Conversion of a Formula SAE Vehicle to Full Drive-by-Wire Capability

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Abstract

The automotive industry is increasingly using electrical control systems in order to assist the driver of a vehicle or to automate certain manoeuvres. This paper describes the conversion of a Formula SAE car into a vehicle with autonomous drive-by-wire capability. This includes control over the braking, steering and throttle functions of the vehicle.

By installing a servomotor and mechanical linkage, the vehicle is capable of braking via an electronic command. Control over the vehicle's acceleration is achieved through replication of the vehicle's original throttle hall sensor output voltage. A DC motor was used to actuate the steering of the vehicle by use of a belt drive on the steering column.

The setup of the low-level controller and the aforementioned actuators are discussed. The design process of the systems used to convert the vehicle to drive-by-wire acceleration, braking and steering are documented along with details of the low-level controller and safety systems. The end result is a vehicle which is capable of being controlled by a high-level system for research into autonomous control algorithms.

Acknowledgements

I would like to thank Professor Thomas Bräunl for providing encouragement and insight during the project. Furthermore, his donation of the SSPS-105 servomotor made completion of the project possible. Additionally, advice from the university's mechanical workshop staff was much appreciated.

Additional acknowledgements goes to Matthias Wandel, creator of the online gear generator used in this project and to Govert for the creation of a conversion program for the HPGL2 files along with the various creators of the Arduino libraries used. Finally, I would like to thank both Thomas Drage and Calvin Yapp who contributed to the construction and testing of the system.

Contents

1. Introduction

In previous years, the Renewable Energy Vehicle (REV) Project has investigated driver assistant systems through the modification of a BMW X5. The conversion process of the X5 enabled both steer-by-wire and brake-by-wire capabilities with the aim of assisting a driver to avoid obstacles. To further research into automotive systems involved increasing the scope of control that embedded systems had over the functions of a vehicle. This meant that full control of all three driver tasks (acceleration, steering and braking) was required. While similarities exist between the introduction of driver assistance systems to the X5 and the automation of complete drive-by-wire capabilities of a vehicle, the motivation behind both projects are slightly different. Modifications made to the X5 are designed to be unobtrusive and only assist a driver in emergency situations when required. The modified X5 is a suitable platform for obstacle recognition and avoidance. Inspiration behind a fully autonomous vehicle lies behind the increasing idea that automation technologies may one day be responsible for full control over a vehicle or provide assistance to drivers to complete tasks that are difficult.

A new test bed that allowed research and development into fully automated vehicle control systems and technologies was required for future work by the REV Project. The form of such a test bed was an electric drive Formula SAE vehicle as shown in Figure 1 and Figure 2. The electric drive simplified the integration of new drive-by-wire systems as the batteries already present on the vehicle provided a suitable power source for any new systems. Access to the existing motor throttle lines was also easier.

Figure 1: Formula SAE-Electric vehicle.

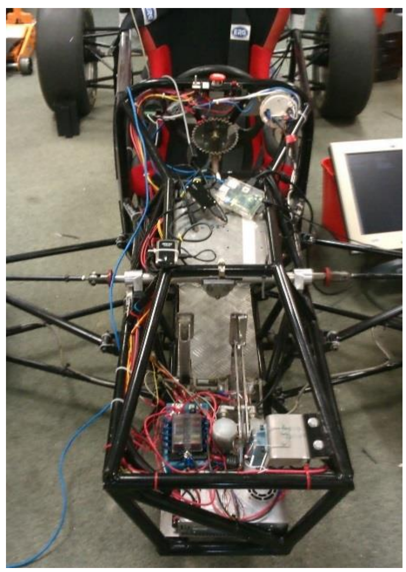

Figure 2: Formula SAE vehicle with drive-by-wire components installed.

Conversion of the vehicle to full drive-by-wire capability required the introduction of new electronics to the vehicle, the installation of actuators and a low-level microcontroller capable of controlling the autonomous system. The design of the system was to meet key design parameters including a design that was unobtrusive to the driver so the vehicle could be driven manually, a USB interface for accepting commands from a high-level controller that would tell the autonomous low-level system how to behave and a focus on safety systems.

2. Literature Review

2.1. Review of Previous REV Work into Drive-By-Wire Systems

In 2010/11 the REV Project implemented modifications to a BMW X5 in order to add electronically controlled actuators to the vehicle. The purpose of these systems was to enable the development of driver assistance aids such as obstacle avoidance or collision mitigation. In order to do this, actuation of both steering angle and brake force was required. Any modifications to the vehicle had to be nonintrusive in order to allow the vehicle to be driven by a human driver.

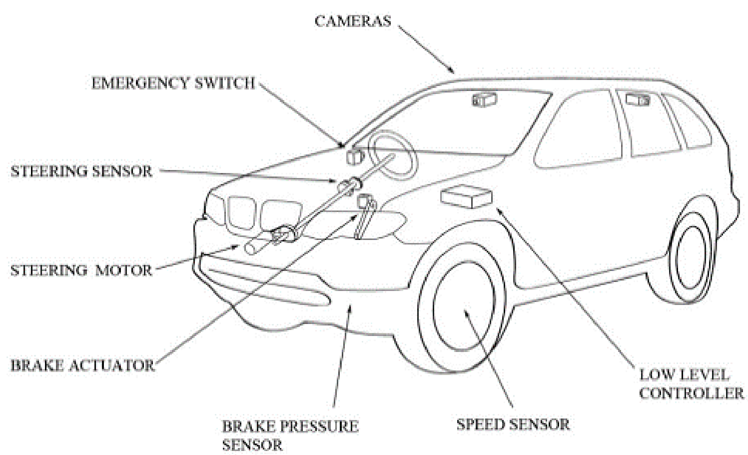

Figure 3: Overview of the BMW X5 modified to drive-by-wire [1].

When considering the best techniques in order to develop drive-by-wire systems, numerous criteria must be met. More specifically, both the reliability of the added system and the system's implications on safety to both the vehicle's occupants and its existing systems are the highest priority and must be critically assessed and tested. It was found that in order to preserve occupant safety and to reduce the impact of drive-by-wire modifications to the X5, the addition of a DC motor (with inbuilt gear box) located in the engine bay was the most appropriate solution to actuate the steering angle of the vehicle [2]. The DC motor was coupled to the steering shaft using a belt drive and is shielded from thermal radiation generated in the engine bay by an aluminium shield. This solution enabled modifications to the interior of the vehicle to be minimised, occupant safety to be preserved and the usability of the vehicle to be unhindered by such modification. Feedback of steering wheel position and hence the heading of the X5 required an additional sensor to be installed. The use of a Vishay 601HE Hall Effect sensor coupled to the steering column via a gear drive enabled accurate steering position feedback to an on-board controller [1].

Actuation of the brake pedal in order to engage the brakes of the X5 was desirable as this did not interfere with the original systems of the vehicle, deemed reliable and was reasonably easy to implement [1]. An SSPS-105 servomotor was installed in the interior of the vehicle above the brake pedal. A bracket couples the servomotor to the brake function by applying a force to the upper arm that the brake pedal is attached to, causing the brake assembly to act as if a human was applying the brakes. For safety reasons, this design allows the brake to be further engaged by the driver if necessary as the bracket is not mechanically fixed to the upper arm of the brake linkage [1].

To coordinate the drive-by-wire components, a microcontroller system based on the Arduino Uno was installed. This microcontroller also communicates with a high-level control system in order to receive steer- and brake-by-wire commands. The high-level system provides decision making capabilities and possesses the processing power to both interface with and process data from sensors that detect if a collision is imminent. Low-level data from the microcontroller is fed back to the high-level system to assess the performance of obstacle avoidance algorithms in order to judge the effectiveness of various techniques. Parameters such as sensor values obtained by the low-level system are also reported.

2.2. Review of Commercial Drive-By-Wire Systems

As manufacturers in the automotive industry continue to take advantage of new technologies the various functions of a vehicle tend to become increasingly automated [3]. Electric power steering or electric power assisted steering is a technology which is being employed by numerous automotive manufacturers to reduce the effort a driver must exert to steer a vehicle. Such a system demonstrates the move from mechanical systems; in this case hydraulic power assisted steering to electronically controlled actuators. While varying designs have been considered on such systems the basic principle behind them is the same: when a driver attempts to control the vehicle, feedback from sensors detect and provide data to control systems. The feedback is interpreted, processed and the electronic control system is able to determine how the driver's input should affect the control of the vehicle.

With the introduction of steering assistance, manufacturers have taken one step closer to completely decoupling driver input from physically actuating a vehicle's systems. While hydraulic systems are typically used to assist a driver to steer, electric assistance is becoming more popular in order to take advantage of characteristics such as lower power consumption [4]. Currently, different mounting positions of the electric assist motor include coupling the motor to the steering column, pinion or rack [4]. Figure 4 shows an example of a column mounted electric assistance setup. To determine the level of assistance required, the control system must collect feedback from torque applied to the steering wheel and speed sensors that take measurements of the vehicle's current travelling speed [5]. Electronic control systems also enable manufacturers to implement additional safety features to a vehicle. Control algorithms that provide capabilities such as keeping a vehicle inside a lane when there is no driver input aim to increase road safety [6]. Legal concerns prevent a full steer-by-wire implementation [5], [6]. While this could reduce driver steering effort considerably, a failure in the steering system would prevent the driver from manually controlling the vehicle's direction. In the event of a failure, it is preferable that a mechanical link is still present, so that control of steering is still possible.

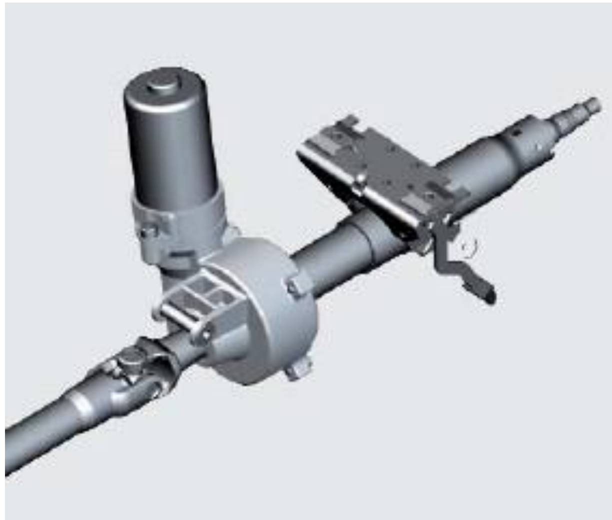

Figure 4: An electric motor (the vertical cylinder) provides steering assistance by driving the steering column [7].

Commercial application of brake-by-wire systems have allowed reduced effort in applying braking forces. Brake control system use feedback from multiple sensors such as Hall Effect sensors that convert brake pedal displacement into an electronic signal [8]. These sensors provide feedback into a brake control unit and also provide sensor fault/error checking capabilities. Brake-by-wire improves braking performance as electronic control systems can be used to adapt the application of brakes according to current factors. Factors such as current wheel speed can be measured from sensors and various control methods (such as new control algorithms, ABS and electronic stability programs) can be developed [9], [10] for use by electronic control system which result in increased performance. Resistance on the brake pedal is still felt by the driver and failure of the brake control unit deactivates electronic control systems while still allowing manual hydraulic forces to be applied to the brakes [9]. Shown in Figure 5 is a hall sensor assembly used in the commercial automotive industry.

Figure 5: A hall sensor assembly that is attached to a brake pedal mounting to allow computer assisted braking. Two hall sensors are present to allow for redundancy [11].

Throttle-by-wire systems use a similar method to that of brake-by-wire systems. A sensor that outputs an analogue voltage proportional to the amount that the accelerator pedal is depressed is used as feedback for throttle control. The accelerator pedal is not mechanically linked to throttle control as in earlier mechanical designs [12]. Instead, an electric motor acts upon a throttle valve to allow alteration of acceleration rate. Electronic control of engine throttle allows more efficient operation of the motor through the use of electronic control systems [12]. Furthermore, sensor failure does not result in a runaway vehicle: upon detection of throttle sensor failure, the output from the vehicle's motor is limited via a mechanical mechanism [13]. Figure 6 demonstrates various engine throttle conditions under differing sensor states.

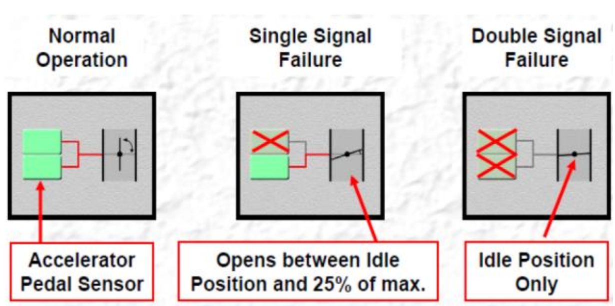

Figure 6: Operational states of engine throttle of Toyota's 2nd generation Electronic Throttle Control System-intelligence [14].

2.3. Review of the Addition of Drive-by-Wire Systems to Existing Vehicles

While commercial vehicles are typically constructed with certain by-wire technologies, conversions or additions to vehicles to allow the introduction of user controlled systems is not new. For example, the National Highway Traffic Safety Administration (US Department of Transportation) has modified vehicles to record driver input during certain manoeuvres (see Figure 7). This allows data to be used in order to quantify ‘reasonable’ driver performance (such as steering wheel turn rate) in manoeuvres that demand driver action [15]. It also provides data to guide manufacturers in the design of steer-by-wire systems as these results can be used as benchmarks during design of commercial systems used in the automotive industry. Naturally, a drive-by-wire system’s design parameters (such as steering wheel turn rate) should meet or exceed human performance.

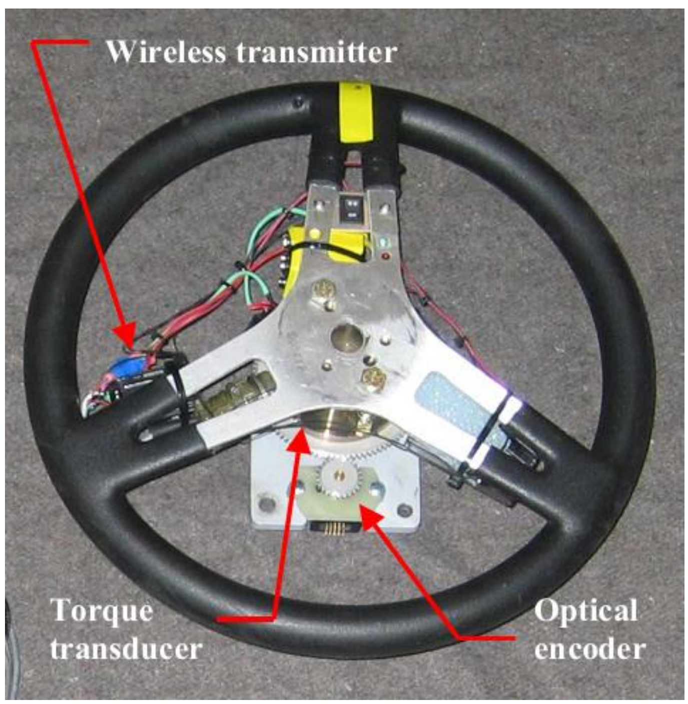

Figure 7: Steering wheel with position and torque feedback sensors [15].

While the sole purpose of the apparatus in Figure 7 is to log data from driver inputs the system shown in Figure 8 is designed to take control of the vehicle. This setup is being used to test control of a vehicle’s heading in the absence of driver input in order to develop lane keeping technology that can automatically keep a vehicle in a road lane

[16]. Using a DC motor connected to the steering column via a belt drive, the setup can apply 20Nm of torque while turning the steering wheel at 700 degrees/second while an encoder is used to provide feedback of the position of the steering wheel [16]. As evident in Figure 8, the modifications to the vehicle in order to achieve this impact on the driver's space and steering wheel.

In addition to conversions for testing of new control techniques, the Defense Advanced Research Projects Agency (DARPA) funds the 'DARPA Grand Challenge'. With the requirement that an autonomous vehicle travel over rough terrain it is a must that reliable control of a vehicle is maintained. Stanford University's entry to the 2005 DARPA Grand Challenge uses a Volkswagen Touareg. Taking advantage of existing throttle and brake-by-wire systems, the Stanford team was able to electronically control these two functions without mechanical systems [17]. Additionally, a motor has been installed inside the vehicle compartment above the driver's foot well. This allows the steering of the vehicle to be controlled as it drives the steering column of the Touareg via a chain drive.

Figure 8: Modified steering setup for actuation by an electric motor [16].

3. Conversion of the Formula SAE Vehicle to Full Drive-by-Wire

3.1. Brake-by-Wire System

The brake pedal on the SAE vehicle directly drives a hydraulic reservoir which applies front disc brakes. There are no existing electronics that assist braking similar to that in a commercial vehicle. In response to the application of the brakes, a constant force acts on the brake pedal, attempting to return the pedal to its original, disengaged position. Additionally, space for modification on the driver side of the pedal is small as demonstrated in Figure 9. As a requirement for the design of the autonomous system is to allow a driver to use the vehicle normally while the system is installed, no modifications could be made that could possibly interfere with a driver's actions. This way the vehicle can still be driven manually. There is limited space above the pedal and as a result a mechanical system could not be installed above the pedal without obstructing space for the driver's foot.

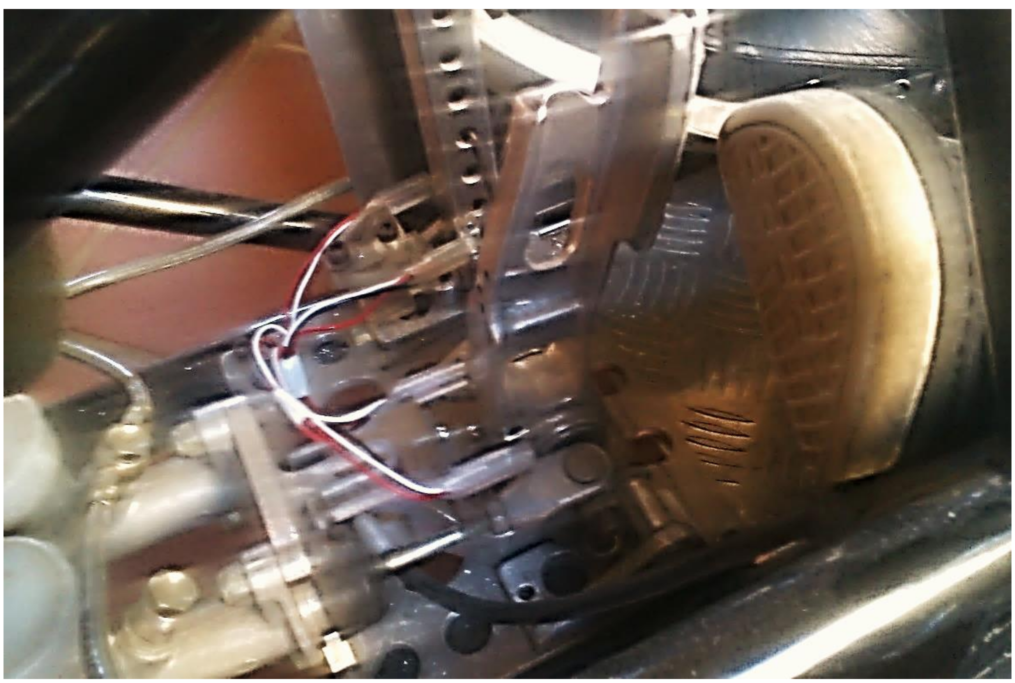

Figure 9: The brake pedal of the Formula SAE vehicle. The beige object is the shoe of a driver.

It was decided that the best method to provide actuation of the brake was to pull the brake pedal back. This would mean that any mechanical systems would be installed at the front of the vehicle where there was ample space. A SSPS-105 CPU-HS variant servomotor was already available and deemed suitable to use for actuation of the brake. For this reason, alternative methods such as investigating replacement braking systems or modifying the braking system to include electromechanical devices capable of altering the hydraulic pressure were not investigated. Such systems would have required further financial expenditure and modification of the existing hydraulic system was seen as a safety risk.

Early conceptual designs focused on turning the servomotor's rotational output into movement appropriate for moving the brake pedal about its fixed axis of rotation. Figure 10 shows an early concept in which a rectangular metal frame could be used to push the pedal downwards. The servomotor would be attached to the open ended axle towards the bottom of the figure and could rotate the metal frame. In doing so, the brake pedal could be pushed in order to apply the brakes. The hydraulic force from the reservoir would be responsible for disengaging the brake as the metal bar was returned to a position that did not apply force to the pedal. Unfortunately this design would interfere with the brake pedal on the driver's side and was consequently eliminated from further consideration due to this factor.

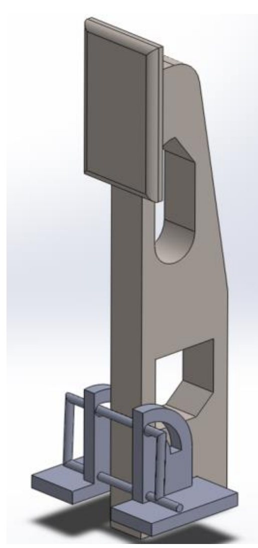

Figure 10: CAD drawing of an early brake acutation concept design.

Alternatively, the servomotor could be used to tension a wire attached to the rear of the brake pedal in order to further engage the brake. However, such a system would ideally require feedback to ensure that the cable is adequately tensioned in all conditions. This would have introduced an additional cost and increased the complexity of the braking system. If no feedback was present, this method could still be used as such a setup could be calibrated to assume certain servomotor positions correspond to a certain displacement of the brake pedal. However, this would not detect if the wire had come slack over time. Additionally, if a driver pushed brake down further than the autonomous system the wire would go slack. This introduced a safety risk as the wire could get caught. If not calibrated correctly, excessive slack in the wire would cause slower application of the brake.

The design that was chosen to implement the brake-by-wire capability involved mounting the servomotor in the front of the vehicle behind the brake pedal. This ensured that it would not interfere with the driver's ability to use the brake. By installing a bracket to the side of the pedal the servomotor could be used to pull the pedal away from the driver and thus engage the brake. The pedal's natural tendancy to return to the neutral, unapplied position is relied upon in order to return the brake to a disengaged position. Figure 11 shows the setup required to achieve this. For safety reasons, a curve in the bracket mounted to the side of the pedal allows the driver to further apply the brakes of the vehicle if necessary. It also serves to decouple manual movement of the brake pedal from forcing the servomotor to move with the pedal's displacement. This prevents unnecessary wear on the servomotor and allows the brake pedal to return to a non-braking position after the brake pedal has been released. By using such a method the vehicle's brake system could still be used when the autonomous system is off and the vehicle is being driven manually. Additionally, the brake can be manually engaged further than the autonomous system's set point.

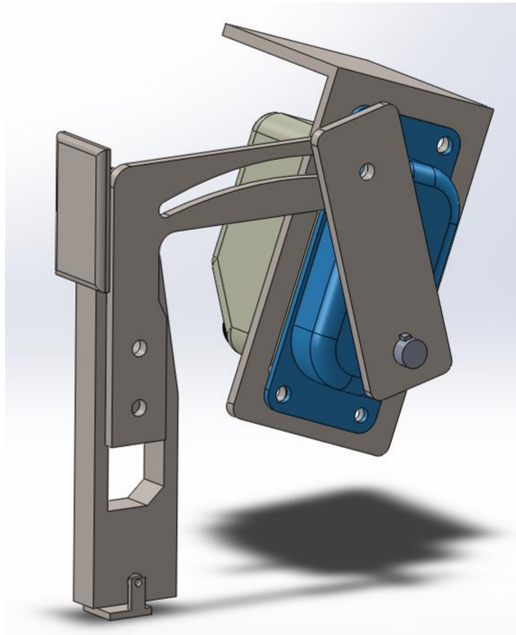

Figure 11: CAD Drawing of an initial brake-by-wire design concept.

Unfortunately, the drawback of the design shown in Figure 11 was that the bracket which houses the servomotor would prevent easy access to the brake hydraulic resivours on the vehicle. The design was modified in order to allow easy access to the resivours by using two extra brackets to couple the servomotor’s movement to the pedal’s slotted bracket. The resulting mechanical coupling is shown in Figure 12.

Figure 12: CAD Drawing of the final brake linkage used for the brake-by-wire system.

3.1.2. Details of Chosen Mechanical Design

As a consequence of the constant hydraulic force attempting to return the brake pedal to the disengaged position, calculations of servomotor torque would have to conform to the continuous torque ratings of the servomotor. The SSPS-105 servomotor used for the brake-by-wire system was a high speed model. The high speed SSPS-105 servomotor is capable of applying a maximum of peak torque of 190Kgcm with a constant torque of 31.6Kgcm [18]. The dimensions of the linkage shown in Figure 13 were designed using measurements of the vehicle, where the red line has length of 20cm, the yellow line has length 21cm and the green line 8cm. Using the equation below, the servomotor can apply 38.75N to the bracket attached to the brake. By using a scale to apply this force to the pedal at the same vertical distance from the pedal's pivot as the attached bracket, it was determined that such a force was adequate to slow the vehicle.

$$Torque = F \times r$$

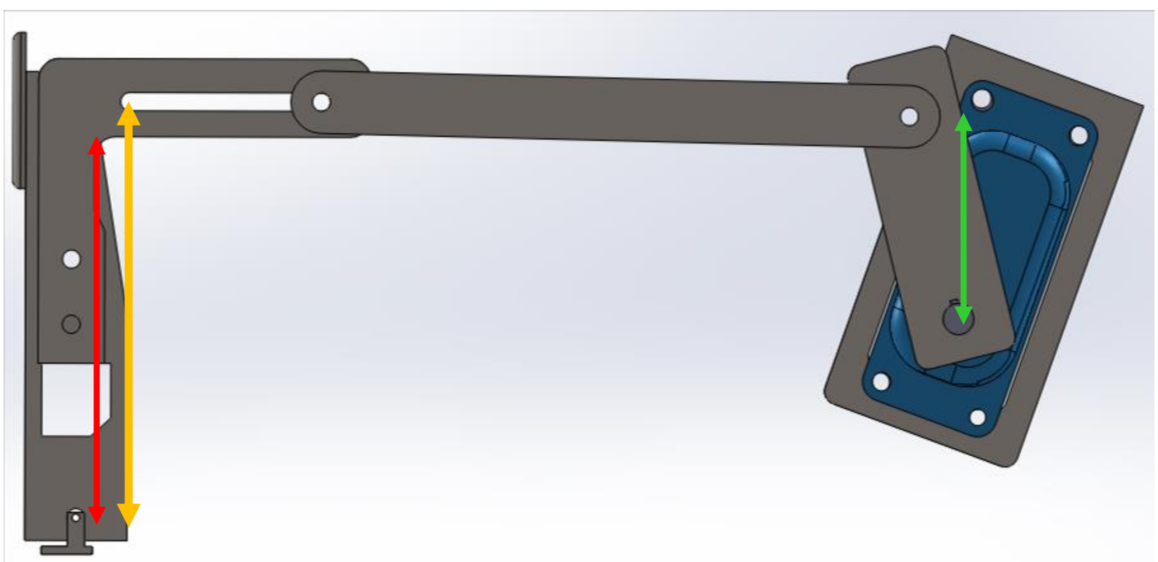

Figure 13: Measurements for design of the brake-by-wire linkage.

In order to ensure the designed linkage was adequate to handle the forces required for applying the brake, the University of Western Australia's Mechanical Workshop staff were consulted. It was decided that in order to preserve the structural integrity of the brake pedal it was not to be modified. Additionally, thrust needle roller bearings were identified to be the bearing to insert between the arms of the linkage in order to reduce wear and friction. Material type was chosen to match the material of the servomotor's key while plate thicknesses were chosen in order to ensure that mechanical strength was over engineered. The assumption that the brackets were adequate for the situation was not backed up with simulation and as such further testing could be carried out to validate this. All parts of the brake linkage were designed with rounded edges to prevent cuts and minimise sharp edges present in the front of the vehicle. Furthermore, designs which were flat and thus could be laser cut were used in order to reduce cost and minimise any required workshop time.

In order to couple the arms of the design together M6 bolts were used. Since the bolts would be taking force in a shear direction the shear strength of an M6 bolt was checked to ensure the shear force was within limits. With a shear strength of 4kN for a threaded M6 bolt (AS1111, AS2451) [19] [20], the use of M6 bolts was appropriate for the task. Additionally, the brake linkage can never become misaligned or miss engaging by design.

3.1.3. Brake-by-Wire Electrical Systems

The electrical interface of the servomotor is by means of a photo coupler which is powered by a 5V power supply and requires 12mA. It accepts a PWM signal with a 15ms period or greater and has under/over run protection to prevent it from being driven past its boundary of operation [21]. The maximum current required on the power rails of the servomotor is 9 amps at 12V. These specifications would have to be met when choosing the microcontroller for the low-level system and when constructing the electrical system as a whole. Of note is the servomotor's requirement of receiving a control signal after the power is switched off due to internal capacitance present in the servomotor power rails [21]. This prevents unusual movement of the servomotor at power down, releases the brake from autonomous control allowing the brakes to function as normal and prevents the servomotor from having to be moved manually to a disengaged position. The REV Autonomous Low-Level Wiring Diagram located in the Appendix reveals the 555 timer circuit (as designed at [22]) responsible for creating the appropriate PWM signal to turn the servomotor to the disengaged position when the low-level system is turned off. The electrical system including the setup of the 555 timer circuit is discussed in further detail in the Low-Level System Circuit Diagram section with diagrams of the electronics that comprise the low-level autonomous system given in the Appendix.

3.1.4. Brake-by-Wire Measurements

After construction of the brake linkage, a scale was used to ensure that the servomotor was operating within its mechanical limits. By analysing video footage of the servomotor applying the brake from disengaged to fully engaged, the servomotor required an average time of 0.29 seconds to complete the task. Measurement of the repeatability of the brake to engage to the same position was measured by the angle in which the servomotor rotated from a referenced angle to the full brake position. This was done with the vehicle at stationary with no driver in the seat of the vehicle. An average error of 0.6° was measured.

3.2. Throttle-by-Wire systems

The Electric F-SAE vehicle had been converted to electric driver systems by previous students at the REV group. The vehicle has two KBL72301 Kelly motor controllers which provide a 5V rail with 40mA maximum current capacity [23] for powering throttle sensors. This provides a unique advantage over the conversion of traditional combustion engine SAE vehicles: conversion to throttle-by-wire control can be achieved through either a mechanical means of actuating the accelerator pedal or through a pure electronic system. In order to reduce the modifications made to the existing vehicle, have less chance of interfering with the vehicle's operation in manual mode, reduce maintenance and reduce the cost of conversion it was opted that the electronic control method be used. This allowed for near instant, precise control of the throttle signal passed back to the drive controllers.

Since the option to control the acceleration of the vehicle electronically was chosen, a method to switch between the existing hall sensors for the driver and the autonomous system had to be devised. Additionally, the original hall sensor signal had to be characterised in order determine what signal had to be reproduced by the low-level controller. Figure 14 reveals the output signal of the existing throttle sensors when the accelerator pedal was initially held at full acceleration and then released. The sensor output comprises of an analogue signal bounded between 4.04V and 849mV. A linear relationship between pedal displacement and output voltage is present between the two bounds when ignoring the abnormality at the upper bound voltage. The abnormality observed near the off voltage of 849mV is due to the pedal bouncing back from its mechanical stopping limit.

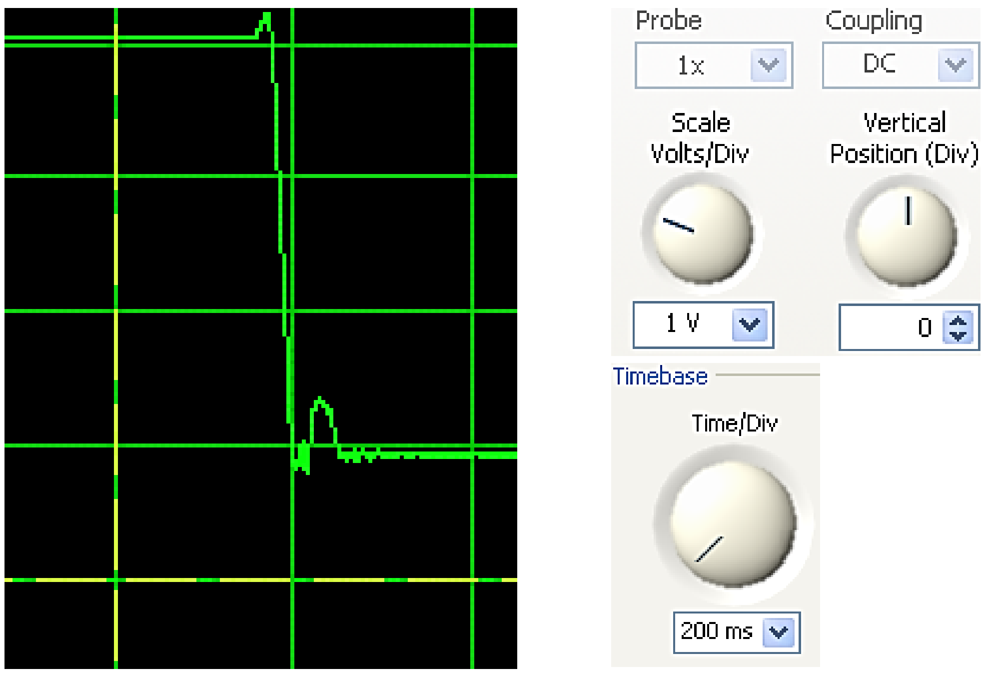

Figure 14: Measurement of the throttle hall sensor from full acceleration to no acceleration.

A relay was used to switch between throttle-by-wire and manual acceleration. This relay is energised when the autonomous system is turned on. When the system is off or if the autonomous system or relay fails, control is given back to the driver as the normally closed contracts of the relay correspond to the original throttle sensor signals being passed to the drive controllers. Additionally, the vehicle’s throttle can be controlled normally without the driver being required to take any action. A switch is also present on a dashboard near the driver that allows manual acceleration while the system is in autonomous mode.

To control the low-level system an Arduino Uno microcontroller was used. The justification for the choice of microcontroller is discussed in the 'Autonomous Low Level Controller' section. The Arduino Uno does not have built in analogue-to-digital converters and the use of the analogWrite command outputs a Pulse Width Modulation signal with period of 490Hz [24]. Additionally the pins of the microcontroller have a 40mA source/sink limit which cannot be exceeded [25]. A Mean Well SD-350C-12 DC-DC converter was used to power the low-level systems from the vehicle's existing battery pack. This DC-DC converter is an electrically isolating power supply. This introduces an additional challenge in the implementation of throttle-by-wire as the control signal from the autonomous system must be fed back to the drive controllers without electrically connecting the two systems together.

In order to construct the throttle-by-wire systems it was clear that the following action had to be taken:

- The Arduino PWM output had to be converted to an analogue voltage
- This signal then had to be passed through an isolating system to the motor controllers
- Any circuits constructed had to conform to both current limits of the Arduino and Kelly motor controllers and use available voltage supplies

In order to provide an analogue feedback signal to the drive motor controllers an ISO124 isolation amplifier was used. This integrated circuit has by default a unity gain amplifier and an electrically isolating setup from an input pin to an output pin. Since existing electrical systems contain only single sided power supplies the datasheet of the ISO124 would suggest a setup as show in Figure 15 below. However, there are two issues with implementing this system:

- The output side of the chip (V_{S2}) requires a 15V supply not currently present on the vehicle

- With the highest voltage available on the input side (V_{S1}) being 12V, a range of -2 to 2V input signal can be used. This is not adequate to reproduce the whole range of the throttle signal.

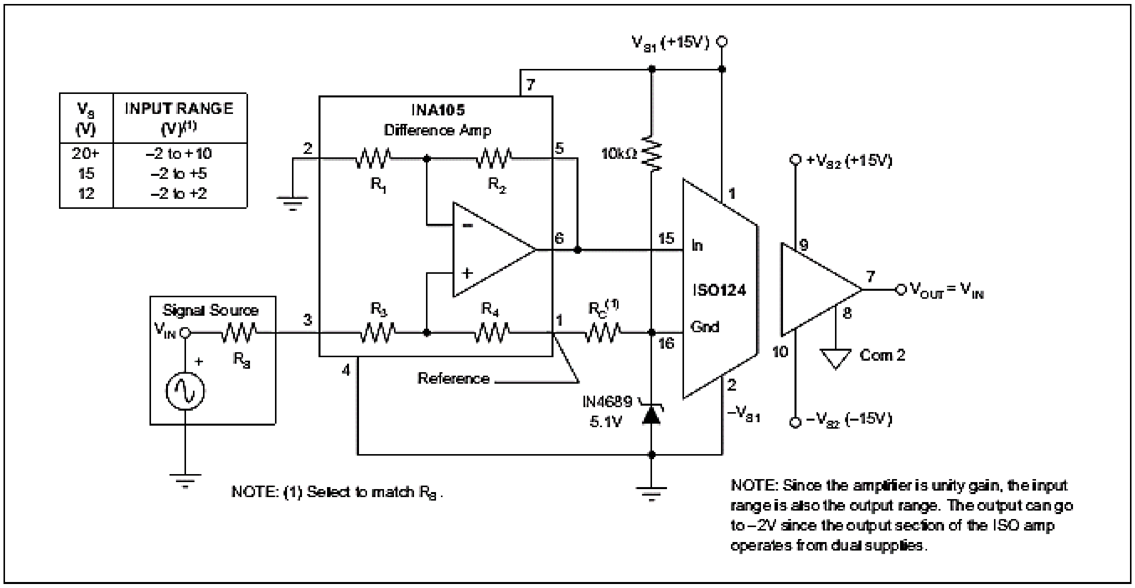

Figure 15: The standard setup for the ISO124 under a single positive rail voltage available on the input side [26].

To overcome this a dual rail power supply was required on both the output and input of the ISO124 chip. The ISO124 could then be used as described by figure 2 in its datasheet. In order to minimise component count and create a compact design two MAXIM680 chips were used to power the ISO124. These chips are dual charge pumps which create ±10V from a single +5V source. However the MAXIM680 does not provide a regulated voltage and as current draw from the output of the chip increases the voltage output provided by the chip sags closer to ground. Using the equation in Figure 16 below and values of maximum quiescent current draw of the ISO124 for I_{L+} and I_{L-} (7mA) along with an RS value of 150Ω as described in the datasheet for the MAXIM680 the approximate minimum output voltage at quiescent load was calculated to be 7.9V on the positive output rail. This value gives a margin of approximately 4V above the maximum required value of the original throttle signal.

$$(V_{DROP}+) = I_L+ \times RS+ = (I_L+ + I_L-) \times RS+$$

Figure 16: The equation which calculates the voltage drop on the positive rail of the MAXIM680 chip with respect to current draw [27].

In order to convert the PWM output of the Arduino microcontroller a first order low pass filter was used to smooth the PWM signal into an analogue waveform. A low pass filter was simulated in OrCAD PSpice with the 200kΩ input resistance of the ISO124. The design criteria of the filter required the following characteristics:

- Both values of the resistance and capacitance of the filter were easily available for purchase
- The filter did not exceed the 40mA source/sink capacity of the Arduino microcontroller pin
- Any delay introduced by the filter should be minimal to restrict the amount of lag introduced between the autonomous system and the drive controllers
- Ripple at the output of the filter should be minimised in order to limit effects such as alternating motor output when a constant throttle target is set by the autonomous low-level controller

Figure 17 reveals the simulation environment for design of the low pass filter. By default the Arduino analogWrite command outputs a 5V PWM signal at 490Hz [24]. In order to improve the waveform output from the filter the Arduino PWM frequency was increased using the method described by the datasheet for the microcontroller used in the Arduino. The highest frequency achievable was 7812.5 Hz as the timer that creates the PWM signal drives two output pins, with a second attached device accepting a maximum PWM frequency of 20 kHz. Using this new frequency for simulation in OrCAD PSpice results in the Pulse Width and Period as shown on the pulse voltage source in Figure 17 for a 50% duty cycle. Simulation of these voltage source values with numerous RC filter values resulted in a 180Ω resistor and a 16.8μF capacitor being chosen to construct the filter. Simulation shows that the maximum current source/sink value of the microcontroller is approximately 28mA. The output of the simulated filter with load is shown in Figure 18.

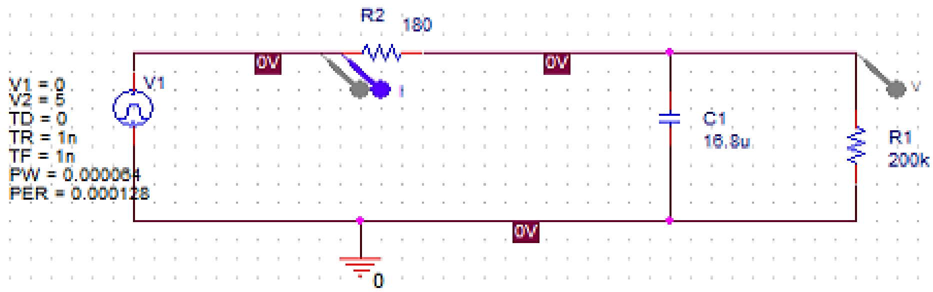

Figure 17: OrCAD PSpice simulation environment for the throttle-by-wire digital to analogue filter.

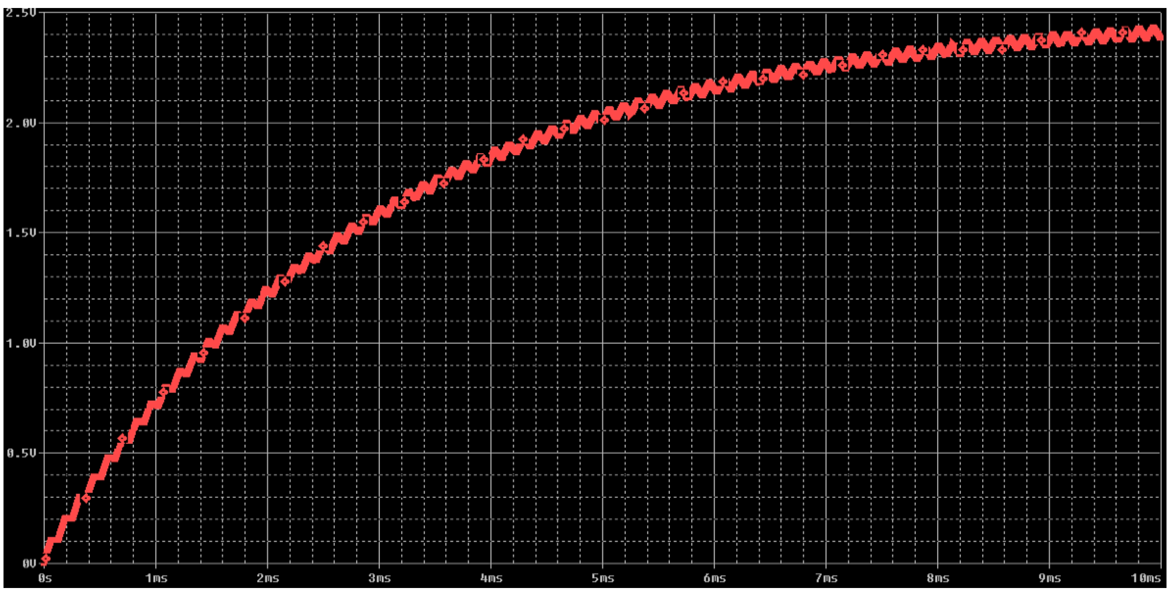

Figure 18: Output signal of the circuit in Figure 17 with a 50% input PWM duty cycle.

The electrical diagram of the throttle-by-wire system is included in the appendix, labelled 'REV Autonomous SAE Low Level Isolation Amplifier', along with a picture of the constructed board.

3.2.2. Throttle-by-Wire Measurements

Through the simulation results the delay introduced by the filter is in the order of milliseconds. The ripple shown in Figure 18 is not noticeable in the drive motor output and is indistinguishable from the use of the original throttle sensors. Figure 18 reveals a steady state offset as a 50% duty cycle should correspond to an analogue value of 2.5V.

This offset is easily overcome by adjustment of software values in the Arduino. By measuring the output of the circuit with a multimeter a linear relationship between the software integer representing the acceleration value of the vehicle and output analogue voltage of the circuit was present through the original range of the existing throttle sensors. It was measured that for every increment in software the output analogue voltage increased by 0.02V.

3.3. Steer-By-Wire Systems

3.3.1. Steering Position Feedback

Through previous research it was revealed that a common method used to obtain feedback of driver input and steering angle was to modify the steering wheel or steering column to introduce new sensors. With the requirement that the F-SAE vehicle still be driveable without needing to remove the autonomous system it was necessary to ensure that any feedback system did not obstruct the driver. Since space was a limiting factor in the driver's cockpit only small modifications could be made behind the steering wheel. Additionally, since the steering wheel is removable in order to aid the driver in exiting the vehicle (such as during an emergency), it was decided that no modifications would be made in the cockpit area.

After inspection of the steering setup of the F-SAE vehicle, the clearest area for mounting a sensor without disrupting the driver was located to be positioned directly behind the steering column mounting close to the driver. This area is shown in Figure 19 where the brown bar represents the steering column and the grey plate is the support that holds the steering column in place. A rotational sensor attached to this plate could then be coupled mechanically to the steering column in order to measure the vehicle's steering position while ensuring that the driver could not accidentally hit the coupling or the sensor when getting into or out of the vehicle. By coupling the steering sensor directly to the steering column, accurate feedback about the vehicle's steering direction is achieved. This overcomes issues of inaccurate data from encoders built in to actuators as issues such as belt slip cannot be detected from sensors built into the actuator.

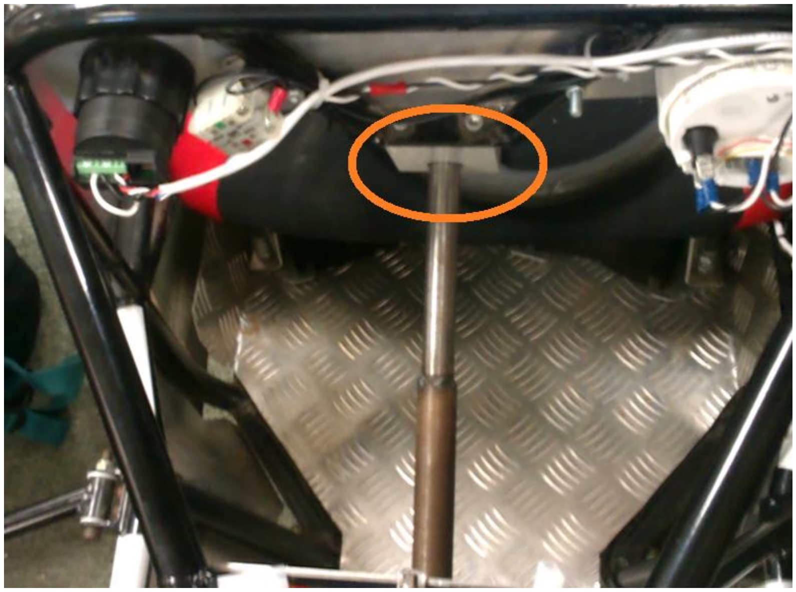

Figure 19: The chosen area to mount a sensor for steering position feedback.

In order to decide which rotational sensor to use, three main types of sensor were researched and the results summarised in Table 1. The use of an encoder would require the autonomous system to either assume that the steering was left in a reference position every time the system was initialised. Alternatively, switches could also be installed so that the system would perform a calibration routine on start-up. This would involve the steering system moving the steering until a limit switch was hit. The low-level controller would then be able to count the pulses from the encoder to determine how far away from this position the steering is. However, the use of a potentiometer or rotary hall effect sensor provided a simpler and less costly solution which would eliminate any undesirable start-up sequences. Ultimately it was decided that the rotary hall effect sensor would be used due to this fact along with its long lifetime characteristics.

Sensor Type	Advantages	Disadvantages
Encoder	• Accurate • Does not have mechanical limits on rotation limits	• Certain encoders are expensive • Requires knowledge of start-up position or start routine • Requires an interrupt pin on microcontroller for timely recording of pulses

Wire wound potentiometer (Bourns 3590)	• Cheap • Large turning range leads to high sensitivity • Analogue output easy to work with	• Relies on a wiper scraping across a track and hence suffers from wear and lower lifetime • Characteristics can change over time and with temperature
Rotary hall effect sensor (Honeywell HRS100SSAB-090)	• Hall effect leads to long lifetime • Analogue output easy to work with • Accurate	• Small rotation range available for purchase from supplier leads to large gears to couple to steering column in order to remain within rotational limits of the sensor

Table 1: A comparison between three different types of sensors suitable for steering position feedback.

3.3.2. Mechanical Design for Feedback System

With the decision to mount a rotational sensor above the steering column, a bracket had to be designed in order to house the sensor. Figure 20 shows the initial design of the bracket that would house the sensor. The slot in the bracket would allow adjustment of the distance between the sensor and the steering column, allowing for the accommodation of different gear ratios between the sensor and column. However, the complication of performing numerous tight bends in close proximity in the material led to this design requiring excessive workshop time. By sourcing prefabricated metal brackets it was possible to not only reduce the cost of the bracket but also increase its flexibility. These brackets were also large enough to house either the wire wound or hall effect sensor. Shown on the right side of Figure 20 is the final fabricated bracket. By including slots on the side of the design it allows the distance between the sensor and steering column to be adjusted. Additionally the design allows the angle between the sensor's shaft and steering column to be adjusted. This is achieved by loosening the nuts which hold the central bracket and rotating it. The hall effect sensor's shaft protrudes through the circular hole and an anti-rotation pin prevents its base from rotating. The nuts on the design are responsible for holding the central bracket, and hence the sensor in place.

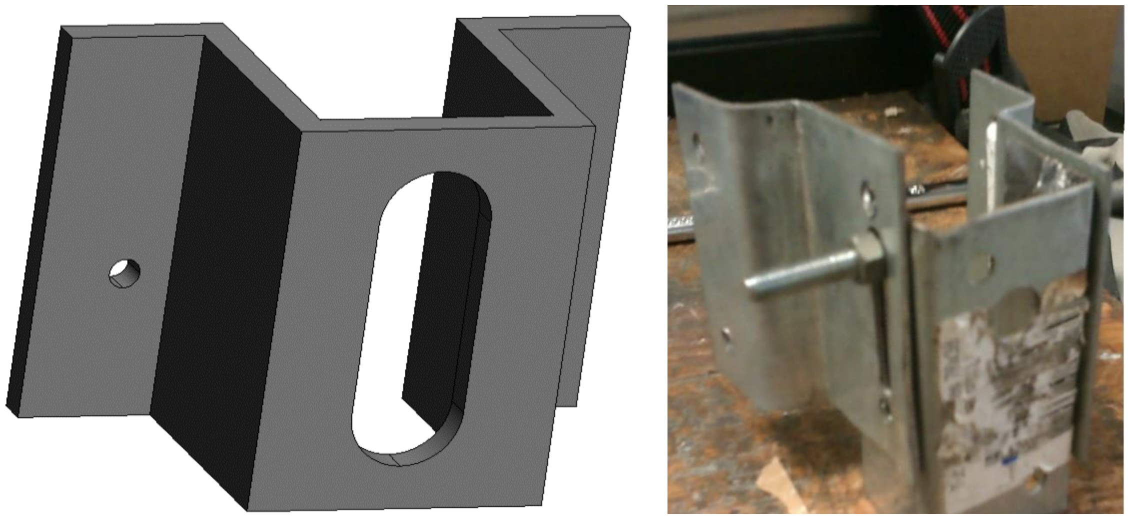

Figure 20: The initial bracket design to house the steering feedback sensor (left), with the final bracket shown on the right.

The Honeywell HRS100SSAB-090 hall effect sensor has a maximum shaft rotational range of 90˚. To turn the wheels of the F-SAE vehicle from full right to full left requires a 320˚ turn of the vehicle's steering wheel and hence steering column. Gears were used to couple to the rotation of the steering column to the sensor as they could easily be obtained. Acrylic was the material used to create the gears as they would be non-load bearing (the hall sensor requires 0.014 Nm to turn the shaft [28]). The ratio of the sensor and steering column angles would require a gear ratio of 3.5:1, with the large gear being on the steering sensor. In order to provide leeway for staying within the bounds of the sensor, a gear ratio of 4:1 was chosen. The diameter of the shaft of the HRS100SSAB-090 sensor is approximately 6.35mm while diameter of the steering column is 19mm. Under the assumption that the effective diameter of a gear mounted on the shaft is 25mm, a 10cm effective diameter gear on the sensor would have to be used. In order to design these gears an online gear generator program was used [29] and the files imported into Solidworks for manufacture. However, due to the geometry of the vehicle's steering column, it was not possible to mount a gear around the upper length of the steering column. A split gear was designed in order to overcome this and is shown in Figure 21. With the setup described, a 1:1 mapping of steering position to sensor output voltage was achieved. The autonomous system would also have the exact steering direction of the vehicle available at start-up without requiring any additional action or intervention beyond reading the analogue voltage from the sensor. The completed assembly is shown in Figure 22.

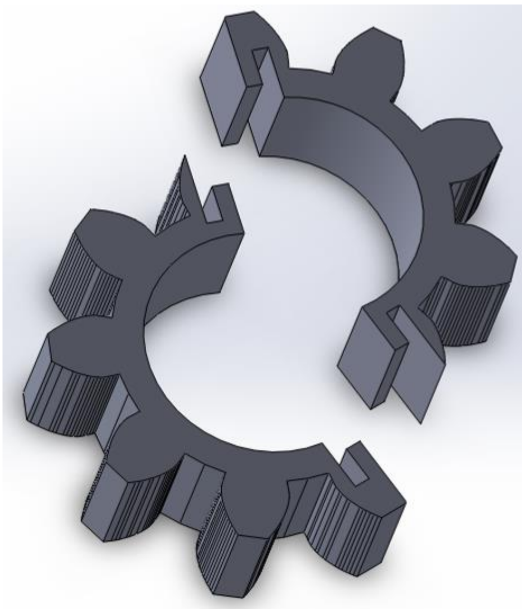

Figure 21: Split gear design.

Figure 22: The complete steering sensor assembly.

3.3.3. Electrical Systems for Steering Feedback

The Honeywell HRS100SSAB-090 hall effect sensor requires a 5V power source and outputs an analogue voltage between 5% and 95% of the applied voltage [28]. This would translate to an output resolution of 4.5V/90˚ or a 0.05 Volt change in output voltage per degree of movement. In comparison, the Arduino microcontroller's Analogue to Digital Converter (ADC) reads from zero to 5V and outputs a value between 0 and 1023 from the analogRead command [30]. This translates to the DAC being able to detect changes of approximately 0.005V. Hence the accuracy of the steering position is not limited by the Arduino ADC. Under the assumption that the hall effect sensor outputs a pure analogue voltage and not a discretised output, the Arduino's ADC can detect steering column movements of 0.39˚.

3.3.4. Steering Motor Controller

In order to control a motor that could steer the vehicle, a motor controller was required that could handle high currents. The Pololu VNH2SP30 breakout board motor controller was selected for use. It is capable of handling peak currents of up to 30A and a continuous current of 15A and is shown in Figure 23. Further reasons for choosing the VNH2SP30 motor controller chip include the support of numerous safety features such as overvoltage and over temperature as well as error reporting capability. It also provides a feedback voltage that is proportional to the current drawn by the connected motor.

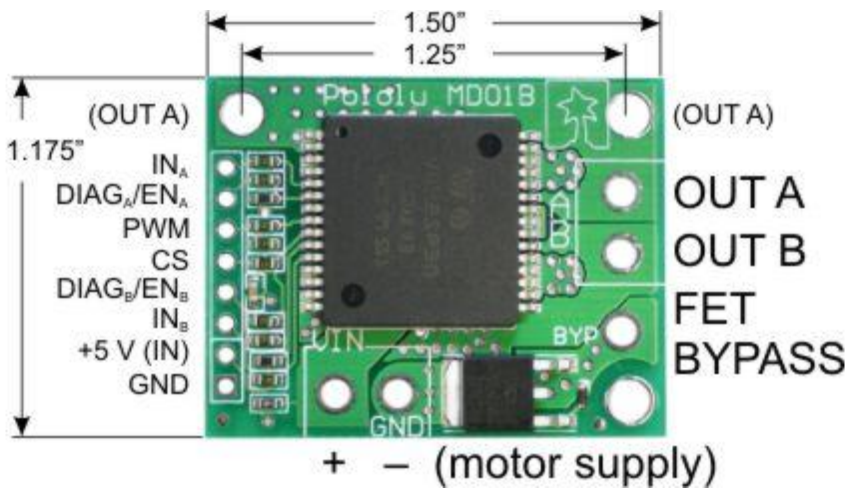

Figure 23: The Pololu VNH2SP30 motor controller breakout board [31].

In order to control the attached motor, the VNH2SP30 requires four digital pins and one PWM capable pin. The PWM pin sets the speed of the attached motor. Two digital pins (IN_X) are used to control the action of the attached motor. The remaining two digital pins (EN_X) are bidirectional digital logic pins. When one of these bidirectional pins are pulled low, the motor is set to coast. If the VNH2SP30 chip pulls either of these pins low, an error is present related to the operation of the motor controller. Additionally, the VNH2SP30 will automatically coast the motor in the event of an error. The bidirectional pins were attached to the Arduino microcontroller so that the error status of the motor controller could be read during operation. Operation of the device is listed in Figure 23 when no error is present.

IN_A	IN_B	$DIAG_A/EN_A$	$DIAG_B/EN_B$	OUT_A	OUT_B	CS	Operating mode
1	1	1	1	H	H	High Imp.	Brake to V_{CC}
1	0	1	1	H	L	$I_{SENSE}=I_{OUT}/K$	Clockwise (CW)
0	1	1	1	L	H	$I_{SENSE}=I_{OUT}/K$	Counterclockwise (CCW)
0	0	1	1	L	L	High Imp.	Brake to GND

Figure 23: Operation states of the VNH2SP30 under no fault conditions [32].

Since the motor controller is capable of delivering such high currents it was housed in a separate metal enclosure so that no other components (such as the Arduino microcontroller) would be damaged in the event of a possible severe failure. To ensure that the motor controller does not overheat, the motor controller was thermally attached to the inside of the protective metal case. Plastic screws were used to mount the board as the mounting holes on the breakout board is not electrically insulated [31]. The metal case is mounted in the nose area of the vehicle with numerous other low-level circuits.

3.3.5. Steer-by-Wire Actuator

In order to determine the appropriate actuator to adjust the steering position of the F-SAE vehicle, characteristics relating to the steering system of the vehicle had to be obtained. It was immediately clear that steering effort without a driver in the vehicle would be small as the addition of the driver would add load to the front wheels. While the purpose of the conversion of the vehicle to autonomous driving does not require a driver to be in the vehicle during operation, it was decided that the system should be capable of operation while a person was in the vehicle. This allowed for the use of drivers in the vehicle during autonomous tests. The purpose of this was to ensure that a 'safety driver' was always present who could shut off the autonomous system if required and take over control of the vehicle. In order to measure the torque required to turn the wheels of the vehicle, a torque wrench was attached to the steering rack. Figure 24 shows how this was achieved; by removing the steering column the torque wrench was inserted into the coupling of the steering rack. Using this method allowed the measurement of the torque required to turn the wheels while a driver was present in the vehicle. Measurements could also be taken of steering effort while the vehicle was moving at walking pace. Unfortunately, this technique would not allow investigation into the effects of the vehicle cornering at higher speeds as this posed a severe safety risk as the driver of the vehicle could not be in a seated position in order to operate the torque wrench and nor could the driver adequately steer the vehicle without the steering wheel and column being attached.

Figure 24: Method used to measure the torque required to turn the wheels of the SAE vehicle.

The torque wrench used had a minimum value of 8Nm. By using the torque wrench, the data in Table 2 was obtained for the F-SAE vehicle. This is in the order of magnitude of many F-SAE vehicles [33]. Measurements were also taken as to how fast the steering wheel could be turned. With the driver’s hands already in the required position to turn the steering wheel, an average of 0.8 seconds was required to turn the wheel from full left to full right. This measurement represents the maximum speed the drivers’ could turn the wheel and equates to a rotational speed of 400˚/second.

Surface Material	Driver weight (Kg)	Torque required at stationary (Nm)	Torque required at walking pace (Nm)
Dry, rough tiles	0	Less than 8	Less than 8
	106	11.5	Less than 8
Carpet	0	Less than 8	Less than 8
	106	11.4	Less than 8
Loose gravel road	0	Less than 8	Less than 8
	60	11.2	Less than 8
	106	11.6	Less than 8

Table 2: Data obtained during testing of the SAE vehicle's steering system.

Since the maximum torque required to steer a vehicle occurs when the vehicle is at stationary [34] it was desirable to meet this target when choosing a steering actuator for the following reasons:

- This would allow the autonomous system to turn the wheels of the vehicle when it is first turned on in order to obtain the correct heading at start-up while remaining stationary
- If the vehicle did stop next to an obstacle, it would not require manual assistance in order to steer away from the object
- Systems would not have to be added that ensured that the autonomous system does not turn the motor when the vehicle is at stationary
- Risk of accidentally using the system at stationary and hence damaging the drive train or actuator was reduced
- Confusion as to the success of steering response is reduced as the low-level system is able to respond to any input steering command at any time
- Concerns that if the vehicle was to be tested at higher speeds the steering actuator could be overpowered during tight cornering were diminished

In addition to quantifying the performance of a human driver and the vehicle's characteristics, a method of actuating the steering of the vehicle had to be determined. With the requirement that the vehicle still be driveable when the system is turned off it was not possible to add modifications near the steering wheel, nor interfere with the driver's leg room. In a similar manner to the converted X5 and systems mentioned in the literature review, a decision was made to control the steering of the vehicle by coupling a motor to the steering column. Particular attention had to be taken to ensure that the leg or foot room of the driver was not intruded upon. The choice of actuation system must also allow a driver to steer normally when the system is off without removal of the system. For safety reasons the system should also allow a driver to be able to take manual control of steering. In other words, the system should not 'lock' the steering in a particular position. Since a rotational movement was required to turn the steering column, a comparison of various electric motor types (shown in Table 3) was conducted. It was decided that a DC gear motor would be the most appropriate type of motor for this task. The use of a worm drive DC motor would have required a mechanical release system to disengage the motor. In an emergency situation, using a mechanical release (which due to space requirements would reside outside of the driver's reach) was not practical.

Motor type	Advantages	Disadvantages
Servomotor	• Easy position control achievable	• Once powered, does not coast • No speed control • May be damaged if moved manually
Worm Drive DC motor	• High torque • Compact	• Use of a worm drive would lock the steering system in place • System would have to be disassembled for manual driving
DC gear motor	• Flexible torque/speed combinations • Allows the steering to be manually used	• Gearbox increases cost • Gear mechanical limit must not be exceeded

Table 3: Comparison of different motor types for actuating the vehicle's steering direction.

The gear motor chosen to actuate the steering system of the vehicle comprises of a Z5D120-12GU DC motor with a 5GU40KB gearhead. The Z5D120-12GU motor is a 12V motor with a maximum current draw of 15 amps while the 5GU40KB gearhead is capable of transmitting a maximum torque of 11.76Nm [35]. This combination meets requirements to steer the vehicle when it is not in motion. By avoiding the use of a worm gear drive system the driver of the vehicle is able to steer in emergency situations while the autonomous system is functioning. Additionally, the motor and gearbox can physically fit in the space available above the driver's leg and next to the steering column. An advantage of mounting the motor in this area is that the motor could reside directly under an existing member of the vehicle's frame. Since the motor is housed underneath, it cannot be accidentally leant on, reducing the chance of damage to the motor's mounting bracket.

A belt drive power train with pulleys were used to couple the motor's output to the steering column. This had advantages over a chain drive as it is not only quieter but by avoiding the use of sprockets above the driver's legs reduces the chance that clothing could be caught by the mechanism. A mild steel plate as shown in Figure 25 was designed to mount the motor and gearbox combination to the vehicle. The motor mounting bracket provides belt tensioning capabilities as the bracket itself is slotted. This allows the belt to be tensioned as required by moving the motor to the appropriate position and securing it at the required distance from the steering column with mounting bolts.

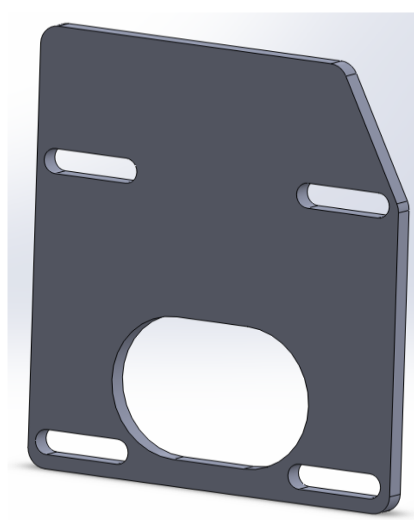

Figure 25: A drawing of the slotted bracket used to mount the steering actuator.

In order to select a belt drive to transmit the forces from the motor to the steering column the following had to be considered:

- The chosen belt had to be sufficient to handle the maximum power output required to move the steering system
- Given the limited space in the vehicle, small belt lengths had to be available for purchase
- If the belt were to be toothed, a sufficient number of meshing teeth on both pulleys had to be present
- Pulleys had to be available that were small enough to be unobtrusive to the driver's leg room and also have small enough diameter to fit side by side in the vehicle
- Pulleys had to have adequate an diameter to fit the 21mm in diameter steering column

By considering the adjustment provided by the bracket in Figure 25 and the available mounting area in the vehicle, a sketch which represents the approximate belt length was created in Solidworks. By using standard pulley diameters and considering the minimum and maximum distances between the steering column and motor shaft, the belt length could be calculated by considering the geometry in Figure 26. The approximate maximum and minimum belt lengths calculated are 372mm and 192mm respectively. By choosing a 1:1 ratio of pulleys, the centre distances between the pulleys can be calculated by:

$$Belt\ length = 2d_{centre} + L_1$$

where d_{centre} is the distance between the pulleys and $L_1 = \pi Pulley_{diameter}$. To centre the shaft of the motor in the adjustable bracket, the belt length was solved using d_{centre}=75mm and $Pulley_{diameter}$=62.5mm, resulting in a 350mm long belt being required.

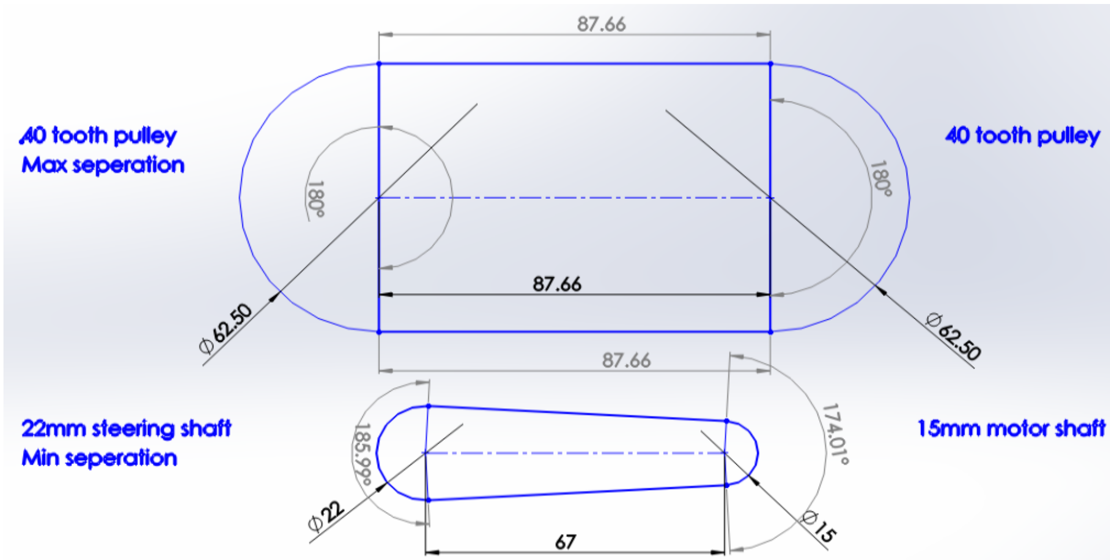

Figure 26: A Solidworks sketch used to determine the maximum and minimum belt lengths possible for use in the steering system.

To size the belt for the power requirements of the motor output, the graph in Figure 27 was used. The widest belt available with a 5M pitch is 25mm and corresponds to the 5M maximum capability line as shown in the graph. With Z5D120-12GU motor being rated at 120 watts, a vertical line at this value in Figure 27 corresponds to the belt being capable of this power transfer at speeds of over 16 RPM. Since the peak torque required to turn the wheels at stationary can be set to 13Nm (with some safety factor) and with the assumption that the belt is transferring the motor's maximum power, the RPM that the belt the belt is capable of handling could be calculated using the two equations below. This resulted in the belt moving at 88 RPM at a torque of 13Nm. By comparing the values of 120 watts and 88 RPM it is clear from Figure 27 that a 25mm wide 5M belt is capable of transmitting this peak requirement.

$$Power = \tau\omega$$

$$\omega = RPM\frac{2\pi}{60}$$

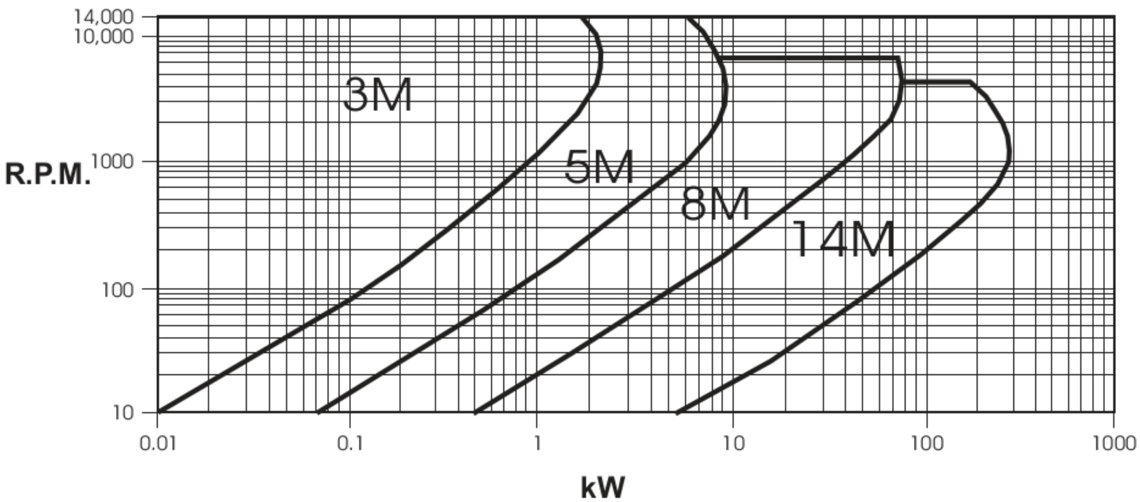

Figure 27: Belt capability graph for numerous pitched belts [36].

Using the above calculations, a 350-5M-25 belt was purchased along with two 30-5M-25 pulleys which had adequate centre to centre clearances. These pulleys did not interfere with the driver's leg room and are attached to their respective shafts with grub screws. The final assembly is shown in Figure 28.

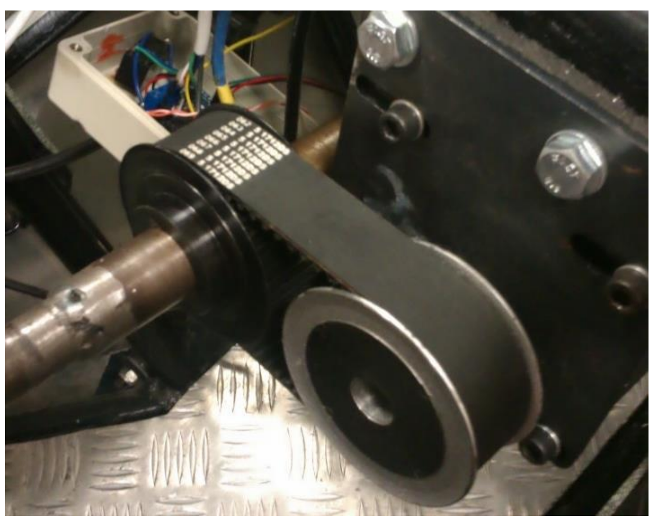
Figure 28: The constructed actuator for the autonomous steering system.

This setup allows the vehicle to be driven normally without decoupling the DC motor from the steering column. While the addition of the steering actuator does introduce the need for extra steering effort when a driver attempts to steer, the vehicle can be returned to its original steering effort (such as for driver training) by decoupling the belt. This way the additional steering effort introduced by the autonomous system can be removed without removal of the whole motor assembly.

3.3.6. Steer-by-Wire Measurements

Testing of the steering system required the speed at which the DC motor can turn the steering column, the ability of the system to return to the same position given the same input command and the linearity between input to the low-level controller and vehicle steering angle. Video footage of the system turning the vehicle from full left or full right to the straight position was used to determine the speed that the system operates. With no driver in the seat, the best case speed corresponded to an average steering wheel turn rate of 190°/second.

Linearity of the system was measured by recording the angle that the wheels of the vehicle were facing, with zero degrees being the position where the wheels point straight. With an R^2 value of 0.9976, a linear line of best fit appropriately describes the relationship between input steering integer commands to the low-level system and the angle that the wheels turn.

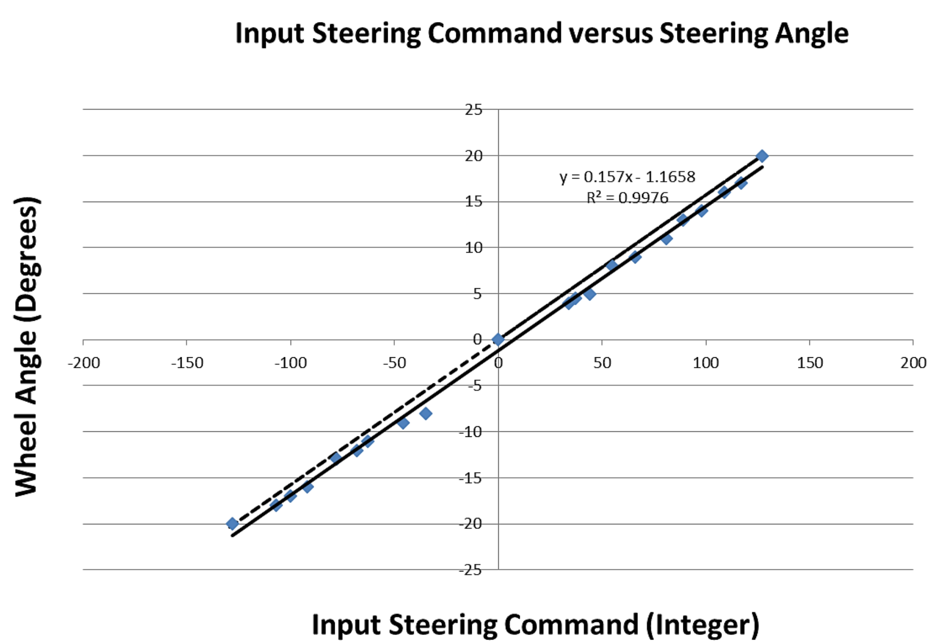

Figure 29: Data for measuring the linearity of the autonomous steering system and vehicle heading (courtesy of Thomas Drage). The dashed line represents the ideal, linear relationship.

Upon testing the steering system, jitter was observed when the system was at the desired set point. Since the motor is set to coast upon reaching the required target in order to make it easier for the driver to overcome the autonomous steering if required, the inertia of the steering system caused constant overshooting of the set point and hence oscillations. To mitigate this, a dead zone was introduced, letting the steering system coast the motor when slightly either side of the desired set point. While this reduced the oscillations, the accuracy of the system was reduced. Therefore, in order to measure the worst case error when using this method, the steering system the steering system was tested without a driver in the vehicle. The system's ability to steer the vehicle to numerous positions was measured, with the results presented in Table 4 and Figure 30. An error of this magnitude agrees with the results presented in Figure 29. New software which temporarily locks the motor upon reaching the desired position to avoid this has been created.

Target Steering Angle (Degrees)	Average Autonomous Steering Angle Error (Degrees)
15	0.86
0	0.93
-15	1.26

Table 4: Average autonomous steering angle error for various steering targets.

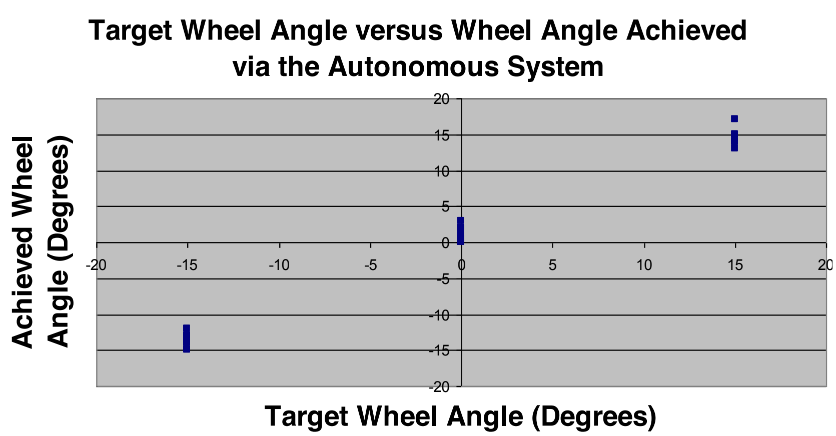

Figure 30: Graphical spread of the autonomous system's steering repeatability.

4. Autonomous Low-Level Controller

In order to coordinate the newly installed systems, a microcontroller solution was required. The chosen microcontroller had to provide the following features:

- Communication via USB interface was required in order to communicate with a high-level control system
- At least three PWM pins capable of having independent duty cycles for controlling the servomotor, accelerator circuit and VNH2SP30 motor controller
- Adequate digital pins in order to control the VNH2SP30 motor controller
- One or more analogue pins in order to read steering position feedback from the Honeywell HRS100SSAB-090 hall effect sensor
- An interrupt capable pin for feedback from a safety supervisor circuit (designed by Thomas Drage)
- Run on existing power supply present on the vehicle

An Arduino Uno was chosen as the low-level microcontroller. Not only did it satisfy the above design criteria, the low-level system would be based on a standard Atmel microcontroller. The Arduino Uno board comes prefabricated, reducing implementation time as a breakout board did not have to be designed and fabricated. It also has a USB connection built onto the printed circuit board. In addition to supporting the C language, the Arduino programming environment comes with established libraries. These libraries greatly simplified the implementation of the low-level control system as they provided support for USB communication, servomotor pulse generation and watchdog libraries along with other mathematical functions.

In order to decide which pins on the Arduino Uno were to be used for the various functions of the low-level system it was necessary to investigate which pins were capable of outputting a PWM signal, which had interrupt capabilities and how the design of the Arduino libraries interacted with the Atmel microcontroller. By viewing the circuit diagram for the Arduino Uno R3 it was clear that an Atmel ATMEGA328P was responsible for the functions attached to the headers on the board [37]. Using the datasheet for the ATMEGA328P and the circuit diagram for the Arduino Uno R3, the relationship between the pin labelling on the Arduino board and the original pins of the ATMEGA328P were established. The ATMEGA328P uses three timers in order to provide PWM capabilities [25] to six PWM pins. Each timer is linked to two digital pins on the microcontroller as demonstrated in table 5.

Timer	Pins on ATMEGA328P	Corresponding pins on Arduino board
0	11, 12	5, 6
1	15, 16	9, 10
2	5, 17	3, 11

Table 5: The relationship between timers and pins on the ATMEGA328P and the Arduino Uno silkscreen.

In order to ensure that adequate PWM pins were available for the accelerator circuit, servomotor and steering motor controller certain aspects had to be considered. The servomotor library uses timer 1 so pins 9 and 10 do not have PWM capability, but a servomotor signal can be output to any pin. An additional constraint is that the Arduino Uno uses timer 0 for many of its inbuilt functions [38]. As discussed previously, the PWM signal that drives the accelerator circuit had an increased frequency in order to increase desired signal characteristics. This meant that timer 0 could not be used for the accelerator output and that the only pins capable of producing a higher frequency PWM output were pins 3 and 1. By altering the frequency of timer 2, pins 3 and 11 would have an increased PWM frequency without affecting any other functions. This frequency could be increased up to a maximum of 20kHz as this is the limit of the VNH2SP30 steering motor controller [32]. Note that pin 2 is interrupt capable [39] and was hence used to enable feedback for an emergency brake command from the safety supervisor circuit while digital pins 0 and 1 are used for USB communication [39]. Figure 31 summarises the relationship between the headers on the Arduino board and the corresponding devices of the autonomous system.

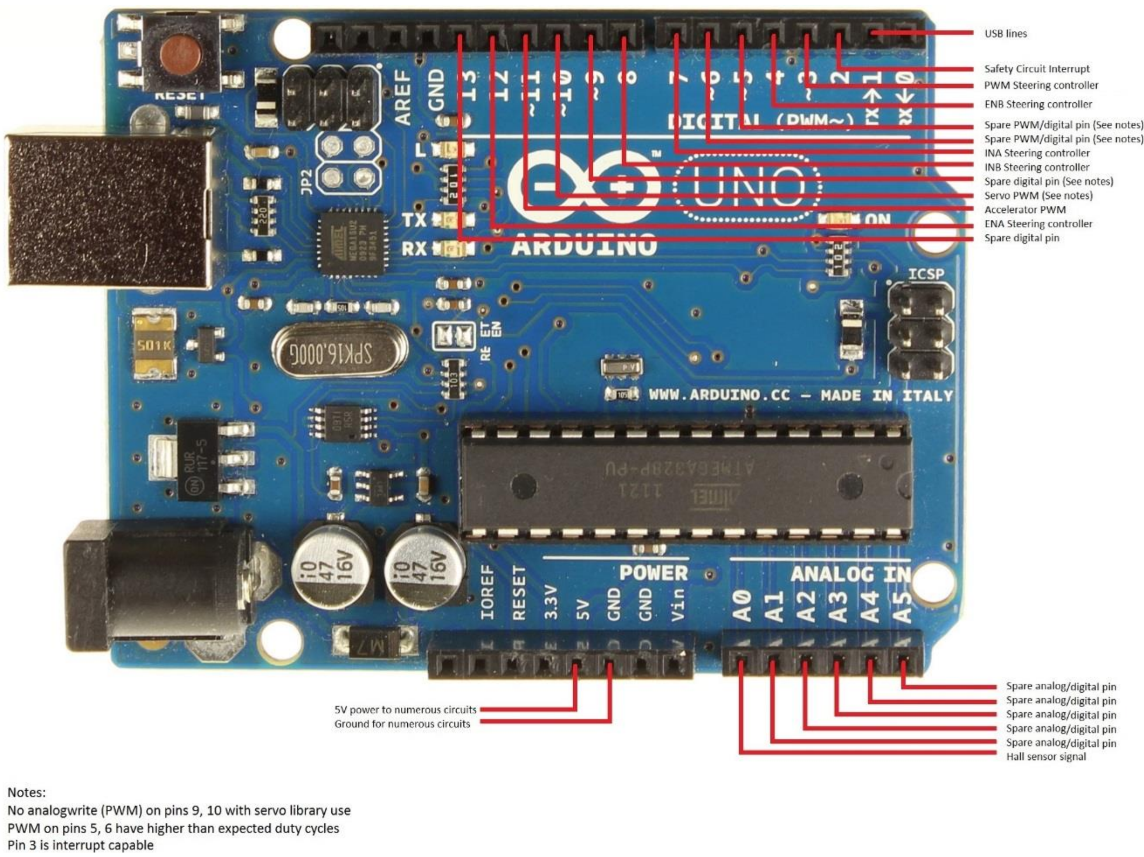

Figure 31: Pin out of the low-level microcontroller (Image modified from [39]).

The Arduino Uno is capable of being powered from two different power sources: an external DC barrel jack mounted on the board and from the 5V rail on the USB connector. Since the maximum recommended input voltage to the barrel jack is 12V [39], the 12V supply for the autonomous system was stepped down to 9V before being used to power the Arduino. This was done to ensure that the DC-DC converter built into the Arduino does not over heat. The Arduino Uno board also provides a 5V output pin which was used to power other circuits. For more details of the wiring of the low-level system, see the ‘Low-Level System Circuit’ section below.

The inbuilt ability for the low-level system to turn on via USB power is convenient when reprogramming of the microcontroller is required and a separate power supply is not present. However, since a separate power supply is used in the system this was seen as a detrimental feature for the following reasons:

- The Arduino (and circuits powered by the 5v header pin) would turn on when a high-level system was plugged into it, despite the low-level system's main power being off
- Interaction between the high-level USB 5V and the Arduino could not guarantee that the 500mA limit on USB power or that the Arduino's DC-DC power limits were not exceeded
- A short circuit fault on the low-level 5V rail would damage the high-level system as the USB cable between the Arduino and the USB hub of the high-level system does not contain a fuse. Such an occurrence would prevent the high-level system from communicating to any devices attached to the hub

Using the circuit diagram of the Arduino Uno, the 5V USB line powers pin 31 (UVCC) of an ATMEGA16U2 [40]. This pin powers a voltage regulator that powers the USB communication of the ATMEGA16U2. By cutting the trace which leads to the pin, and wiring it to the 5V voltage regulator on the Arduino, the above problems were avoided.

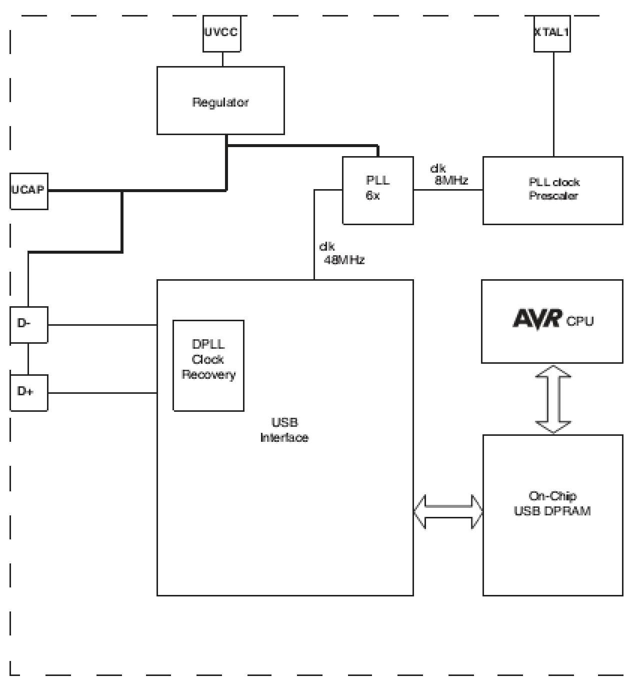

Figure 32: The diagram of the USB communication circuit located inside the ATMEL16U2 on the Arduino board ([40], page 185).

The low-level circuits (including accelerator board, Arduino and brake delay circuit) were placed into a box for protection in the nose of the vehicle as shown in Figure 33. All fuses for the low-level system are mounted on the top of the box, allowing for replacement without having to opening the box. The blade fuse holder has LED indicators which light when a fuse is blown, allowing for quicker troubleshooting if a particular subsystem of the low-level setup is not working.

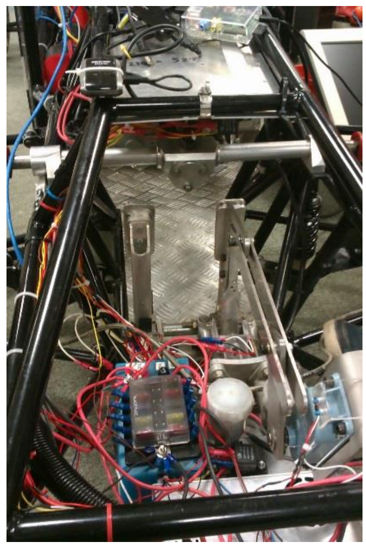

Figure 33: The nose of the vehicle which houses most of the low-level autonomous system. The brake mechanism is shown on the right with numerous electronic circuits housed in the blue box on the left.

5. Low-Level Software

When the low-level system is turned on, the Arduino first sets the appropriate pin directions (output or input), adjusts the PWM timer frequency of timer 2, enables a watchdog timer, safety circuit interrupt and activates serial communication. It also sets the accelerator circuit output to a state which results in zero output throttle but is sufficient to prevent the Kelly driver motor controllers from believing a sensor failure has occurred. Similarly, the brake servomotor is commanded to move to an off position while the steering is set to lock on the position it is in when the system is turned on. Initially, the low-level software would set the vehicle to steer straight once started to ensure that the steering of the vehicle was always in a consistent, predictable position. However, numerous people considered this movement to be an unexpected reaction to the system powering up and for safety reasons was changed so that it would lock to the position the steering was already at upon start-up.

Use of the Arduino serial library greatly decreased the time required to implement the serial communications between the low-level systems and the high-level controller. Using the serialEvent function, if a check for data in the serial buffer indicates that new data is available, a routine which accepts bytes of data commences. The low-level system accepts commands which begin with a command type identifier: B for brake, A for accelerate and S for steer. Table 6 summarises the types of valid commands and the respective range of allowable values. The command type is stripped out and the atoi function is used to interpret the received ASCII characters.

Command Identifier	Minimum Value	Maximum Value
B (Brake)	0	255
A (Accelerate)	0	255
S (Steer)	-128	127

Table 6: Valid commands which the drive-by-wire controller accepts over USB communication.

The numerical command sent by the high-level system is linearly mapped to values which lie between maximum and minimum integer values for each command type. For example, a sent brake command is mapped between values which provide no to full braking of the vehicle. A PID loop is used to control the speed of the motor that steers the vehicle with additional code to ensure that the motor is turning the correct direction to reduce the steering error. During the main loop, error detection is run and a minimal use of while loops helps to ensure that the low level system cannot lock up.

As inconsistent behaviour can possibly result from software errors or other instabilities the drive-by-wire software uses a watchdog timer to ensure that the low-level controller does not lock up or become unresponsive. A watchdog on the microcontroller detects if the system is waiting for serial data for too long and will interrupt the system, triggering an emergency brake. Additionally, the microcontroller checks that new serial data has been received every 300ms. If a new data has not been received from the high-level system then an emergency brake condition is set. Both of these features ensure that if unreliable communication between the low-level and high-level system occurs action is taken to prevent the autonomous system causing undesired behaviour. This also creates an emergency brake condition if the high-level controller locks up. Additionally, any received commands are echoed back to the high-level system for verification and low-level variables are printed to the high-level system periodically for debugging purposes.

5.1. Low-Level Software Safety

In addition to standard communication over USB with the high-level system, an interrupt line on the Uno allows the high-level system and additional safety circuits on the vehicle (designed by Thomas Drage) to trigger an emergency brake. The low-level controller software supports the checking of multiple values for consistency. In most cases an emergency brake condition is met if any error is detected. Table 7 documents all possible error codes and the action that the low-level controller takes when the error occurs. Errors that are detected are communicated to the high-level controller via ASCII characters sent over the USB link to inform the high-level system if a fault or loss of control exists. Error detection includes the use of the watchdog function, checking of the diagnostic pins of the VNH2SP30 motor controller, serial communication timeout and the detection of abnormal steering sensor feedback.

Low-level Error Code	Description of Error	Action Taken
ER0	Serial communication array overflow error. Command received too long.	Command ignored.
ER1	Emergency brake condition currently present.	-
ER2	Watchdog timeout occurred.	Emergency brake engaged.

ER3	Brake servomotor on for too long.	Brake disengaged to prevent servomotor pole burnout.
ER4	The motor controller that controls the motor responsible for steering reports a fault.	Emergency brake engaged, steering motor set to coast.
ER5	No new commands received within 300ms.	Emergency brake engaged.
ER6	Steering sensor feedback out of physical bounds.	Emergency brake engaged, steering motor set to coast.

Table 7: A summary of drive-by-wire controller error codes. In addition to any Action Taken, every error causes the corresponding error code to be sent to the high-level control system.

6. Low-Level Safety Circuit

Supplementing the safety software programmed to the Arduino is a separate circuit termed the "Low-Level Safety circuit". To increase driver safety when the autonomous system is controlling the vehicle, the Low-Level Safety circuit was introduced. The circuit is created from combinational logic and comparators. These logic chips drive relays which can physically disable parts of the low-level autonomous system. Being separate from the Arduino microcontroller, these will continue functioning regardless of the code run on the system or if microcontroller develops a fault. With the addition of hall sensors near the brake pedal and voltage feedback from the VNH2SP30 motor controller (which is proportional to the current draw of the DC motor that steers the vehicle), combinational logic was used to perform numerous functions dependent on driver action:

- If the driver attempts to steer in a different direction to the autonomous system, a relay cuts power to the steering motor, allowing the driver to control the direction of steering. An emergency brake command is sent as well.
- If the brake is applied by the driver when the autonomous system is not braking, a relay cuts power to the steering motor. Control of the steering motor is returned to the driver and an emergency stop command is sent to the low-level controller.

Additionally, with the brake applied the autonomous system is unable to cause acceleration of the vehicle as a relay physically disconnects the accelerator signal line. Instead, a trim pot set at the idle throttle voltage is feed back to the Kelly drive motor controllers.

A more logical explanation which describes the system's logic given various sensor outputs is below:

If brake engaged and servomotor not causing braking then:

- Cut off power to drive motors
- Unlock steering wheel
- Send emergency brake command

If current limit of steering motor above threshold then

- Unlock steering wheel
- Send emergency brake command

In order to trigger an emergency brake command, relays provide feedback to a safety supervisor circuit designed by Thomas Drage. This enables the safety supervisor to use the emergency interrupt line to trigger an emergency brake on the low-level system. Additionally, the safety supervisor is capable of communicating with high-level systems and checking additional parameters to ensure they are within limits. It should be noted that the error codes of the low-level system report an emergency interrupt trigger through the sending of a single error code, ER1. Any other events that cause an emergency brake will also send an ER1 but will be proceeded by the appropriate error code as discussed in table 7.

The circuit diagram of the Low-Level Safety circuit is given in the appendix and is labelled 'REV Autonomous Low Level Safety Circuit'. This system essentially allows a driver in the vehicle to have control over the autonomous system without having to turn the system off during operation. This is desirable should the system cause unexpected behaviour or if an emergency should occur

7. Low-Level System Circuit Diagram

The circuit diagram for the complete low-level system is shown in the appendix, and is labelled 'REV Autonomous SAE Low Level Wiring Diagram'. Further detail of the diagram is discussed below.

The circuit involving the 555 timer on the left hand side of the diagram is the brake servomotor reset signal generator. The output of the 555-timer reset circuit is connected to the signal line of the servomotor through a relay that is only energised for a short period after the system is turned off by the delay circuit consisting of a diode, trimpot and the IRF540N MOSFET.As this relay is only energised during the reset process the reset signal can never be applied when the autonomous system is functioning. The Arduino microcontroller and reset circuit should not be operating at the same time. Diodes between these systems were used to ensure that the signal waveform from either system could not attempt to power the other, unpowered system. This also prevents the Arduino from being damaged if both circuits are active at the same time as the 555 timer can drive more current than the maximum limit on the Arduino. A time delay of about half a second is present to allow the servomotor to disengage from the brake. Due to this, the autonomous system should not be turned on and off quickly. A complication in the construction of the delay circuit is that the servomotor contains considerable capacitance, and the voltage present on the NO contact decays slowly as shown by Figure 34. This capacitance would discharge into the time delay circuit when the autonomous system was turned off and cause an infinite loop of the delay circuit turning on and off. To combat this, two STPS1545F diodes were inserted between the servomotor power and the NO contact line. While a single STPS1545F diode is rated for a current of 15A [41], two were used to ensure that a failure of the brake would not occur due to diode failure. Naturally, such a failure would present a severe safety hazard of the low-level system.

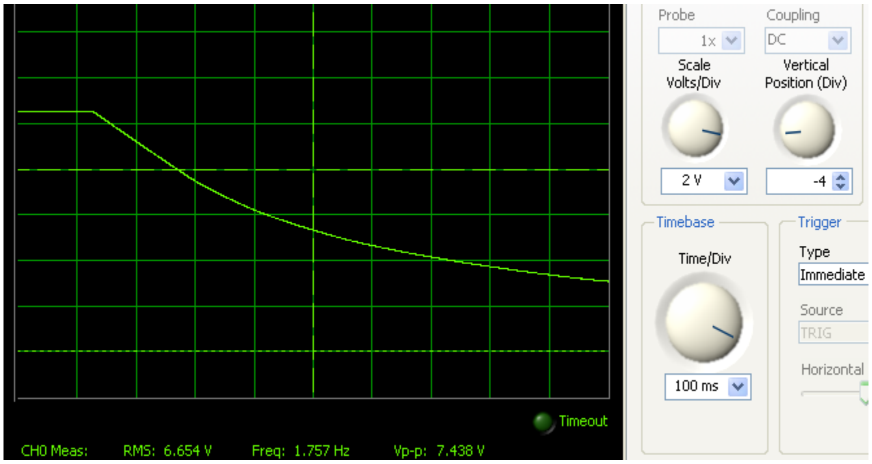

Figure 34: Voltage decay caused by the capacitance of the SSPS-105 servomotor.

Numerous relays were used in the low-level system. Attention was made to ensure that a relay coil failure or a failure to energise the coil of the relay would not cause a dangerous situation. For example, a relay switches the power source of the brake servomotor between a 12V power source that is active when the autonomous system is on, and a secondary 12V source that is active when the autonomous system is turned off. The normally closed contact of the relay corresponds to the servomotor being powered from the autonomous system's 12V source while the normally open contact is connected to the temporary 12V power source. This ensures that if a failure of the relay or electronics in the autonomous system occurs and the relay does not energise, the servomotor is still powered for normal use by the autonomous system. The only function of the servomotor that would be affected would be the servomotor's ability to move back to a disengaged position when the autonomous system is turned off. However, given the voltage decay on the power rail of the servomotor as shown in Figure 34, it may be possible for the servomotor to complete this manoeuvre without requiring additional power. This choice of contacts for the relay increases the safety of the autonomous system.

The low-level system was designed to provide easy disengaging of the steering motor by loosening the belt that coupled the motor to the steering column. However, on numerous occasions, the car was driven manually without disengaging the belt. When the driver turned the steering wheel at a high enough rate, the steering motor would act as a generator. By powering the low-level system for a split second, the Kelly drive motor controllers would fail, suspecting a throttle sensor failure. A relay was introduced in the motor's power line to ensure that this undesired event would not occur.

The interface between the driver and autonomous system is shown in Figure 35. A large safety switch is responsible for turning the autonomous system on or off and is within arm's reach of the driver. A switch between manual and autonomous system acceleration resides to the right of the button. The switch's pole must be pulled upwards in order to change the mode the system is in. This prevents the switch changing acceleration modes from being accidentally hit. By pulling the switch's pole towards the driver, the system is in manual acceleration mode while moving the switch towards the autonomous system activates autonomous acceleration. This switch improves safety when testing changes to the autonomous system. It can also be used to control the speed of the vehicle when the autonomous mode is activated. Additionally, a flashing light positioned next to the switch which engages the Kelly drive motor controllers is present to warn the driver if the autonomous system is turned on or not. It should be noted that the autonomous system needs to be turned on before the Kelly drive controllers in order to create an idle throttle voltage signal. Furthermore, since the Kelly motor controllers do not function if they receive a voltage when turning on that would cause acceleration, the high-level system must not command the low-level system to accelerate until after the Kelly controllers are turned on.

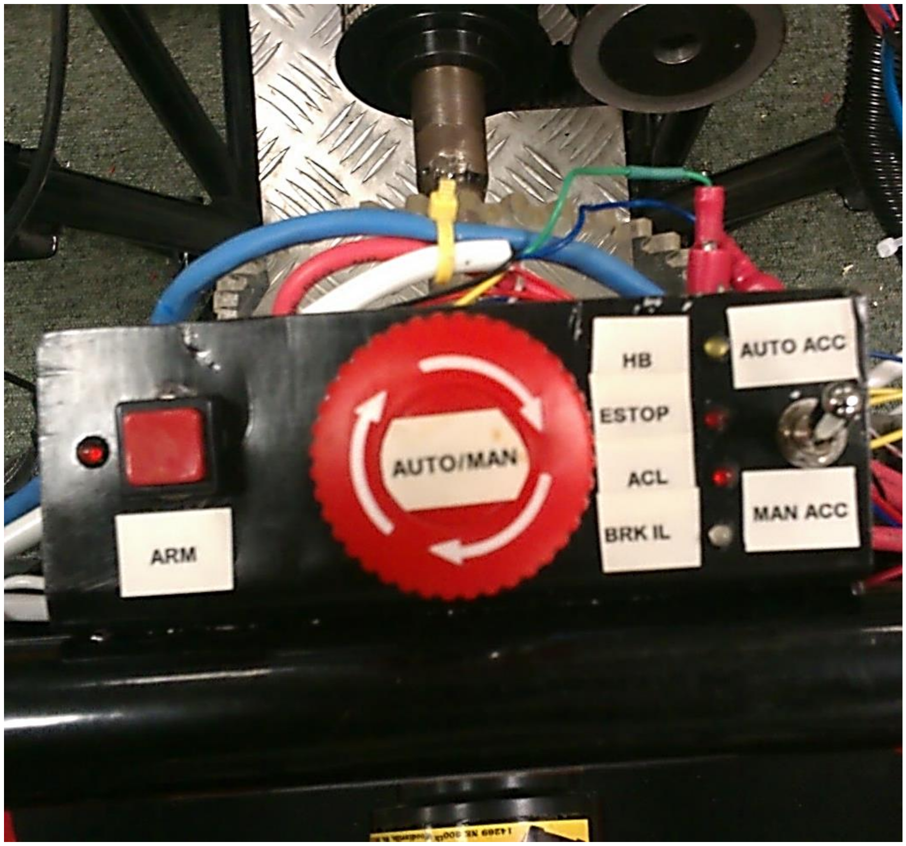

Figure 35: The interface between the driver and the low-level autonomous system. Components of the safety supervisor circuit designed by Thomas Drage are also present.

The Mean Well SD-350C-12 DC-DC converter used to power the low-level system has a maximum output current limit of 25 amps. To ensure that this was adequate for the low-level system the following table was constructed. Using the maximum manufacturer current draw specifications, half an amp is available for running other systems on the vehicle. In practice, the actual total current draw is significantly less than these maximums and hence there is a greater capacity for running further systems.

Item	Maximum Manufacturer Rated Current Draw (A)	Maximum Measured Current Drawn (A)
SSPS-105 servomotor	9	3.2
Arduino Uno	0.5	0.2
Steering motor	15	15 (unmeasured)

Total	24.5	18.4

Table 8: Measurements of current draw by various components of the low-level system.

Care must be taken when future work is carried out to ensure that the total current limit of the Mean Well SD-350C-12 DC-DC is not exceeded and that the electrical isolation between the autonomous system and the rest of the vehicle's electronics is not accidentally bridged.

8. Conclusion

The low-level system described in this thesis provides the necessary control over the electric F-SAE vehicle to mimic a driver's actions and thus has fulfilled its design criteria. Steering, braking and acceleration of the vehicle using the autonomous system is adequate to control the vehicle's motion. The autonomous low-level controller has been used for real time interfacing with a high-level control system responsible for determining the path of the vehicle. Testing of the system has been performed and it has already been used by the REV autonomous vehicle group to conduct research into higher level control algorithms. During these tests, the system has proven capable of providing a platform for research into higher level vehicle control functions.

Future Work on the Low-Level Autonomous System

While the current low-level autonomous system fulfils the required design criteria, future work would lead to improvements in vehicle data logging, safety and performance. Future work that would improve the low-level system includes:

- Configuring a fuse readout system so that the Arduino microcontroller can cause an emergency brake command if a part of the system no longer has power
- Setting up reversing capability that can be controlled by the microcontroller, with the inclusion of a buzzer to warn people near the vehicle as rear view is poor from the driver's seat
- The hall sensor used for the safety circuit that detects if the brake has been engaged could be used as error checking in the Arduino to determine if the brake servomotor has engaged the brake
- A pressure sensor could be installed on the brake pedal. This could be used to detect the pressure a driver applies to the brake pedal. A slight tap could be used to disengage the autonomous system while an extremely hard press could indicate and emergency and hence application of the autonomous system's brake
- Mechanical limit switches could be installed to prevent the brake servomotor and steering motor from travelling too far. These switches would not be reliant on code and can therefore prevent damage to the system should it malfunction

- The installed steering motor could be used to provide power assisted steering to the driver of the vehicle
- With additional sensors, the low-level system could provide additional performance features to the vehicle. These include stability control, ABS and wheel speed indicators which could be used as direct feedback to a high-level system

While not originally considered within the scope of this project, further work could be carried out in order to allow physically impaired people the ability to drive the vehicle. By modifying the steering wheel with buttons and other feedback, a driver could rely on the low-level system to provide full drive-by-wire support.

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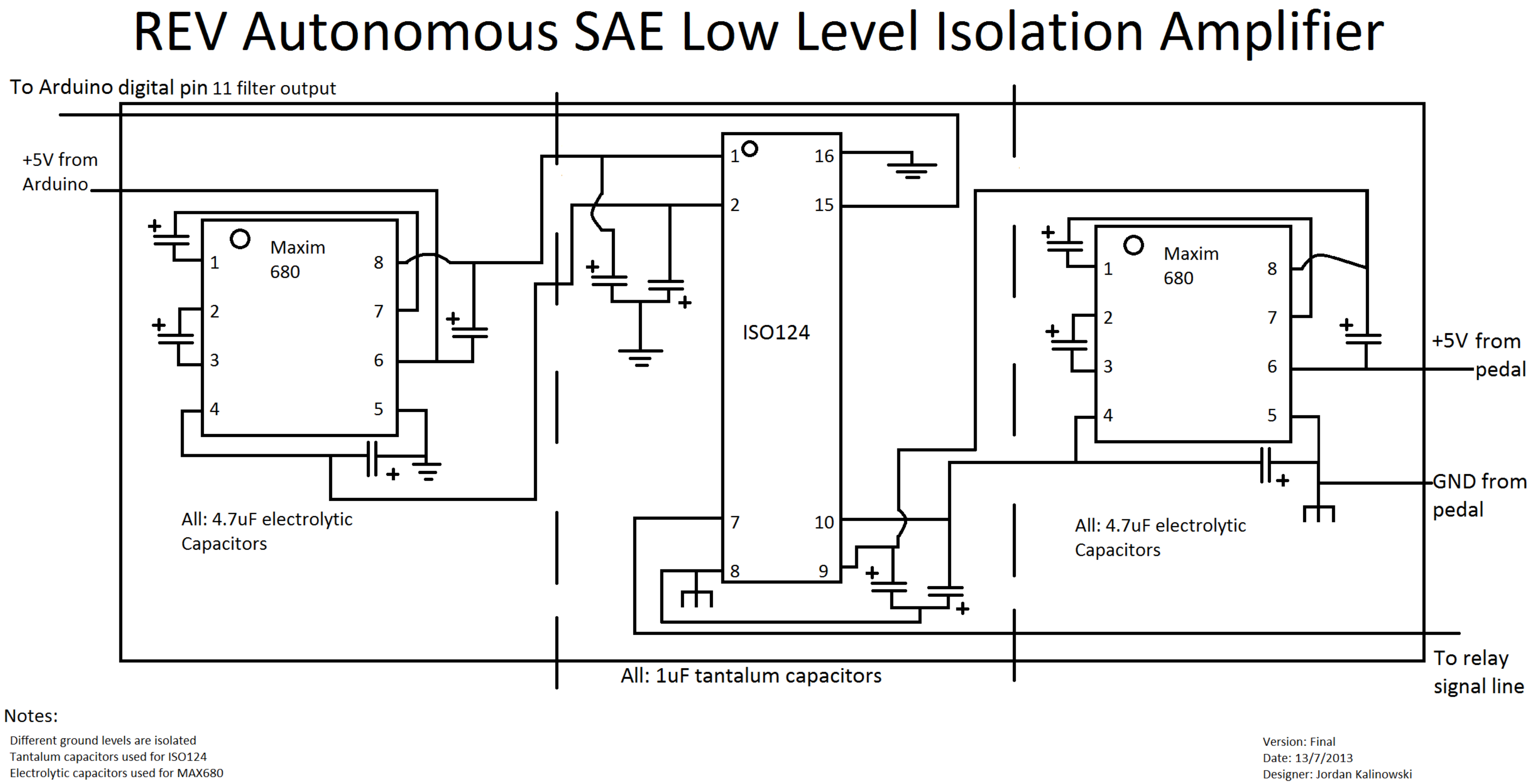
Appendix


REV Autonomous SAE Low Level Isolation Amplifier
To Arduino digital pin 11 filter output
+5V from Arduino
Maxim 680
1
2
3
4
8
7
6
5
All: 4.7uF electrolytic Capacitors
ISO124
1
2
7
8
16
15
10
9
All: 1uF tantalum capacitors
Maxim 680
All: 4.7uF electrolytic Capacitors
+5V from pedal
GND from pedal
To relay signal line
Notes:
Different ground levels are isolated
Tantalum capacitors used for ISO124
Electrolytic capacitors used for MAX680
Version: Final
Date: 13/7/2013
Designer: Jordan Kalinowski

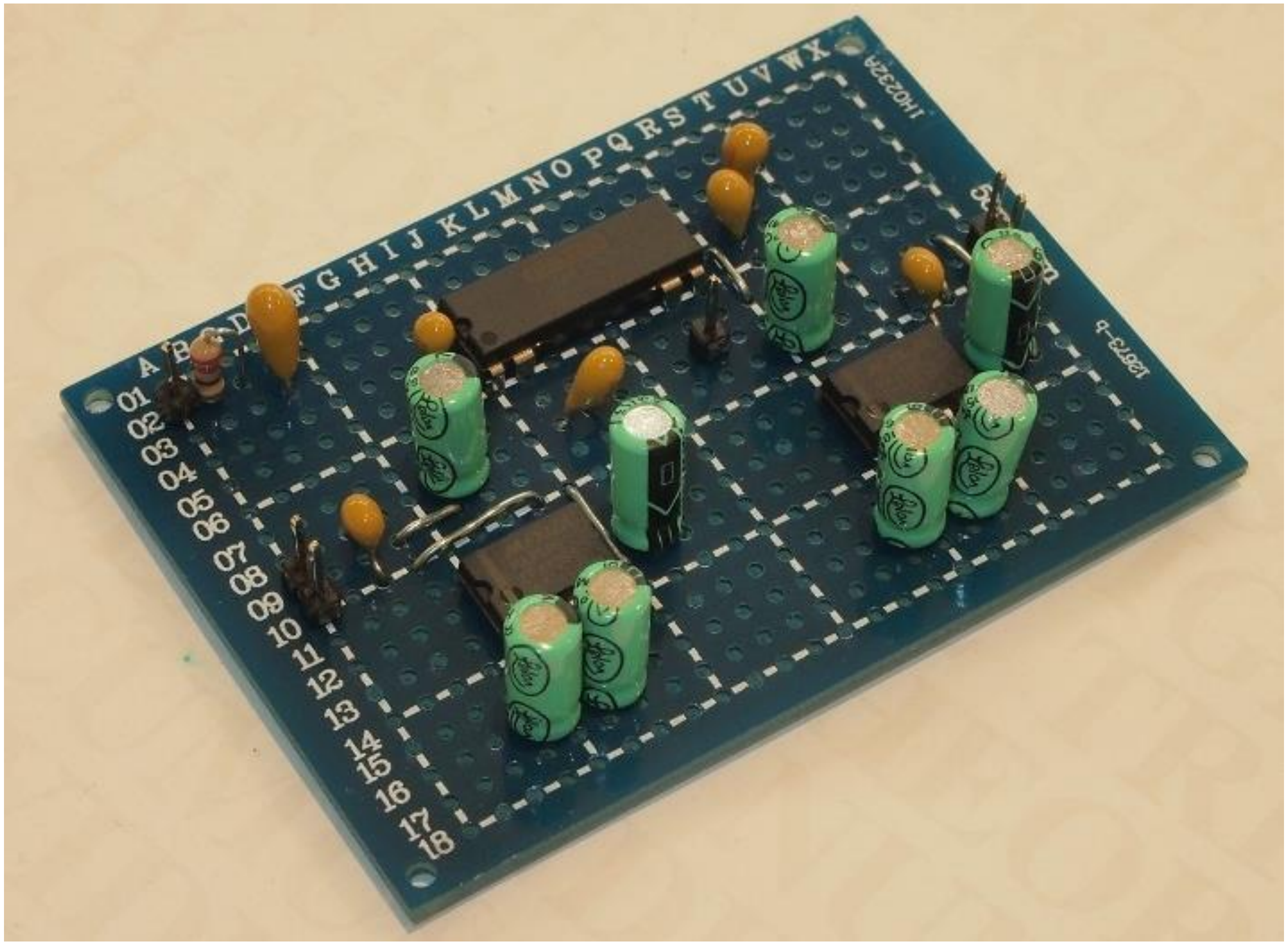
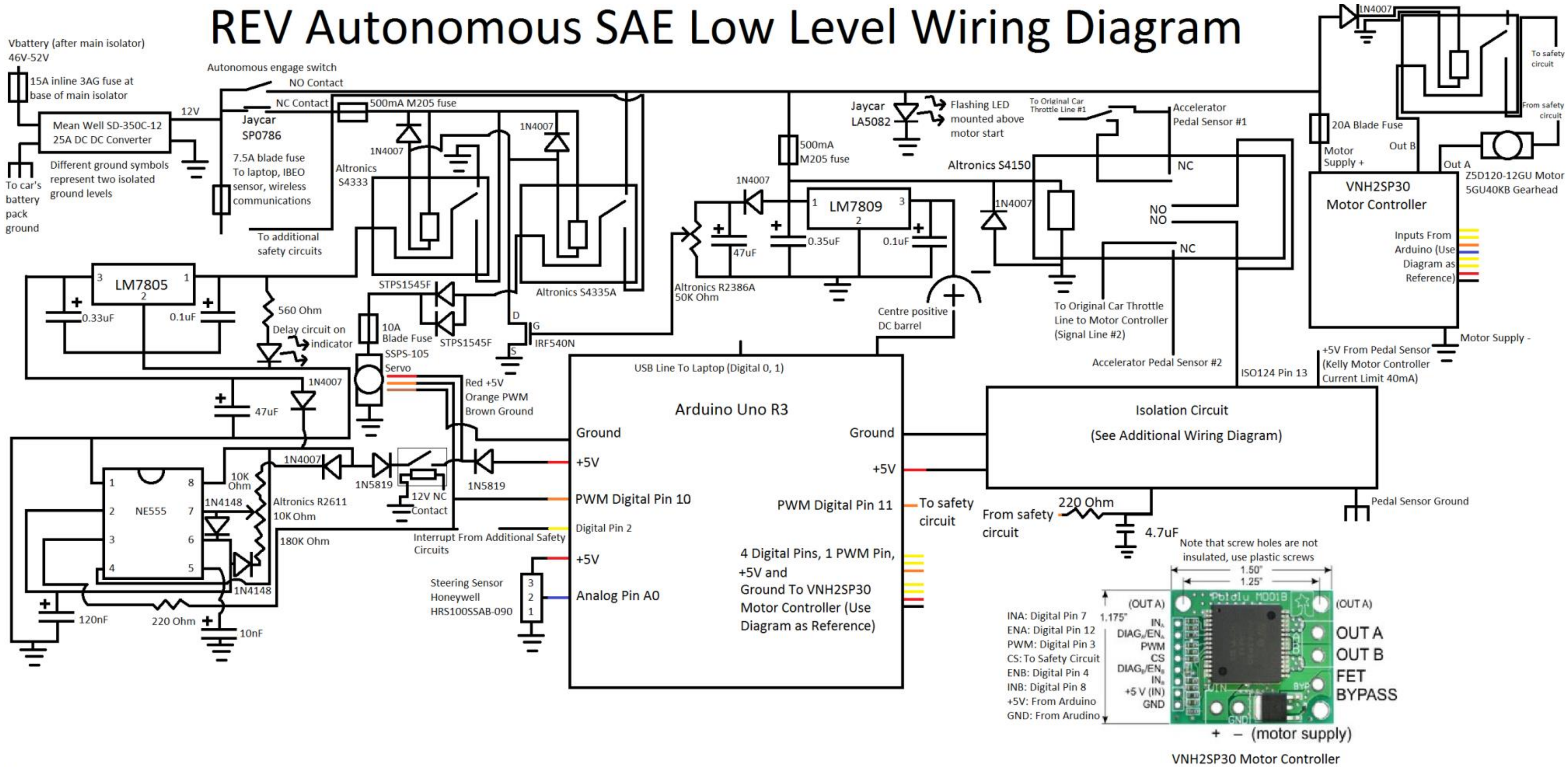


Image of the throttle-by-wire isolation amplifier system courtesy of Thomas Drage.

The filter for the Arudino's PWM signal can be seen on the upper left of the board.

REV Autonomous SAE Low Level Wiring Diagram



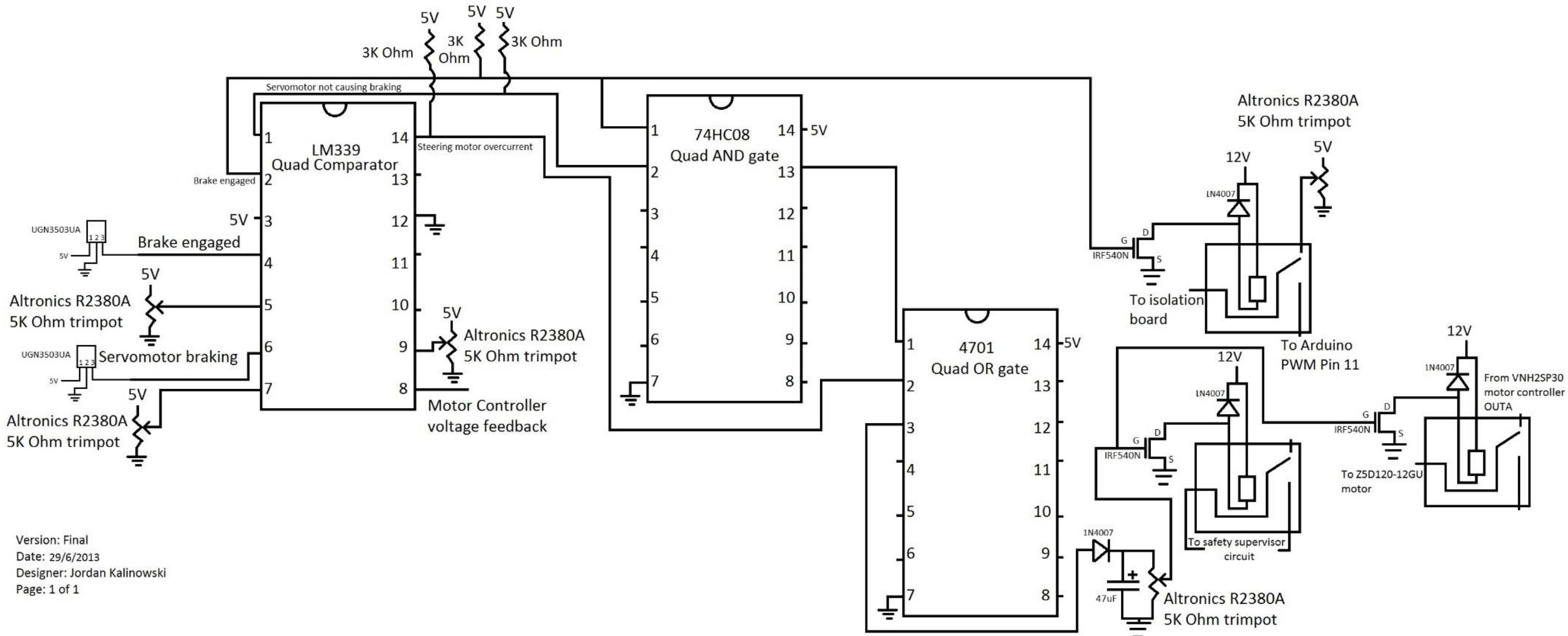
Notes:

Diodes inline with servo power prevent servo discharging into circuit when turned off.
Two are included for redundancy.
Switch between manual acceleration and auto acceleration
Digital pin 2 is externally pulled down via safety circuit. When low, an interrupt is triggered.
VNH2SP30 Motor Controller Board contains components neccessary for direct connection to Arduino

Wiring colour scheme:
Red: +
Back: Ground
Yellow: Digital
Orange: PWM
Blue: Analog

Version: Final
Date: 11/07/2013
Designer: Jordan Kalinowski
Page: 1 of 1

REV Autonomous Low Level Safety Circuit



Version: Final
Date: 29/6/2013
Designer: Jordan Kalinowski
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