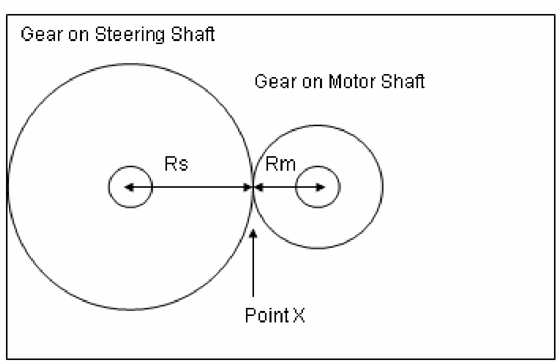

Figure 24: Steering Gear Ratio

The torque required to turn the steering shaft ($\tau_{steering}$): 10 Nm

The force, F, at point X due to torque $\tau_{steering}$:

$$F_x = \tau_{steering} / R_s \tag{2.2}$$

Motor force to counter F_x at point x;

$$F_{motor} = \tau_{motor} / R_m = F_x \tag{2.3}$$

$$\tau_{motor} / R_m = \tau_{steering} / R_s \tag{2.4}$$

$$\tau_{motor} = \tau_{steering} \text{ x } (R_m / R_s) \tag{2.5}$$

Table 2 below presents the torque requirements on a motor, based on the calculations presented above.

Table 2: Motor Torque Requirement

Ratio (Motor/ Steering) (R_m / R_s)	Motor Torque Requirement (Nm)
1	10
0.75	7.5
0.5	5
0.4	4
0.3	3
0.2	2

The calculations suggest that the motor used would need a torque output in the range of 3-7 Nm, dependant on the gear ratio used.

5.8.1.2 Steering Speed

The speeds at which the steering wheel is turned vary greatly dependant on the driving situation at hand. As a base measurement, tests were performed to see how fast various drivers turn the steering wheel when the vehicle is stationary with the engine running (power steering system functioning). The results ranged from 45rpm to 91rpm, with an average speed of 60 rpm.

The motor speeds required to turn the steering shaft at 60 rpm, dependent on the gear ratio used, are presented in Table 3 below.

Table 3: Steering Speed

Ratio (Motor/ Steering) (R_m / R_s)	Motor Speed Requirement (Rpm)
1	60
0.75	80
0.5	120
0.4	150
0.3	200
0.2	300

Table 3 indicates that a motor with a final shaft speed in the range of 80 to 200 rpm is required.

Figure 25 below represents the speed-torque curve for a 12V DC Motor (Groschopp 2009). Although this graph specifically represents the performance of a Groschopp #60511 motor, general DC motors exhibit similar performance characteristics (Hayashi 2003). The maximum speed of the motor is not attainable when the maximum torque is required. As such, the steering motor chosen should be capable of a higher torque output than required (dependant on the gear ratio used), in order to maximise the speed and the efficiency at which the motor is running.

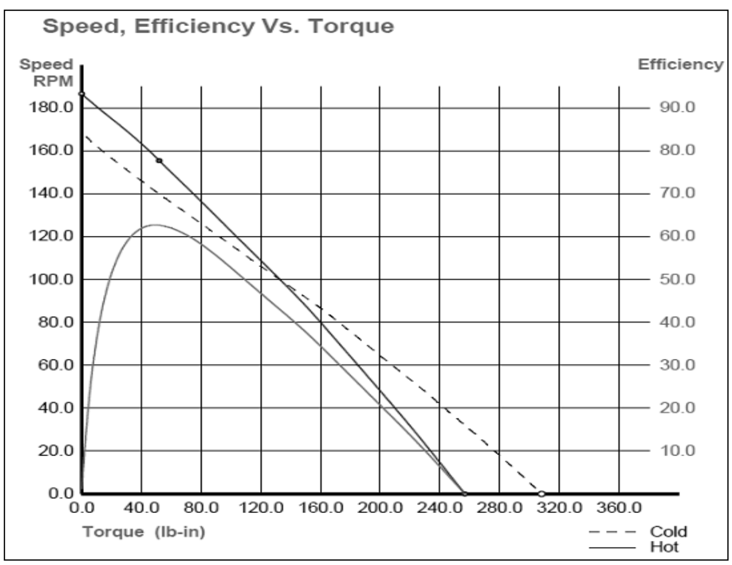

Figure 25: Speed, Efficiency, Torque Curve

5.8.1.3 Steering Motor Requirements

Based on the information presented above, it is recommended that the motor used is capable of a torque output in the range of 3 to 7 Nm, and a speed output in the range of 80 to 200 rpm, dependant on the gear ratio used.

5.8.2 Braking

5.8.2.1 Braking Force

The braking force required, or more specifically, the pedal force required to actuate the brakes on a vehicle is dependant on a variety of factors including vehicle speed, road surface, tyre material and conditions, the deceleration rate required, and the particular vehicle braking system in use (Stockel 2001). As such, the pedal force required in a driving situation is difficult to predict. However, the Australian Design Rules specify that the maximum brake pedal force in a passenger vehicle is 50 daN (ADR 31/01 2005). The BMW X5 is designed to comply with this regulation, and as such 500 N can be used as the thrust requirement for the linear actuator.

5.8.2.2 Brake Pedal Travel

The brake pedal travel in the X5 is dependant on various factors, for example, brake pad wear, brake line temperature and pressure, and brake line material (Stockel 2001). Maximum pedal travel was measured to be approximately 80mm in the X5, at stand-still. To accommodate for variances in pedal travel, a linear actuator can be used in conjunction with a mechanism to reduce the stroke at the brake pedal. An initial rendering of such a mechanism is presented in Figure 26 below. This mechanism has the additional benefit of allowing for more accurate control of the brake pedal travel as the brake pedal travels a shorter distance in relation to the actuator travel.

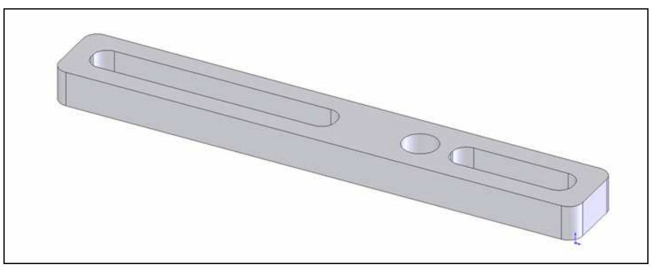

Figure 26: Brake Stroke Reduction Mechanism

A linear actuator with a stroke of approximately 200mm is recommended. This stroke length would accommodate for variances in pedal travel and allow for accurate pedal travel control using the reduction mechanism presented above.

5.8.2.3 Braking Speed

The speed at which the actuator travels is also important. A driver's brake reaction time is dependant on various factors. However, studies indicate an average reaction time of 1 second, with faster reaction times in the range of 0.6 seconds (NTSEL 2007). This will be used as a benchmark for the braking system. In order to actuate the brakes in the same time as (or better than) a human driver, the brake actuator should be capable of travelling the full brake pedal travel length within the reaction times presented above. Using an approximate pedal travel of 80 mm (as measured in the X5 at stand still), brake pedal speeds range from 80 mm/sec to 130mm/sec.

It is recommended that a linear actuator capable of travelling at approximately 200mm/sec is used. This represents a brake pedal travel speed of 100mm/sec using a 2:1 reduction mechanism.

The reduction mechanism used to limit the pedal travel also has the added benefit of reducing the load on the actuator. As for a DC motor, using a linear actuator capable of higher loads than required permits a faster actuator stroke speed and higher efficiency (Hayashi 2003).

5.8.2.4 Brake Actuator Requirement

Based on the information presented above, it is recommended that the linear actuator used for the braking system is capable of a load of 500N and a stroke of 200mm at a speed of 200mm/sec.

5.8.3 Throttle

The standard BMW X5 throttle system is a by-wire system where two sensors are used to determine the throttle pedal position. The first sensor outputs a voltage from 0.5 to 4.5 V while the second sensor outputs a voltage from 0.5 to 2 V. These signals are monitored by a control unit and if implausible, the lower of the two signals is used to control the throttle body valve (BMW 2000). It is possible to replicate these signals using a controller and associated electronics. The system should also be capable of switching to driver control if it detects any movement on the accelerator pedal.

Figure 27 below presents a throttle control system overview. Signal conditioning is performed on a controller signal to replicate the two signals that are generally expected from the standard throttle position sensors. Relays control the input to the ECU such that the conditioned signals are fed to the ECU when required by the controller, and the throttle position sensor signals are fed to the ECU at all other times.

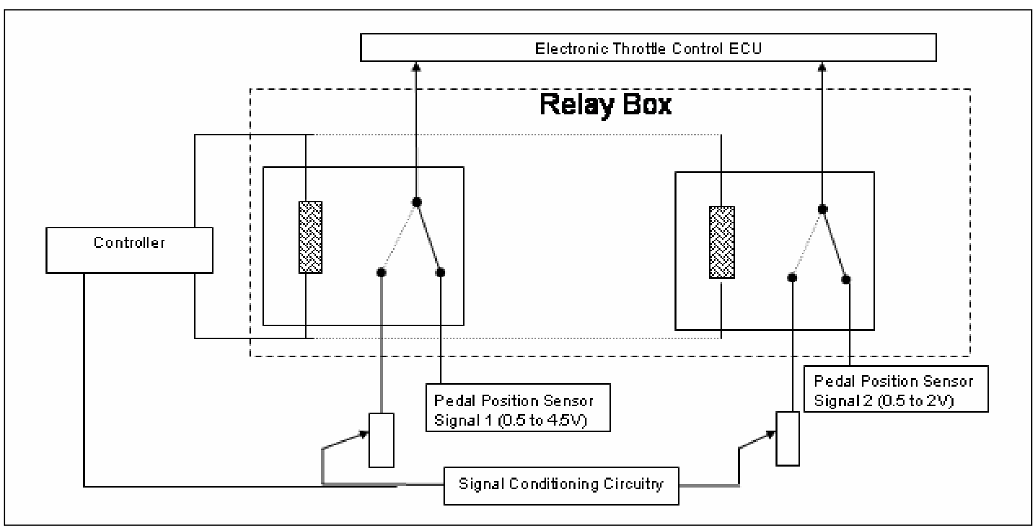

Figure 27: Throttle Control System Overview

5.8.4 Controller

There are 3 major components that require control input within the system; steering DC motor, braking linear actuator, and throttle control.

The steering and braking systems can both be controlled by DC motor controllers (ball screw linear actuators are systems with DC motors mated to a screw mechanism that converts rotational torque to linear travel and thrust (Servomech 2005)).

It is beneficial to have a single controller that is capable of controlling the three sub-systems. The particular controller required is dependant on the performance characteristics of the steering DC motor and braking linear actuator, in particular, the output voltage and current required, the type of motor control necessary and additional sensor inputs required for the controller.

During the initial installation phase of the system, the controller should be capable of accepting user inputs via a computer. Later, the controller should be capable of accepting user inputs from a secondary microcontroller which allows for interfacing with systems such as the vision based driver assistance system.

The BMW X5 uses a 12V electrical system. To avoid additional voltage regulation components, it is recommended that the controller accepts a 12V power supply. It is also beneficial for the controller to have inbuilt voltage regulation and current amplification circuitry to avoid the need for additional components and minimise system complexity.

Conclusively, the controller used should be capable of controlling all three major subsystems (steering, brakes and throttle) without the need for significant additional components or circuitry, using a 12V power source, and allow for user input via an external computer or secondary micro-controller.

5.9 Component Selection

Based on the information contained in Section 5.8 above, a search for components matching the required specifications was conducted. 12V DC motors capable of producing the required torque at the required speed were surprisingly difficult to source. Similarly, whilst a large number of 12V linear actuators were capable of actuating 500N loads, ones that could do so at the required speeds were scarce. A large number of DC motor controllers were available, however, one company in particular made controllers which met all the requirements which allowed for easy system integration. A summary of the components sourced, and their specifications, can be found in Appendix B.

The following major components were recommended;

Steering DC Motor; Bison Engineering 348DC-011-348-3010

(Availabe from:http://www.bisongear.com/specs.asp_Q_catID_E_3_A_subCatID_E_18_A_prodID_E_57_A_skuID_E_564#)

Braking Linear Actuator; Servomech ATL10-RH2-C100-FO-12V

(Available from: http://www.motiontech.com.au/assets/pdf/Servomech%20Actuators.pdf)

Controller; Roboteq AX3500

(Available from: http://www.roboteq.com/brushed-dc-motor-controllers/ax3500-dual-60a-brushed-dc-motor-controller.html)

The components proposed above were based on implementing a system that is capable of optimal performance. However, these components represent a significantly high cost. To limit the cost of implementing the system, the feasibility of using high torque servos was considered. The EyeBot controller used for the vision system has inbuilt servo control capability and hence eliminates the need for the additional Roboteq controller (Braünl 2008). The use of servos was initially disregarded due to difficulty in sourcing models which perform within the torque and speed requirements. However, a high torque servo with significantly lower cost than the components listed above was located. This warranted further investigation into the feasibility of using servos to actuate the steering and brakes.

6 Design Feasibility (Servos)

The standard model servo is capable of producing 36Nm of torque at a speed of 1.8 seconds for 180 degrees of travel. A model with 18 Nm of torque at a speed of 0.9 seconds for 180 degrees of travel is also available (Vantec 2009). Full servo specifications can be found in Appendix C. The following sections investigate the feasibility of using these servos for the steering and braking systems in the X5.

6.1 Steering

6.1.1 Requirements

Steering speed: 60rpm = 360 deg/sec

Steering torque: 10 Nm

Steering rotation: 3.4 Turns Lock-to-Lock (± 612˚)

6.1.2 Validation

Table 4 below presents the various steering performance parameters for a range of servo and gearing combinations.

Servo Type	**Gear Ratio**	**Travel**	**Speed (deg/sec)**	**Steering Torque (Nm)**
Standard	1:1	± 180˚	100	36
	1:2	± 360˚	200	18
	1:3	± 540˚	300	12
	1:3.4	± 612˚	400	10
High Speed	1:1	± 180˚	200	17.6
	1:2	± 360˚	400	8.8
	1:3	± 540˚	600	5.9

Table 4: Steering performance using a Vantec servo

The standard servo is capable of providing the required torque with a variety of gear ratios. However, the total steering rotation is only achieved with a 3.4 gear ratio. No other combinations of servos and gear ratios can achieve this steering rotation whilst maintaining the required steering torque.

The standard servo is also suitable if a reduction in steering rotation is acceptable. This compromise is plausible as the steering rotation is generally low at higher vehicle speeds; it is unlikely that a driver would turn the steering to its maximum revolution in a scenario other than slow speed manoeuvres such as parking.

Based on the above information, the standard servo is suitable for steering actuation. Flexibility in system performance can also be achieved as a variety of steering rotations and speeds are attainable using various gear ratios.

6.2 Brakes

6.2.1 Requirements

Maximum Pedal Travel: 80mm

Maximum Pedal Force: 500N

Required Actuation Speed: 80mm/sec

6.2.2 Validation

Pedal range: 80mm

Required pulley radius (180˚ travel) = 80/ л = 25.4 mm.

Maximum force (F) exerted by the servo using a pulley with a 30mm radius (r):

$$F=\tau /r \qquad (3.1)$$

Servo (τ)	Force (N)	Speed (mm/sec)
Standard (36 Nm)	1200	44.4
High Speed (18 Nm)	600	88.9

Table 5: Brake performance using Vantec servos

Although the standard servo meets the brake force requirement, the speed at which it actuates is slower than the required speed of 80 mm/sec. The high speed servo accommodates for this with a maximum force of 600N and a brake actuation speed of 88.9 mm/sec and is therefore suitable for use as a brake actuator.

The above information indicates that the Vantec servos are suitable for the steering and braking application. A system design based these servos is considered next.

7 Servo System Design

7.1 Steering System

To reduce the potential for injury to the user, a v-belt and pulley system was initially considered as the steering drive mechanism, as opposed to the chain and sprocket system proposed in Section 5.3.2. However, an accurate and repeatable steering response cannot be achieved using a v-belt and pulley system (Wright 2005).

As such, a synchronous belt and pulley system was considered next. This option allowed for the use of a belt whilst maintaining the accuracy and repeatability required for the steering system. The proposed method to actuate the steering shaft involves attaching the timing pulley to the steering hub, and using the existing steering hub spline to rotate the steering shaft. This method was employed as space constraints between the steering wheel and dash board (Figure 28) do not allow for the attachment of the pulley directly to the shaft. .

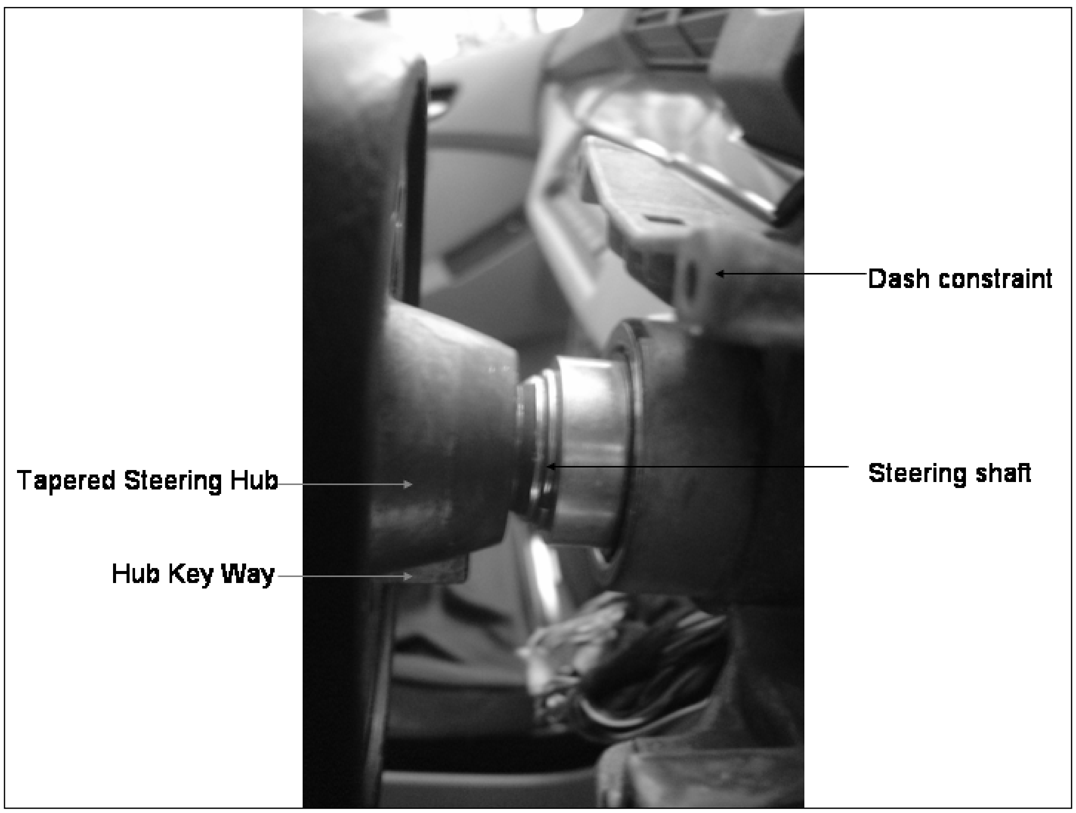

Figure 28: Steering wheel and dash constraint

The timing pulley requires machining to match the tapered steering hub and key way shown in Figure 28 above. The base of the tapered hub has a diameter of 45mm and therefore, a timing pulley hub diameter greater than 44mm is required. Appendix D shows a range of metric timing pulleys, out of which, the 22-AT10-16F has a hub diameter of 52mm. A rendering of a machined timing pulley is shown in Figure 29, with detailed drawings in Appendix E.

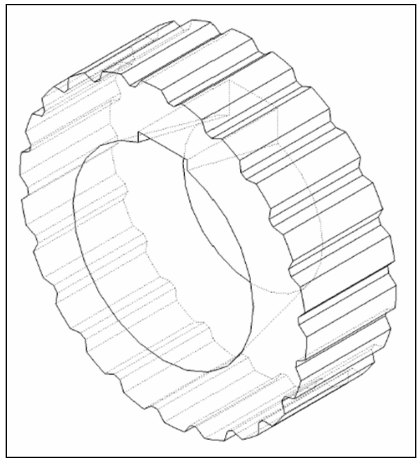

Figure 29: Machined Timing Pulley

Figure 30 below shows a rendering of the steering system. The mounting plate (Appendix F) bolts directly to the existing steering bracket labelled "Dash constraint" in Figure 28 above. The steering servo is attached to the mounting plate, with the exact position being dependant on the steering belt length and the required belt tension.

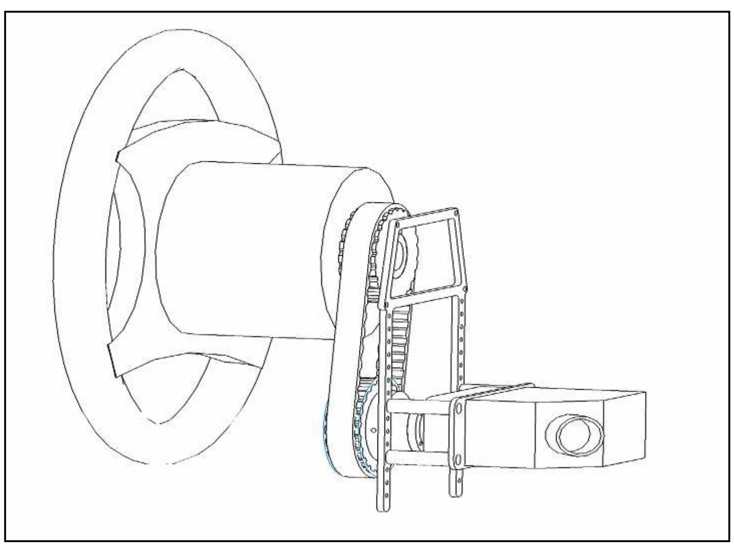

Figure 30: Servo Steering System Rendering

7.2 Braking System

The braking servo is positioned in between the firewall and the brake pedal, without interfering with the normal operation of the accelerator, brake, or clutch, pedals. A pulley is attached to the servo, and a cable is attached to the pulley. The other end of the cable is attached to the brake pedal, allowing the servo to actuate the brakes, whilst also allowing the driver to depress the brakes further if required. Figure 31shows a rendering of the system. A detailed drawing of the servo mounting bracket is presented in Appendix G.

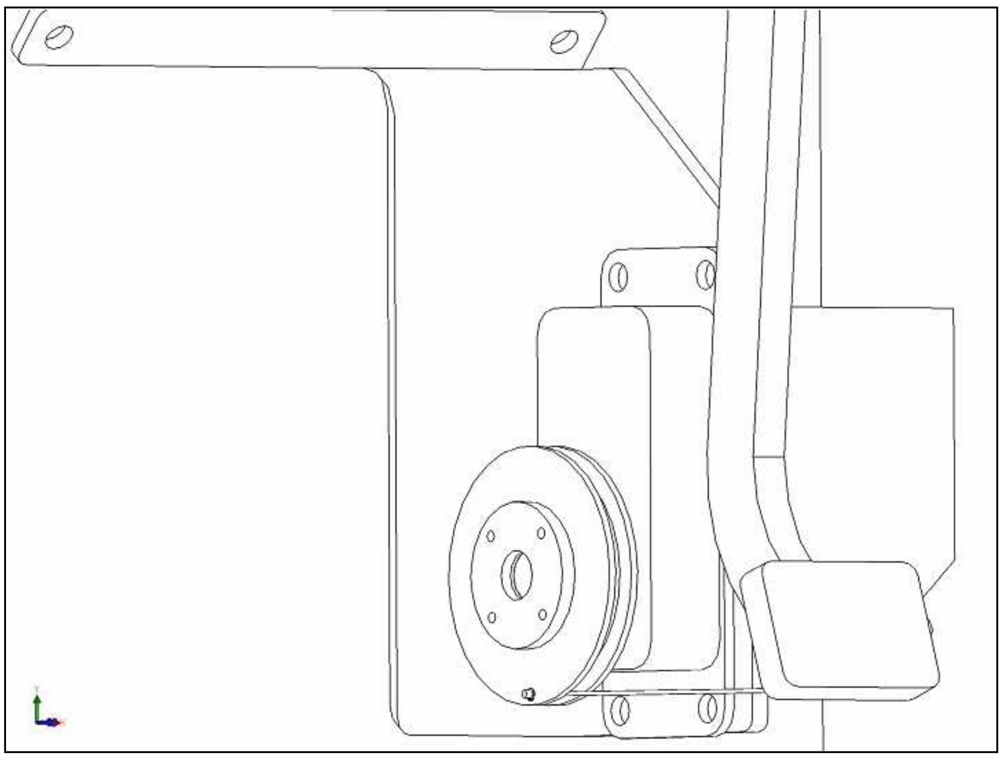

Figure 31: Braking System Rendering

7.3 Safety Considerations

Various safety devices prevent damage to the system components, and more importantly, injury to the driver. Figure 32 presents an overview of the control system. An emergency safety switch impedes power to the servos. A self-resetting poly-fuse trips if the servo draws more current than necessary and a conventional fuse is used as an additional safety backup. Optocouplers are used to prevent damage to the EyeBot.

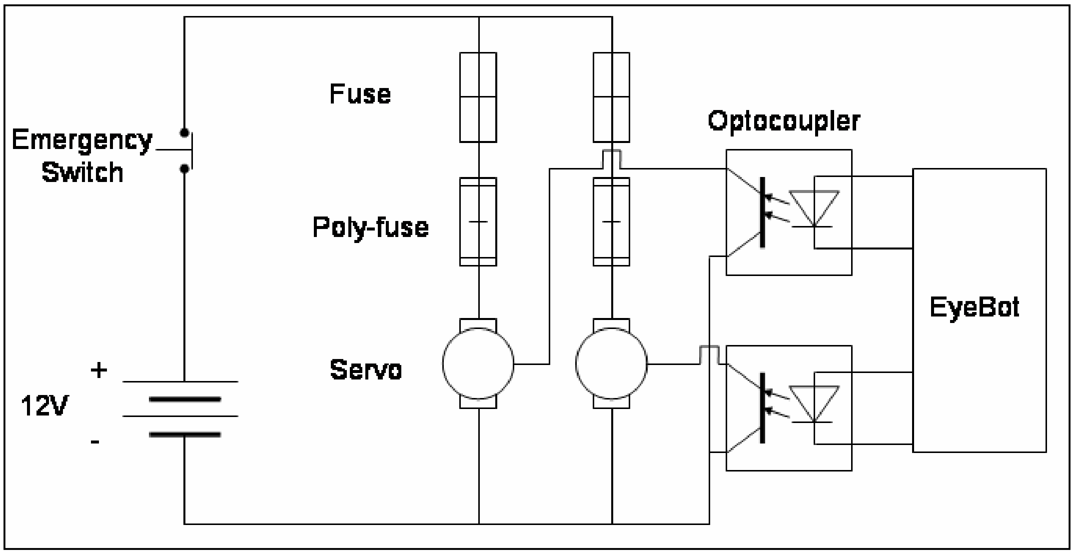

Figure 32: Control System Overview (Ong 2009)

Additionally, shear pins are used to prevent damage to the servos due to excessive torque requirements. The proposed shear pin arrangements for the braking and steering systems are shown in Figure 33 and Figure 34 respectively.

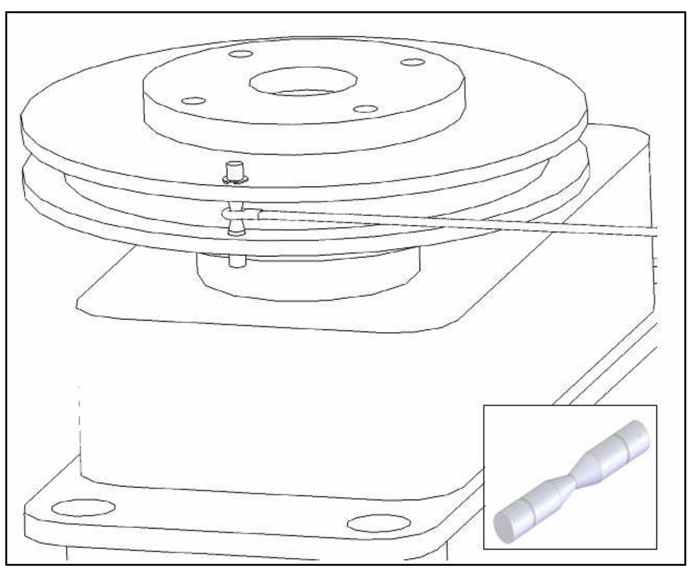

Figure 33: Braking System Shear Pin Arrangement (Inset: Shear Pin)

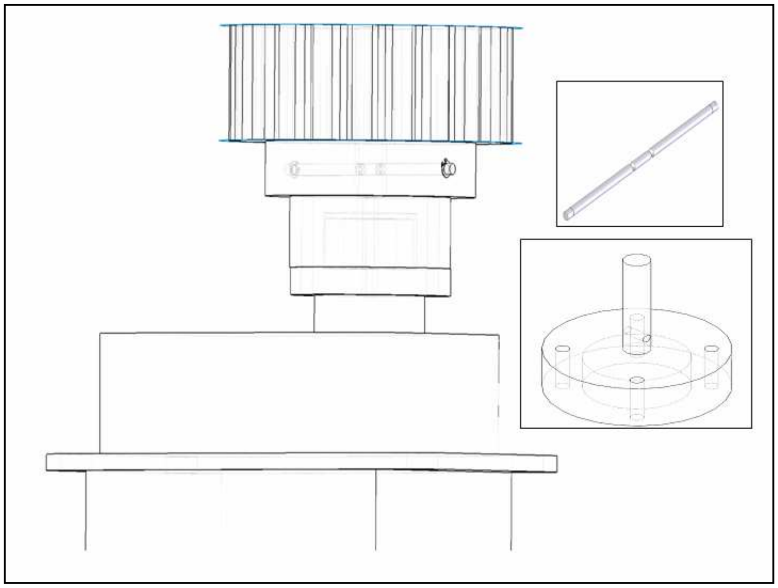

Figure 34: Steering System Shear Pin Arrangement
(Inset: Shear Pin (Top), Servo Hub (Bottom))

The dimensions and materials of the shear pins are dependant on the maximum torque limit required. The braking and steering servo are capable of producing a maximum of 18 Nm and 36 Nm of torque respectively. The limit at which the shear pins fail should be set lower than these maximum outputs. The initial dimensions of the shear pins can be determined using a torque limit of 75% of the maximum servo output (Table 6). The optimal dimensions and material of each shear pin can be determined based on the results of system testing.

	Brake	Steering
Torque Limit (Nm)	13.5	27
Effective Radius (mm)	30	3
Force (N)	450	9000
Shear Strength (Mpa) (Pin Material)	230 (Brass)	230 (Brass)
Shear Area (mm^2)	1.96	19.56*
Pin Diameter (mm)	1.6	5

*Double shear arrangement (See Figure 34)

Table 6: Shear Pin Diameter Calculation

8 Recommendations and Future work

Complete installation and testing of the system is recommended to determine the performance characteristics of the system. The optimal dimensions and material used for the shear pins can be determined after system testing is conducted. Safety considerations are paramount at this stage, and system testing should only be carried out when it is safe to do so.

It is recommended that safety covers are designed for the steering and braking systems. These covers serve as a safe guard against injury to the vehicle occupants, and also improve the aesthetics of the system. Relocation of the indicator and wiper stalks onto the steering cover is also required to maintain the driveability of the vehicle.

Large open spaces should be used to test the vehicle response to the control system. Vehicle speeds should be increased incrementally once satisfactory system performance is achieved at lower speeds. It is recommended that two people are present in the vehicle at all times. The driver should concentrate on the vehicle path and take actions to rectify any potentially dangerous situations. The passenger should monitor the performance of the control system, and should be prepared to engage the emergency safety switch if unacceptable system behaviour is observed.

The successful integration of the vision system and vehicle control systems is dependant on accurate steering and braking response. As such, it is recommended that once the initial system has been implemented and tested for basic function, the implementation of a feedback control system is considered. Furthermore, the feasibility of integrating existing BMW sensors, such as vehicle speed and steering angle sensors, with the vision system should be considered.

Once satisfactory brake and steering response has been achieved, the implementation of a throttle control system may be considered. The safe performance of this system is paramount to prevent uncontrollable vehicle acceleration, and automated throttle control should only be implemented once satisfactory results are obtained through system testing.

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10 Appendices

Appendix A. Failure Modes and Effects Analysis

System	Component	Failure Mode	Effect	Consequence without system redundancy	Severity	Redundancy Measure	Consequence with system redundancy	Severity
Brakes	Pedal Sensor	Loose connection	Incorrect pedal position signal	Sub-optimal or unpredictable brake performance	4	Additional pedal position sensor	No effect to braking performance	1
			No pedal position signal	Complete loss of braking capability	5	Additional pedal position sensor	No effect to braking performance	1
		Partial sensor failure	Incorrect pedal position signal	Sub-optimal or unpredictable brake performance	4	Additional pedal position sensor	No effect to braking performance	1
		Complete sensor failure	No pedal position signal	Complete loss of braking capability	5	Additional pedal position sensor	No effect to braking performance	1
	Brake Actuator	Loose connection	Incorrect brake actuation at one wheel	Sub-optimal or unpredictable brake performance	3	Additional brake actuator	No effect to braking performance	1
			No brake actuation at one wheel	Sub-optimal or unpredictable brake performance	3	Additional brake actuator	No effect to braking performance	1
		Partial Actuator Failure	Incorrect brake actuation at one wheel	Sub-optimal or unpredictable brake performance	3	Additional brake actuator	No effect to braking performance	1
		Complete Actuator Failure	No brake actuation at one wheel	Sub-optimal or unpredictable brake performance	3	Additional brake actuator	No effect to braking performance	1
Steering	Steering Position Sensor	Loose connection	Incorrect steering position signal	Sub-optimal or unpredictable steering performance	3	Additional steering position sensor	No effect to steering performance	1
			No steering position signal	Complete loss of steering capability	4	Additional steering position sensor	No effect to steering performance	1

		Partial sensor failure	Incorrect steering position signal	Sub-optimal or unpredictable steering performance	3	Additional steering position sensor	No effect to steering performance	1
		Complete sensor failure	No pedal position signal	Complete loss of steering capability	4	Additional steering position sensor	No effect to steering performance	1
	Steering Actuator	Loose connection	Incorrect steering actuation	Sub-optimal or unpredictable steering performance	3	Additional steering actuator	No effect to steering performance	1
			No steering actuation	Complete loss of steering capability	4	Additional steering actuator	No effect to steering performance	1
		Partial actuator failure	Incorrect steering actuation	Sub-optimal or unpredictable steering performance	3	Additional steering actuator	No effect to steering performance	1
		Complete actuator failure	No steering actuation	Complete loss of steering capability	4	Additional steering actuator	No effect to steering performance	1
Throttle	Pedal Position Sensor	Loose connection	Incorrect pedal position signal	Sub-optimal or unpredictable throttle performance	2	Additional pedal position sensor	No effect to throttle performance	1
			No pedal position signal	Complete loss of throttle capability	3	Additional pedal position sensor	No effect to throttle performance	1
		Partial sensor failure	Incorrect pedal position signal	Sub-optimal or unpredictable throttle performance	2	Additional pedal position sensor	No effect to throttle performance	1
		Complete sensor failure	No pedal position signal	Complete loss of throttle capability	3	Additional pedal position sensor	No effect to throttle performance	1
	Throttle Actuator	Loose connection	Incorrect throttle actuation	Sub-optimal or unpredictable throttle performance	2	Additional throttle actuator	No effect to throttle performance	1
			No throttle actuation	Complete loss of throttle capability	3	Additional throttle actuator	No effect to throttle performance	1

		Partial actuator failure	Incorrect throttle actuation	Sub-optimal or unpredictable throttle performance	2	Additional throttle actuator	No effect to throttle performance	1
		Complete actuator failure	No throttle actuation	Complete loss of throttle capability	3	Additional throttle actuator	No effect to throttle performance	1
Control System	Controller	Partial controller failure	Incorrect throttle, brake and steering actuation	Sub-optimal or unpredictable vehicle control	4	Additional Controller	No effect to system performance	1
		Complete controller failure	No throttle, brake and steering actuation	No vehicle control	5	Additional Controller	No effect to system performance	1

Appendix A: FMEA Analysis

Severity	Description
1	Minimal Severity (No discernable effect)
2	Low Severity (Sub-optimal performance)
3	Medium Severity (Loss of non-critical system control)
4	High Severity (Partial loss of vehicle control)
5	Extreme Serverity (Critical loss of control)

Appendix B. Component Alternatives

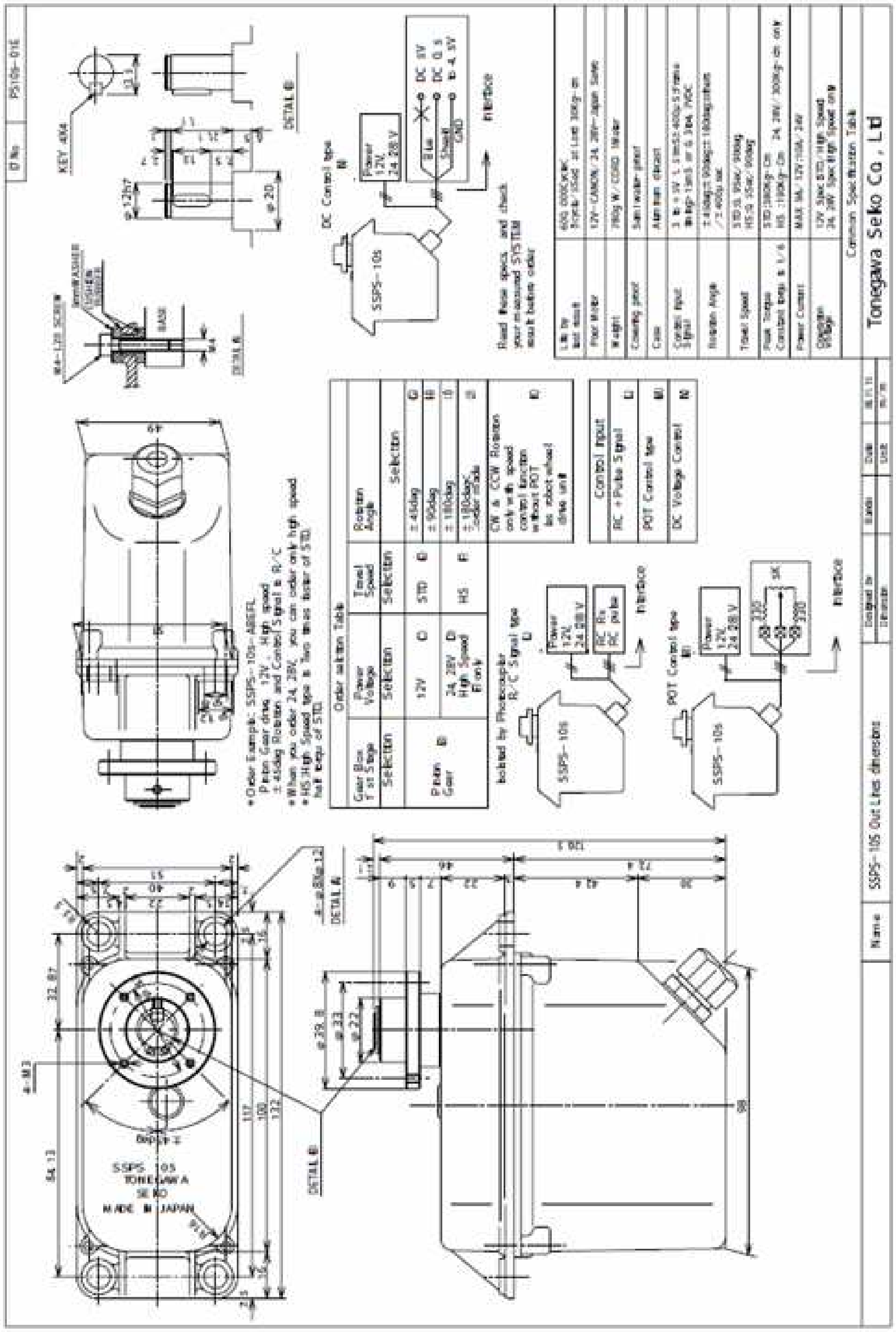
US$ to AUD Conversion Rate:(as at 9/03/09) *1.56323277*		**Alternative 1**	**Alternative 2**	**Alternative 3**
Motor Controller	**Company**	*Roboteq*	*Roboteq*	*Roboteq*
	Model #	AX-3500	AX-1500	AX-2850
	Price	US$	US$	US$
	Unit	400.00	400.00	620.00
	Postage	110.00	110.00	110.00
	Total	510.00	510.00	730.00
	Total (AUD)	797.25	797.25	1141.16
		2x60A	2 x 30A	2 x 140 Amps
		Encoder modules built in	Requires additional optical	Dual Channel
			encoder module	Inbuilt Amplifier
			(Included in price above)	Servo Control
				Similar application history

DC Motor	**Company**	*Bison Engineering*	*Groschopp Motors*	*EMP Australia*
	Model #	Bison-348DC-011-348-3010	Groschopp #60511	EMP M3-5656007G/1
	Price	US$	US$	AU$
	Unit	560.00	645.23	251.79
	Postage	235.00	100.00	100.00
	Total	795.00	745.23	351.79
	Total (AUD)	1242.77	1164.97	351.79
				*Cannot get an in-line gearbox!
	Torque (Nm)	6.44	5.88	3.75
	Speed (rpm)	170.00	155.00	175.00
	Weight (kg)	7.30	4.00	5.00

Linear Actuator	**Company**	*ServoMech*	*Linak*	*Linmot Actuators*
	Model #	ATL10-RH2-C200-FO-12V	LA365A01+0P200A20	PS01-48x240-C
	Price	AU$	AU$	AU$
	Unit	2376.00	1375.00	5552.00
	Postage	100.00	100.00	101.00
	Total	2476.00	1475.00	5653.00
	Total (AUD)	2476.00	1475.00	5653.00
				Linear Motor; higher speeds and accuracy, however, expensive and requires separate drivers (included in price)
	Voltage	12V	12V	12V
	Stroke (mm)	200	200	240
	Load (N)	450	1700	500
	Speed at full load (mm/sec)	100	68	2200
	Motor	DC	DC	N/A

Appendix B: Component Alternatives

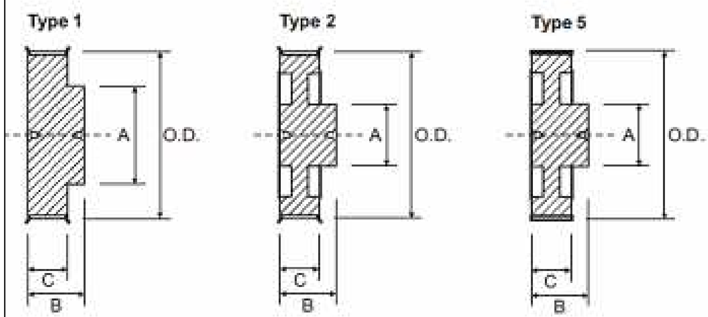
Appendix C. Vantec Servo Specifications



Appendix C: Vantec Servo Specifications (Vantec 2009)

Appendix D. Timing Pulley Size Chart

AT10 Metric Timing Pulleys



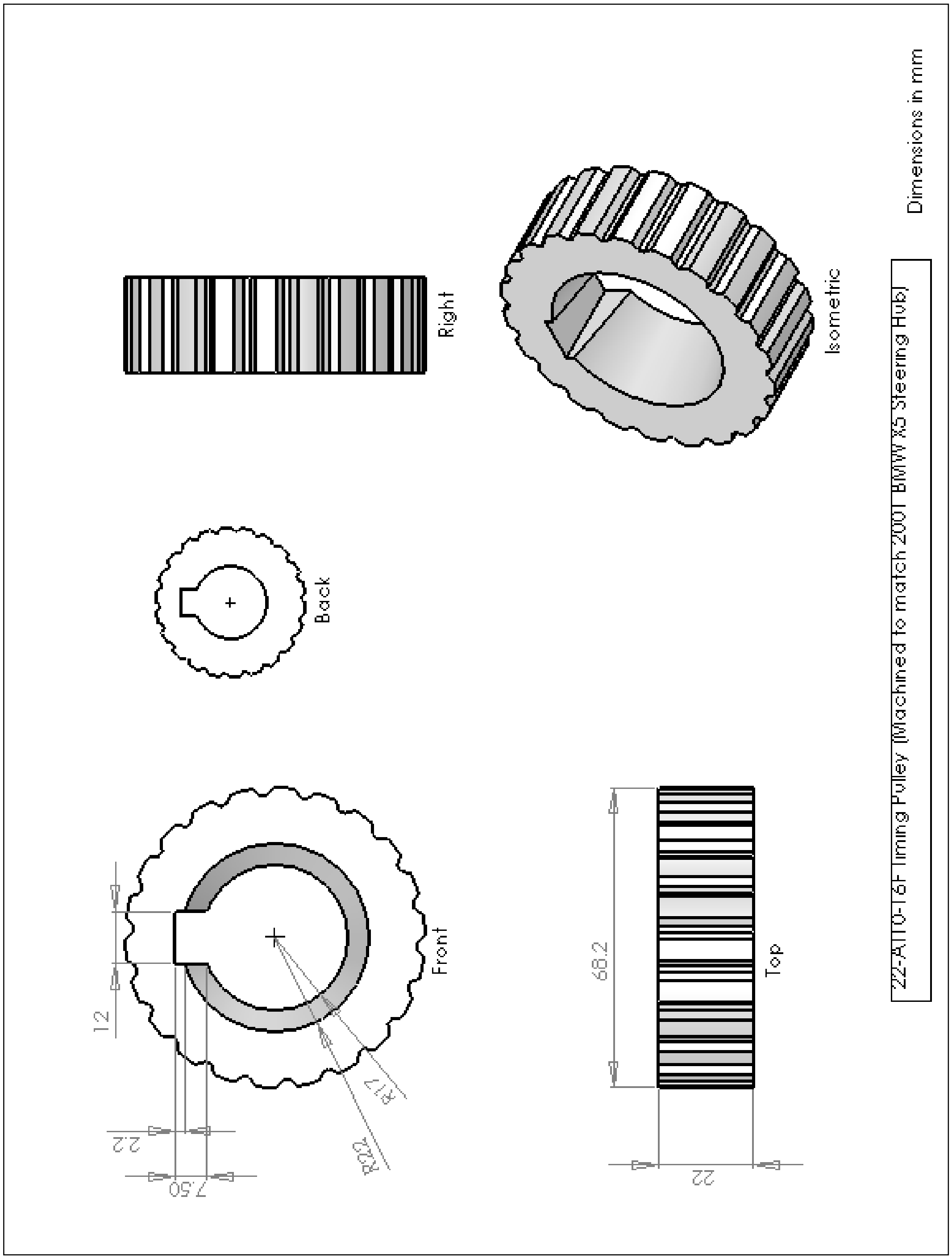
AT10-16						
Suit 16mm wide belt						
Part No.	O.D.	Type	A	B	C = 21.0	
15-AT10-16F	45.9	1	32.0	31.0		
16-AT10-16F	49.1	1	35.0	31.0		
18-AT10-16F	55.5	1	40.0	31.0		
19-AT10-16F	58.6	1	44.0	31.0		
20-AT10-16F	61.8	1	46.0	31.0		
22-AT10-16F	68.2	1	52.0	31.0		
24-AT10-16F	74.6	1	58.0	31.0		Flanged
25-AT10-16F	77.7	1	60.0	31.0		
26-AT10-16F	80.9	1	60.0	31.0	Aluminium	
27-AT10-16F	84.1	1	60.0	31.0		
28-AT10-16F	87.3	1	60.0	31.0		
30-AT10-16F	93.7	1	60.0	31.0		
32-AT10-16F	100.0	1	65.0	31.0		
36-AT10-16F	112.8	1	70.0	31.0		
40-AT10-16F	125.5	2	80.0	31.0		
44-AT10-16	138.2	5	88.0	31.0		
48-AT10-16	151.0	5	95.0	31.0		N.F.
60-AT10-16	189.1	5	110.0	31.0		

AT10-25						
Suit 25mm wide belt						
Part No.	O.D.	Type	A	B	C = 30.0	
15-AT10-25F	45.9	1	32.0	40.0		
16-AT10-25F	49.1	1	35.0	40.0		
18-AT10-25F	55.5	1	40.0	40.0		
19-AT10-25F	58.6	1	44.0	40.0		
20-AT10-25F	61.8	1	46.0	40.0		
22-AT10-25F	68.2	1	52.0	40.0		
24-AT10-25F	74.6	1	58.0	40.0		Flanged
25-AT10-25F	77.7	1	60.0	40.0		
26-AT10-25F	80.9	1	60.0	40.0	Aluminium	
27-AT10-25F	84.1	1	60.0	40.0		
28-AT10-25F	87.3	1	60.0	40.0		
30-AT10-25F	93.7	1	60.0	40.0		
32-AT10-25F	100.0	1	65.0	40.0		
36-AT10-25F	112.8	1	70.0	40.0		
40-AT10-25F	125.5	2	80.0	40.0		
44-AT10-25	138.2	5	88.0	40.0		
48-AT10-25	151.0	5	95.0	40.0		N.F.
60-AT10-25	189.1	5	110.0	40.0		

N.F. - No Flanges

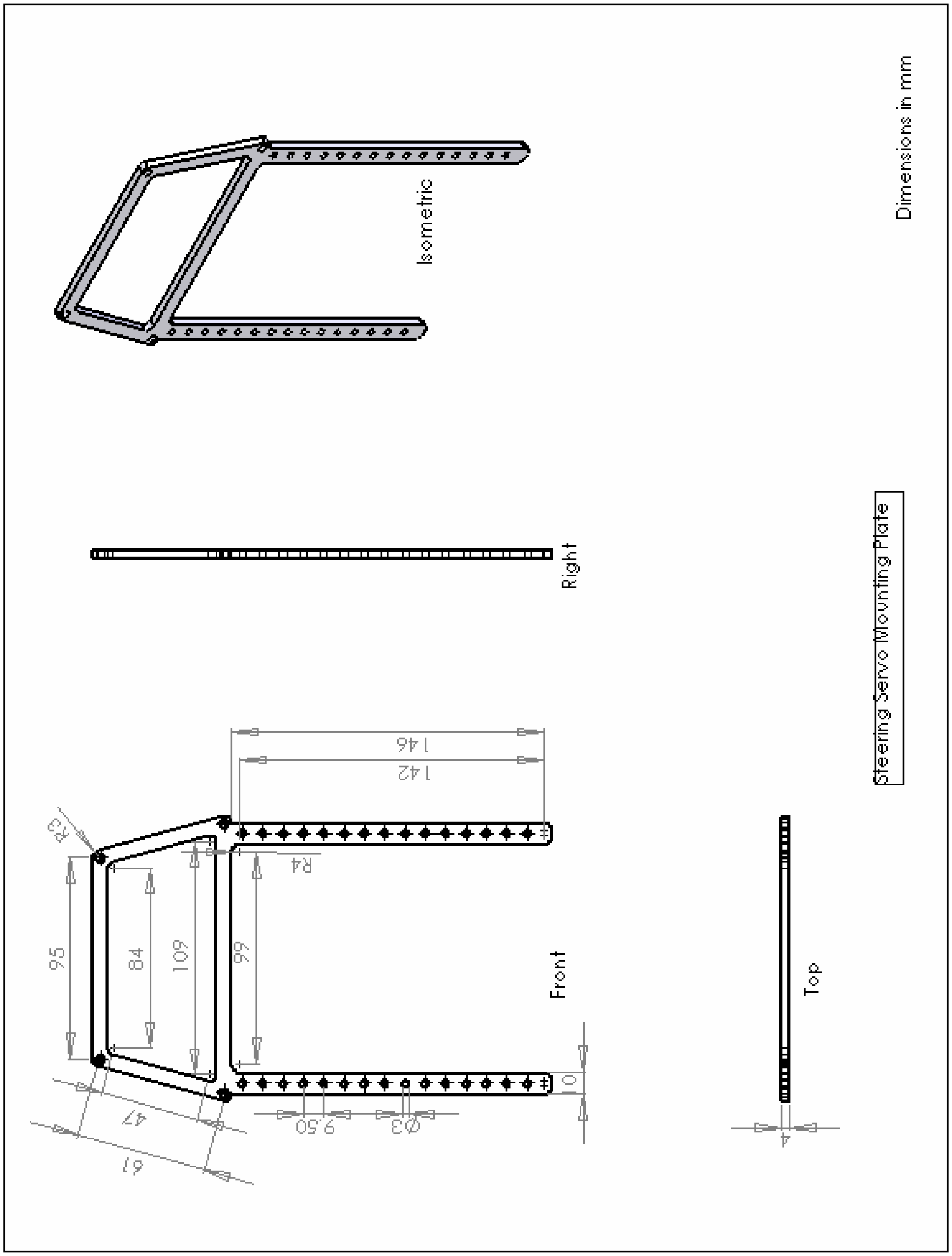
Appendix D: Timing Pulley Chart (Nai Smith Engineering 2005)

Appendix E. <u>Timing Pulley Drawing</u>



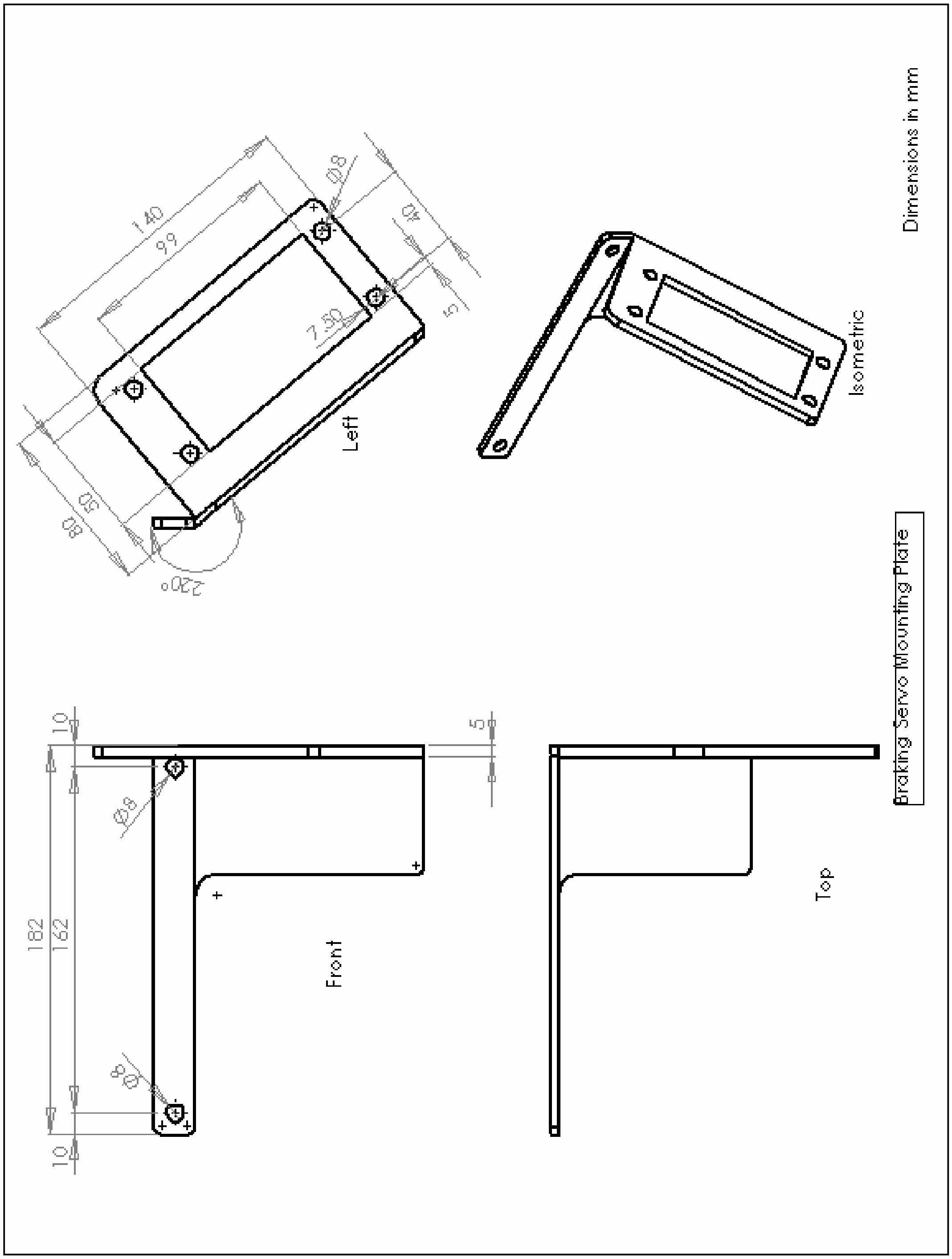
Appendix E: Timing Pulley Modifications

Appendix F. Steering Servo Mounting Plate Drawing



Appendix F: Steering Servo Mounting Plate

Appendix G. Braking Servo Mounting Plate Drawing



Appendix G: Braking Servo Mounting Plate