The Conversion of a General Motors Cadillac SRX to Drive-By-Wire Status

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Abstract

In the fall of 2004, the High Speed Autonomous Vehicle Team, a group of 16 students took on the goal of converting a vehicle to drive-by-wire status. The main goal of this project was to convert a Cadillac SRX donated by General Motors, to fully by-wire control. This thesis presents the HSAVT brake-by-wire and the steer-by-wire solution. In addition, the results of a literary search on drive-by-wire systems are presented. The results of the project proved that the team came up with a solid, effective drive-by-wire vehicle and that the project met all of the primary goals of the project.

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Acknowledgments

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Chapter 1

Introduction and Background

For the past 25 years, by-wire systems have been used in the most advanced flying machines known to man. In the 1960s, McDonnell Douglas, now The Boeing Company produced the F-15 Strike Eagle, a magnificent fighter jet with fly-by-wire capability. Fly-by-wire is where each mechanism is controlled electronically. The mechanical linkages are removed and every movement is communicated through electric signals alone. The idea of fly-by-wire forever changed the concept that a mechanical linkage has to initiate movement (i.e. pitch, roll, and yaw) of a vehicle. The use of electronic motors to control movement has proven to be more responsive and a more efficient use of space and energy. The responsiveness of the fly-by-wire system is one of the heralding accomplishments that make the F-15 such an engineering accomplishment which can fly at 2.5 Mach speeds. Thus the by-wire control is now setting the stage for better, faster vehicles in the air and on land.

By-wire systems are a means for quick communication between the driver and the components that control the vehicle. Every action that a vehicle can make (i.e. turning, accelerating, braking) is controlled via an actuator or motor. Each motor is controlled by an electronic signal via some form of human-vehicle interface (i.e. a steering wheel, a brake pedal or throttle pedal). In the F-15, a control stick serves as the controller for all maneuvers. All flaps, the air brake, and even the landing gear are controlled by hydraulic actuators. In previous jets, the controls surfaces (ailerons, flaps, air brake, etc.) were actuated through the hydraulic system, which were directly linked to the pedals and joystick. Now though, instead of using mechanical linkages to control the hydraulics directly, an electronic actuator controls the hydraulics via an electronic signal from the joystick. Before by-wire technology, flying an aircraft was a labor-intensive task. Flying inherently is a system which can become unstable if the pilot does not stay in control of the vehicle during all maneuvers. By taking out the mechanical linkages and reducing the weight of the aircraft, pilots can therefore concentrate on military operations instead of physically actuating the control surfaces.

One of the biggest advantages of by-wire systems is that they react more quickly and thus are more responsive than the mechanical equivalent. Conventional vehicles use mechanical linkages to actuate motion, which requires energy transfer from one link to another. This energy transfer inherently introduces nonlinearities and losses due to friction and flexing of materials. In by-wire systems, however, these nonlinearities are reduced by simply replacing the energy transfer from mechanical linkages to electronic signals. According to electronic theory, an electric current can flow through a wire more quickly and with fewer losses than virtually every mechanical arrangement. This increase in responsiveness also increases the performance since brakes are more efficient and respond more quickly. Moreover, the use of motors in place of mechanical linkages is arguably the biggest jump in automotive technology since the Model T was created in the 1920s.

Thanks to the success of fly-by-wire systems that are used in avionics today, by-wire technology has been proven to be effective and reliable. In order to ensure this reliability, multiple redundancies of sensors are incorporated in by-wire systems. Furthermore, to assure that there is redundancy and therefore safety, repeated sensors for each component (i.e. brake potentiometers, throttle sensors, motor encoders, etc.) are installed to verify that the signals read from each sensor agree. Also, mechanical backup systems are used in case a fault is found which serves as a fail-safe.

By-wire systems are also versatile. Since a central computer or an ECU (Electronic Control Unit) is used to process the signals sent from brake and throttle sensors, by-wire technology allows the potential to add new operating programs to the ECUs of by-wire vehicles. New technologies are being developed to make driving safer and can be added to current by-wire systems. Such programs that are being researched are obstacle avoidance, Anti-Slip Regulation (ASR), Brake Assistance (BA), stability control systems, and even cruise control. All of these programs can be modified easily through by-wire systems.

In addition to being faster, electronic actuators are lighter and take up less room. Most mechanical systems are heavy and take up excessive room within the vehicle architecture. Hydraulic braking, for instance, is a complicated system requiring a reservoir and room for hydraulic lines throughout the vehicle. Electronically driven actuators on the other hand, can completely replace complex and heavy hydraulic systems and can be placed easily in a vehicle.

Lastly, by-wire systems are also more cost effective. Since actuators only initiate mechanical movement, they can be easily replaced. Also, the diagnostic capabilities are inherently increased. Since the ECU processes every signal that is sent from each sensor, every signal can be monitored simply by tapping into the ECU. Moreover, by-wire vehicles have fewer parts to install and thus result in lower cost and time in production.

There are several different types of by-wire systems, such as, brake-by-wire (BBW), steer-by-wire (SBW), throttle-by-wire (TBW), shock control, and automated gear shifting. Throttle-by-wire is an already widely used application of by-wire technology. Most vehicles have a version of throttle-by-wire in place already with the use of cruise control. Instead of the driver having to depress the throttle consistently to keep the vehicle going a certain speed, a driver simply indicates what speed he or she wishes the vehicle to maintain. Once the desired speed is indicated to the ECU, the driver’s request is processed in the ECU and an appropriate signal is sent to the throttle valve. An electronic actuator located at the throttle valve opens the valve to the corresponding position to maintain a desired speed. Thus the concept of throttle-by-wire has been incorporated into automobiles since the late 1970s.

This thesis will focus on two types of by wire technologies: brake-by-wire and steer-by-wire. There are two brake-by-wire technologies that are used today: electrohydraulic braking and electromechanical braking. Electrohydraulic braking makes use of a motor and hydraulics to actuate the brake system. The job of the motor, most likely a linear actuator in this case, is to initiate the hydraulic fluid flow through the brake lines. In traditional hydraulic brake systems, there are four main components; the master cylinder, the hydraulic fluid, the brake lines, and a component to actuate the master cylinder. In electrohydraulic braking, a linear actuator moves the master cylinder, thus pushing the hydraulic fluid through the brake lines into the corresponding disc or drum brakes. In traditional braking, the brake pedal is directly connected to the cylinder head which pushes the hydraulic fluid though the brake lines.

By-wire technology makes it possible to remove heavy and slow mechanical linkages and replace those linkages with fast and light electric motors.

Mercedes-Benz is the first company to produce a brake-by-wire vehicle called the SL500. This V8, five liter vehicle is outfitted with a brake-by-wire system. The SL500 has electrohydraulic braking, using an actuator to initiate and control the hydraulics system. Also, as a back up, the SL500 has a second hydraulic system that is also driven by an electric motor which initiates braking at the front in case there are problems sensed by the ECU.

Another technology that Mercedes has incorporated into its vehicles is the Electronic Stability Program (ESP). This technology acts as a selective braking technology where each brake can be actuated by itself. In order to accomplish this, an array of valves control to which wheel braking is applied to. Further, instead of braking at all four wheels every time the vehicle needs to slow down, the ECU processes variables such as wheel speed, g-forces, steering angle, and engine output in order to decide what brake to use. In most vehicles, braking is performed at two or even four wheels every time braking is requested by the driver. In the SL500, however, the ECU has the option to use one or more of the four disc brakes. Thus, the ECU takes in the information read from sensors and uses algorithms to decide how to brake most efficiently and safely. The by-wire technology makes it possible to enhance cornering capabilities and to keep all four wheels to the ground at all times. Mercedes-Benz is well known for manufacturing agile, finely tuned machines with superior cornering capability, while offering a luxurious, smooth ride. Unfortunately, the backup hydraulic system adds back any of the weight and space that was initially saved by taking out the mechanical linkages in the first place.

An even more exciting type of brake-by-wire technology is electro-mechanical braking. This new system eliminates the use of hydraulics completely. Instead of using a complex, heavy hydraulic system with a reservoir, hydraulic fluid and brake lines, all of that is replaced with compact, individual brake actuators located at each wheel. This system is much less complex than purely mechanical systems in the sense that it can actuate each brake individually therefore making active braking programs easy to implement. All other braking programs can also be used with this completely electrical system such as Anti-lock Braking Systems (ABS), Active Braking (AB), collision avoidance, etc.

One of the advantages of using electromechanical braking is that there is less hardware, which reduces the cost of production, as well as the weight of the vehicle overall. Additionally, electromechanical braking systems are also environmentally friendly since the need for hydraulic fluid is eliminated as well. Also, brake maintenance is reduced since only pads and discs need to be checked and replaced regularly as with any vehicle.

The second topic that this paper will focus on is steer-by-wire systems. The principle for the by-wire steering is the same as by-wire braking. The goal is to take out the mechanical interface between the driver and the mechanism that actuates wheel turn. The purpose of the steering is to control the heading of the vehicle. There are several different arrangements for actuator control of steering. Electro-mechanical steering is where a motor is installed on the steering shaft or at the rack and pinion configuration underneath the vehicle to initiate wheel turn. A signal is sent directly to the actuator and from there, the motor turns the wheels to the desired position. In electromechanical steering there is no need for a steering wheel even since the wheels are not connected mechanically to the wheel. Several new age vehicles such as the Bertone SKF FILO use a control system that is similar to a joystick which controls steering (left and right steering control yokes), acceleration, braking, gear shifting, and clutch actuation. The Guida, which means "drive" in Italian, controls the steering, acceleration, and braking all by-wire. The FILO which is Italian for "wire" is developed by Bertone, an Italian company that partners with other car companies such as Aston Martin and BMW. All of these vehicles are fully drive-by-wire and are designed to be technologically advanced yet sleek and sophisticated.

Many other vehicles such as the Grand Challenge vehicles developed by Virginia Tech students are manually controlled via a joystick. A steering wheel is no longer a necessity and therefore can be taken out completely. Due to the unpopularity of using a joystick for driving, however, steering wheels are being designed into fully drive-by-wire vehicles even though they are not necessary.

Another form of electronic control for steering is fully electronic actuation where each wheel is controlled individually by a motor. The advantage of four wheel actuation is greater mobility since each wheel can be turned by itself and the mechanical elements are taken completely out of the drivetrain. Therefore, a four wheel actuated vehicle is lighter and faster because the wheels are actuated more easily without mechanical links to transfer energy, and has more mobility. Since an all wheel actuated vehicle is faster and has more mobility, it can respond more easily to emergency situations. Moreover, since the steering signals are controlled by the ECU, programs can be implemented into the ECU to automate steering completely. Four wheel actuation or even front wheel actuation makes autonomous ventures possible for future vehicles. With the incorporation of vision sensors and path planning algorithms, the ECU will be able to drive the vehicle by itself without human input.

One of the issues with electronic control is the pedal and steering ‘feel’. Most drivers rely on the feel of the throttle pedal and brake and steering wheel in order to decide if more braking is needed, for instance. The feel that the driver senses is due to the mechanical linkages that push the brake back to neutral position and correct the heading of the vehicle. This issue is important but can be easily addressed by either completely taking out the brake, throttle and clutch pedals and each of those components with a control stick as in the F- 15 and F-16 or even in the FILO. Pedal and steering feel has been addressed but is beyond the scope of this thesis.

There are several drive-by-wire vehicles that have been developed as concept cars but the idea of autonomy or of taking the steering wheel out of a vehicle is not necessarily popular yet to the public. Understandably, the sense is that people enjoy being in complete control of their vehicles. Cruise control is a form of by-wire control and that took nearly 20 years for people to trust and accept enough to use on a regular basis. Just as with cruise control, it may take several years of good press and marketing for people to start being comfortable enough to buy a vehicle that is so drastically different than the vehicles used today.

The mission of the High Speed Autonomous Vehicle Team project (HSAVT) was to implement a solid functioning drive-by-wire vehicle. Initially, in the start of the project, the goal was to have a fully autonomous vehicle capable of high speeds (25 to 125 mph) however, due to late delivery of the base vehicle, the project mission was adjusted. The HSAVT was made of eight mechanical engineering seniors, three undergraduate volunteers, two master's candidate advisors, and one PhD candidate advisor at Virginia Tech. The team's mission was to produce a vehicle that can drive a circle without having a person directly touch the steering wheel, the throttle, or the brake.

As a master's candidate advisor, my role in the HSAVT was to lead the group and to assist technically with the drive-by-wire design. I conducted an extensive literary search on drive-by-wire and fly-by-wire technology. A summary of the findings from my literary search is presented in the introduction of this thesis. The information found from the literary search is also used as a base for comparing other methods for by-wire design to the by-wire methods used in the SRX. Also, in order to choose a sufficient actuator for the brake and steering, I conducted research on motor selection. My research included calling motor manufacturers such as Danaher Motion to find out details of motor and actuator capability as well as referencing several books on motor selection.

In addition to research, I also helped to define the specifications that were needed for selecting both motors. Particular specifications defined were torque and speed requirements for steering. The torque requirement for steering was found experimentally by approximating how much weight had to be hung on the steering wheel in order to turn it. I also worked on tuning the brake motor using the Flexmotion software package. Initially, the brake motor took about 5 seconds to settle after actuation so I had to adjust the PID gains in order to reduce the settling time. I also assisted with selection of the brake method and design. I helped brainstorm ideas on how to transfer the motion from the brake actuator to the brake pedal. Such methods included mounting the brake actuator underneath of the steering wheel and attaching an L-shaped linkage to the actuator and the brake pedal to actuate the pedal. We discussed other methods of actuation such as hydraulics and other linkages to transfer motion from the brake actuator to the brakes.

Once the brake system was installed, I helped troubleshoot problems with the power for the brake motor. Since the brake motor required 24 *Volts* of power and the base system in the SRX is 12 *Volts*, we had to use a DC-DC converter to step the voltage up to 24 *Volts*. The source of the problem came from a faulty converter which had to be replaced.

For the steering system, I helped to choose the method of steering and then assisted with the design of the steering assembly. I conducted several meetings where we discussed possible methods of steering assemblies. On the physical side, I helped to take out the steering column and brainstorm ways to attach a pulley to the steering column. I also analyzed data that was logged during testing of the steering motor to see the response of the steering curves.

This thesis documents my literary search of by-wire technology and presents the brake and steer-by-wire design for the SRX. For both systems, I also present the control scheme. Lastly, this thesis presents recommendations for future teams on how to improve the by-wire design and process for testing and setting specifications in the beginning of the project.

The base vehicle, a Cadillac SRX, was donated by General Motors. This vehicle is outfitted with a 4.6 liter, Northstar V8 engine with variable valve timing. Figure 1 shows the SRX.

Figure 1: The Cadillac SRX and the HSAVT

In addition, this vehicle is all wheel drive with several automated programs such as all-speed traction control and Stabilitrak, an all-speed stability enhancement system. Other noteworthy specifications include speed sensitive, variable assist power rack-and-pinion steering and 4-wheel disc brakes with anti-lock brakes and brake assist. A background on the brake and steering systems will be discussed in depth in later chapters.

Since the SRX is already equipped with throttle-by-wire, the team merely had to find a way to tap into the SRX's ECU to control the throttle. That left the team with two other components to outfit with by-wire controls, the braking and steering.

This thesis is a record of how the Cadillac SRX was converted to drive-by-wire status. First, a description of the brake-by-wire system will be presented. Second will be an overview of how the brake system is controlled. Third, results and recommendations of this system will be presented. This results section will include recommendations for the use of different brake-by-wire systems for future projects based on the results and performance of the system the HSAVT chose. Next, the steer-by-wire system will be presented. As with the braking chapter, a chapter on the control will be presented, and then lastly, a results and recommendations section will be presented for future steer-by-wire projects.

Chapter 2

The Brake-By-Wire Solution

In future projects, the GM Cadillac will serve as the base vehicle for high speed applications. Therefore it was very important to make a vehicle that has a reliable and effective brake. As discussed in the background chapter, there are two ways that brakes can be electronically controlled: electrohydraulic braking and electromechanical braking. The HSAVT decided to use the electrohydraulic braking technique. There are two main reasons why the electrohydraulic approach was chosen. First, we wanted to utilize the Antilock Braking System (ABS) technology that was already engineered into the hydraulics of the SRX in order to prevent wheel slip while testing at high speeds. Secondly, while electromechanical braking is an extremely useful technology, it is also very expensive to implement. Therefore, electromechanical brakes were not an economically viable option.

As discussed in the background section, the brake can be actuated at two different places within the vehicle architecture. The brakes can be actuated at the brake pedal itself or at the master cylinder which controls the hydraulic system. Despite the benefits of actuating the brakes at the master cylinder (spacing and more direct control of the hydraulic fluid and hence more control of the brakes), we decided to actuate the brakes at the brake pedal.

There are several benefits of actuating the brakes at the brake pedal. First, installation is much easier since the motor can be installed inside the vehicle. Second, the placement allows for easy access to the actuator at all times. In addition, having the motor inside the vehicle protects the actuator from damage due to weather and possible harsh driving conditions. Conversely, if we had decided to actuate the master cylinder directly, the motor would have to be mounted underneath the vehicle and we would have had to make absolutely positive that the actuator was weather proofed and protected from damage. This is important because the brake must be reliable and fail safe. In addition, we would have had to crawl under the vehicle to work on the system any time an adjustment needed to be made. For these reasons, the HSAVT decided to actuate the brake from inside the vehicle at the brake pedal itself.

Next, we had to choose a mechanism to actuate the brake pedal. There were several guidelines which helped narrow down the options for motor placement. First, the SRX must be capable of being manually operated. So, one guideline was to make sure the hardware installed in the SRX does not interfere with the driver’s space. Secondly, the hardware must be installed in such a way that a person can drive the vehicle without having to move any components of the by-wire system. Thirdly, the by-wire system must be robust and durable.

Several areas were considered for actuator placement. For instance, we considered mounting the actuator posterior or anterior of the brake pedal. Both of these options, however, were eliminated for several reasons. First, the Cadillac SRX has limited space in the foot well, where the brake pedal is located. Therefore, a brake actuator could not be mounted behind (or posterior to) the brake pedal. Second, as was discussed previously, all actuators cannot interfere with the normal operation of each driving component (i.e. the throttle pedal, the steering wheel, the brake pedal). Therefore, a motor could not be mounted in front (or anterior) of the brake pedal.

The last area that was considered was under the driver's seat. This option adheres to all of the criteria that were defined previously. Placing the actuator under the driver's seat serves the dual purpose of protecting the actuator as well as completely hiding it. Furthermore, since the actuator is covered by the seat, it should not interfere with the driver's space on the floor. In addition, since the actuator is mounted inside the vehicle, the actuator is protected from the elements. Thus, we chose to mount the brake actuator under the driver's seat.

Since the motor had to be placed nearly two feet away from the brake pedal, the next step was to decide how to transfer the actuator motion to the brake pedal. Once again, several mechanisms were considered in order to transfer the actuator motion. Mechanical linkages were ruled out because they would interfere with the driver since the arrangement would have to be installed on the floor in front of the driver's seat. Also, a cable pulley system would be difficult to arrange effectively due to nonlinearities associated with using pulleys. Another consideration was to actuate the brake pedal with the use of a steel cable and linear actuator. This arrangement connects the brake pedal and linear actuator directly with a steel cable. The cable arrangement could be routed along the wall of the driver's side door on the floorboard. From the floorboard, the cable could be routed up along the foot well and fixed to the armature posterior to the brake pedal.

A marked advantage of using a cable system to initiate braking is that it simulates an actual person depressing the brake pedal. Once the actuator is initiated, the motor retracts the linear actuator. Since the cable is connected to the end of the actuator rod, when the actuator receives a signal to translate backward, the actuator rod pulls the cable, thus pulling the brake towards the foot well and actuating the brake system. The cable-actuator arrangement pulls the brake pedal towards the floor just as if a person were driving. When the motor receives a signal to stop braking, the motor turns the actuator rod to the neutral position which in turn loosens the cable tension therefore releasing the brake. So, when the motor is at the neutral position, the brake is completely released.

The cable-actuator approach is similar to the way cruise control is implemented in most vehicles. In cruise control, when the desired speed is set for the vehicle, an actuator is engaged which is connected to a cable which in turn is connected to the throttle valve. As the driver changes speed via buttons located on the steering wheel, the throttle valve is opened more in order to accelerate, and the throttle valve is closed more in order to decelerate. Thus the cable-actuator approach has been used for the past 30 years ever since cruise control was invented.

Lastly, the cable arrangement is advantageous because it makes use of the entire hydraulic system of the SRX including the Antilock Brakes System and Brake Assist (ABS and BA). As was briefly discussed in the introduction, the hydraulic system is controlled by the brake pedal which is mechanically connected to the hydraulic system. Figure 2 shows an overview of a hydraulic braking system.

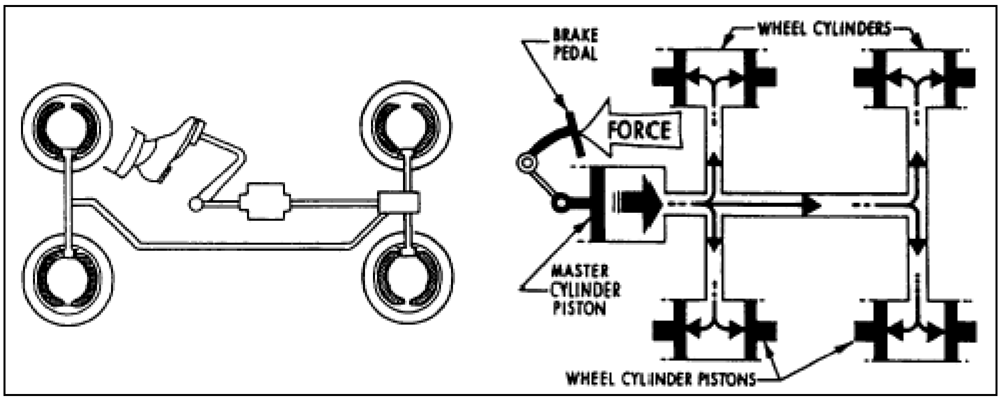

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Figure 2: A simplistic hydraulic braking system

Most vehicles, including the SRX, have a function called Brake Assist (BA), which is the equivalent of power brakes. A component called the brake booster makes BA possible; it is located between the master cylinder and the brake pedal. The brake booster uses pressure differences supplied from the atmosphere and through a tube connecting the booster to the SRX engine. A power brake system is shown in Figure 3. The brake booster, or vacuum booster, is composed of a compartment with a diaphragm where the left side of the compartment has a vacuum hose which attaches to the engine, and the right hand side of the diaphragm is open to the atmosphere. When the brake is disengaged, a low pressure is created on the left hand side of the diaphragm which keeps the brake in the neutral position. When the brake pedal is depressed, the diaphragm is pushed forward allowing the atmospheric pressure to overtake the right hand side of the compartment. When the higher pressure overtakes the right hand side of the brake booster, the diaphragm is forced forward. The diaphragm is connected to the master cylinder via a connecting rod which in turn engages the master cylinder. The brake booster assists braking by making it easier to engage the brakes as well as returning the brake pedal to the released position.

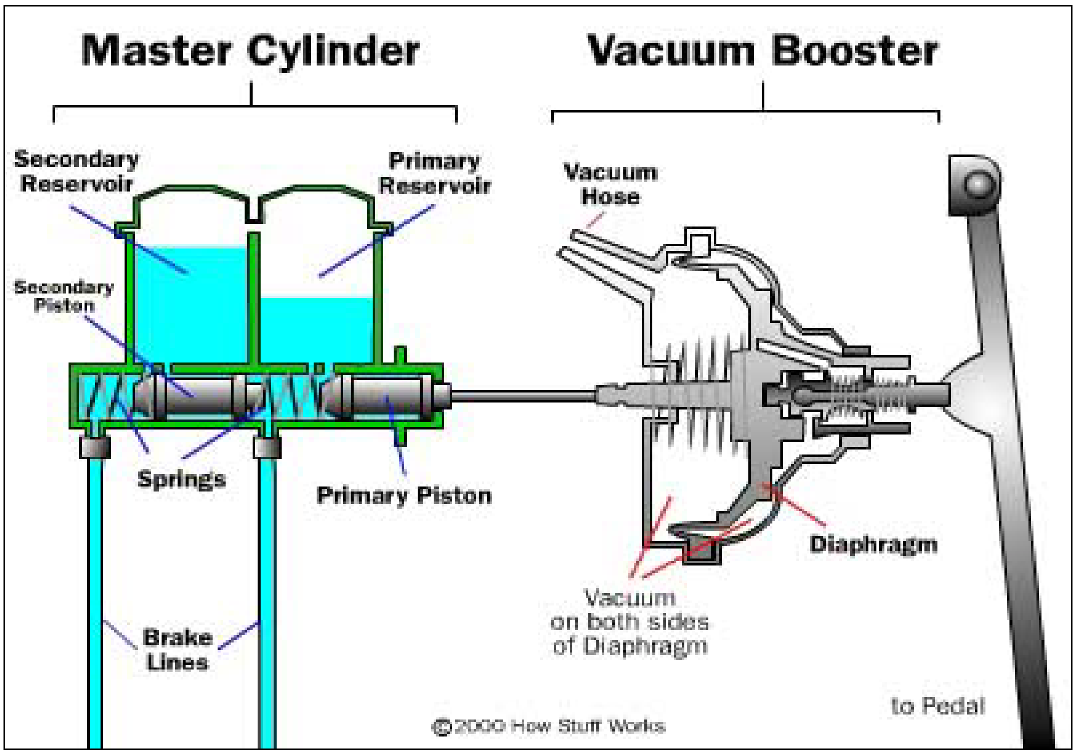

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Figure 3: A Power Brake System

As mentioned in the introduction, BA is what creates the pedal 'feel' where the driver can feel the brake pedal disengaging. Many technical papers address ways to simulate brake feel to make by-wire driving more real to drivers, but this aspect is out of the scope of this thesis. Nevertheless, BA is another reason why engaging the brakes via the brake pedal is an advantageous approach.

The next step was to choose a motor. We chose a Danaher Motion Linear Actuator with an encoder. This motor can provide 700 pounds of thrust and has a maximum speed of one inch per second. Included in the motor is a potentiometer which counts the number of rotations that the worm gear moves in order translate the shaft out of the actuator housing. Figure 4 shows a Computer Aided Design (CAD) drawing of this motor. As a trade off for the high level of thrust that can be provided, this motor requires a 24 *Volt* power supply. The power supply of the SRX is a 12 *Volt* system, so changes had to be made to the power supply in order to power the brake motor which will be discussed in the controls section.

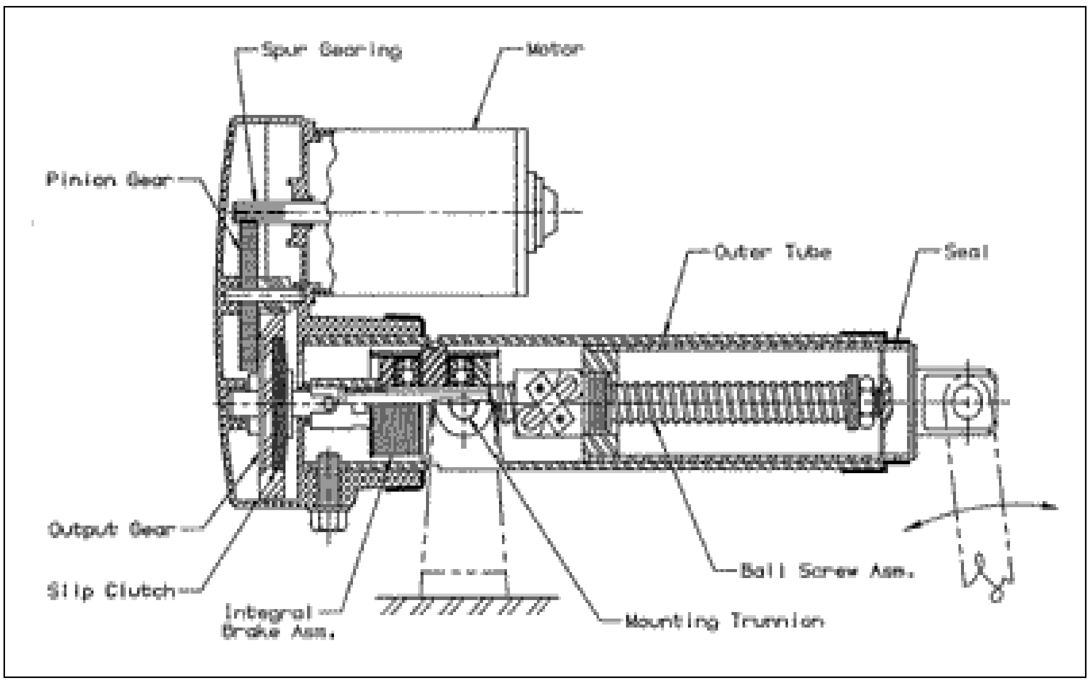

Figure 4: A Danaher Motion Performance Pak 24 *Volt* DC actuator

Two steps were taken to secure the linear actuator underneath the driver's seat. First, the motor was welded directly to a steel plate. Second, the steel plate was fastened to the floor of the SRX. To prevent the motor from shifting under the driver's seat, holes were drilled in the steel plate and into the floor of the SRX. Then 4 ½ " x 2 " galvanized steel bolts were drilled through the steel plate securely fixing the motor on the floor of the SRX. This design makes it so that motor doesn't move under the driver's seat during testing.

At this point, we installed the steel cable and the hardware that was necessary to guide the cable. Figure 5 shows a picture of the cable assembly that we devised. The steel cable is 0.1 *inches* in diameter and is made of braided steel. One end of the cable is connected to the linear actuator located underneath the seat. This end is fastened with a custom bracket and swaged aluminum stops. In order to guide the cable, a steel tube was installed along the left wall on the floorboard of the SRX. The tube serves as protection and as a guide for the cable. The tubing is 1/4 inch outer diameter and 1/8 inch inner diameter. Aluminum eyelets with rubber liners secure the steel tube at three points and were screwed into the floorboard of the SRX along the wall in order to secure the steel tube.

Figure 5: The HSAVT brake-by-wire solution

The function of the steel tubing is to facilitate easy translation of the cable and to serve as protection for the cable line. The tube allows the cable to slide without catching on anything inside the vehicle, and it also allows us to place the carpet over the entire system. Once the steel cable is routed through the steel tube, the cable is then fastened to the brake. A brass split bolt secures the cable to the back of the upper armature of the brake pedal. Also, the cable is routed against the driver's side wall so it is out of the way of the driver. The cable assembly is hidden from the driver underneath of the stock floorboard carpet. Figure 6 shows a picture of the cable system covered by the carpet.

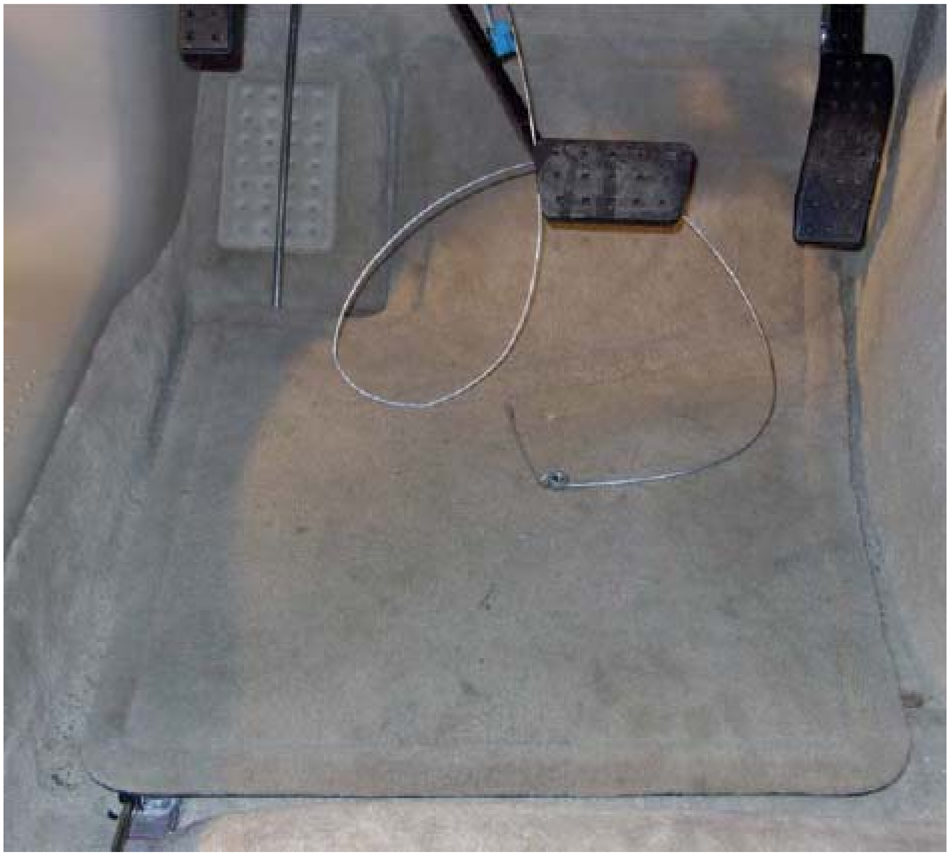

Figure 6: The final HSAVT brake-by-wire system

CHAPTER 3

Control of the Brake System

This section will explain how the brake motor is controlled. First, the control architecture will be explained. Second, an overview of the software programs used will be presented. Third, all other control considerations such as calibration of the motor and motor feedback will be discussed.

An electric motor controls the linear actuator. In order to control the linear actuator, a voltage signal must be sent to the motor. From this point, the motor drives the actuator to the position of the corresponding voltage signal. The issue of control is very important because the motor replaces the role of the human operator to depress the brake pedal. When programmed properly, the motor is much faster and more responsive than a human. The difference is largely due to the fact that motors do not get distracted or get confused like humans. The following section will give a general description of each component that is needed to actuate the brake pedal.

One of the most important components of driving is the user interface. An interface mechanism is what the driver of the vehicle will be using to control the vehicle (i.e. a steering wheel and brake pedal set up, a joystick, a control stick, etc.) Several types of interface controllers were considered but the one that seemed most applicable was a controller that is used for video automotive racing games. Figure 7 shows the Logitech Wingman Formula GP which is the controller used.


Figure 7: The Logitech Wingman Formula GP controller mounted inside of the SRX

The Logitech Wingman Formula GP interface works nicely because it has the necessary connections to communicate with the Personal Computer (PC). In addition, the game controller simulates a real driving interface that drivers are used to, unlike the joystick that is used in other by-wire vehicles such as the Virginia Tech Grand Challenge vehicles. For these reasons, the HSAVT decided to use a mock up of the brake and throttle pedals and steering wheel.

To accommodate safer testing when the vehicle is driven at high speeds, the team installed a wireless hub. The Linksys wireless hub makes it possible to remotely control the vehicle. This remote control is created by using a laptop which is hooked up to the game controller. So, with this set-up, we can take the laptop out of the vehicle and drive the SRX with the game controller from within 100 foot radius. In addition, the remote connection is useful for remote data logging and observation for all computer programs running during testing. Most importantly, this remote connection allows the team to see exactly what vehicle commands are being sent to the vehicle.

In the back seat of the SRX sits the desktop PC which is really the 'brains' of the by-wire control system. Here, the PC records and processes all data. Data is sent from both actuators communicating what position the steering actuator and the brake are located at. The PC also runs the software programs. In addition, the game controller is connected directly with the PC via a USB cable. The game controller sends corresponding voltage signals to the PC in order to drive the vehicle. Figure 7 shows a flow diagram illustrating the layout of the hardware described in this section.

Inside the PC, voltage signals are converted to a corresponding brake percentage in the NI software. This conversion is discussed in depth later in this section. The brake percentage can then be viewed on the screen of the PC in the backseat of the SRX. An overview of the control scheme is shown in Figure 8. This screen is updated at five *hertz* where the desired braking percentage requested of the game controller is displayed in real time.

The team added two other components to the PC to enhance our processing capability: a National Instruments Motion Control Board (NI, MCB) and a Data Acquisition card (DAQ). The DAQ card serves as a data hub through which several signals can be relayed. To allow external signals to flow in and out of the PC, a breakout board with a 68 pin connector is connected to the DAQ card. The NI Motion Control Board also has a breakout board called the Universal Motion Interface (UMI) also by

National Instruments. For this project, the UMI has two jobs: first, it controls the brake actuator, and second, it sends feedback to the PC from the brake actuator. This feedback is provided by a potentiometer that is located inside of the brake actuator. The purpose of reading in feedback to the PC is so that the PC can record exactly where the actuator is at all times. Feedback will be discussed in more detail later in this section.

Through the UMI, the PC sends a voltage to the Advanced Motion Controls Amplifier (AMC). An amplifier is a vital component for any motor. The purpose of the amplifier is simply to amplify the voltage signal to be sent to the motor. From the amplifier, a voltage is relayed to the brake motor, and then the actuator rod is moved to the specified position for braking.

The degree of braking that the motor relays is a function of what voltage was sent to the PC from the game controller. As the game controller's brake pedal is depressed, a corresponding voltage is sent to the PC. Then the PC sends a corresponding voltage signal to the brake actuator through the UMI and amplifier.

Figure 8 is a diagram showing how the signals flow through all of the components that were just described.

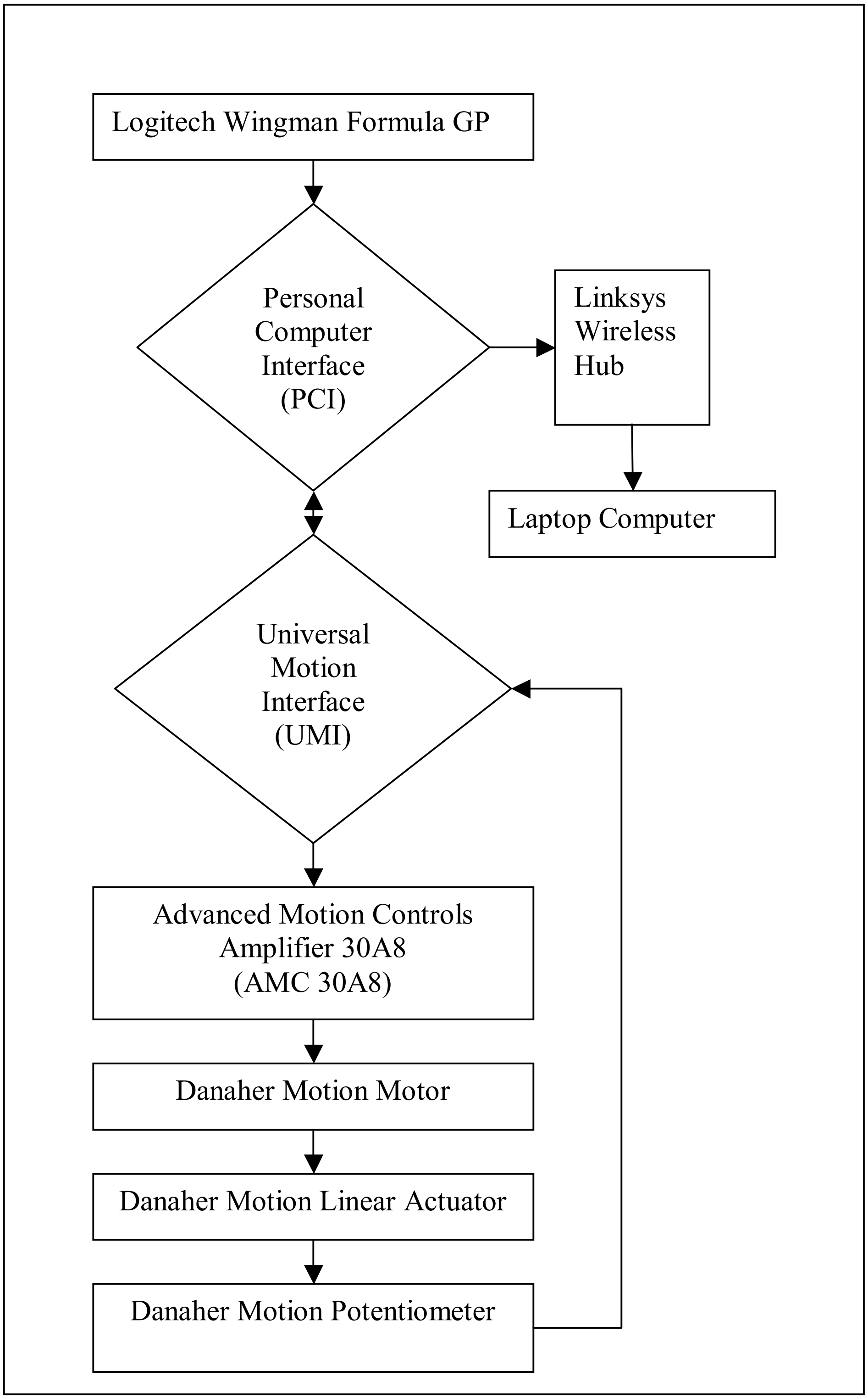

Figure 8: A flow diagram of the control architecture for braking

To review, the flow signals from the game controller to the brake occur as follows. From the game controller or the laptop computer, a signal is sent through the DAQ card to the PC. Then, the signal is processed by the NI software in the PC. Once the signal is processed, a corresponding voltage signal is sent to the UMI through the Motion Control Board. From the UMI, the voltage signal is sent to the amplifier and from the amplifier, the voltage is sent to the motor under the driver's seat. The motor reads the voltage signal and moves the actuator rod to the specified position. From this point, the actuator rod pulls on the steel cable in turn depressing the brake pedal. As the motor moves the actuator rod, a potentiometer inside the actuator relays a signal back through the UMI to the PC. Here, if data is being logged, the signal is processed in the PC and a corresponding position is calculated and recorded in the software.

The software program we used is LabVIEW by National Instruments which is run by the PC. The team decided to use LabVIEW partially by default since all robotic programs at Virginia Tech use it, but also because the user interface is user friendly. The software programs that were developed serve many purposes for by-wire control. First, the software is programmed to record the brake motor position during testing. Second, the software program converts the voltage signals to a corresponding percentage of braking which is discussed further later in this section. Third, the software serves as an interface for the HSAVT. This interface is how we can see what we are telling the vehicle to do.

The software programs serve many purposes for controlling the vehicle. First, it serves as a visual aid for the driver. This is so he or she knows what brake percentages are being sent to the SRX. Having an interface that is connected directly to the game controller is especially important so the driver is cognizant of exactly how much braking is being requested during testing. Furthermore, these NI programs allow the SRX to be controlled directly from the PC. This is useful because the team then is not reliant solely on the game controller. Lastly, an emergency stop is programmed into the software in case of an emergency.

If an emergency does occur, the SRX has an emergency stop procedure. We made the procedure short to help ensure the vehicle stops as quickly as possible. There are two ways to initiate emergency procedures. The first is to press the emergency stop button located on the front panel next to the driving wheel. The second way to initiate emergency procedures is to press the 'soft' e-stop button that is programmed in the software. When an e-stop button is pushed, if the vehicle is moving, all other signals are negated and a 100% brake signal is sent to the motor. Thus full brakes are applied and the SRX should stop. Several options for a second and totally separate mechanical emergency brake were considered but were not implemented for this project.

One of the biggest advantages of using LabVIEW is that it allowed us to use a program called FlexMotion. This program is used especially for motor control so it was perfect for our purposes. The FlexMotion program first processes the desired brake percentage that is specified by the game controller to the PC. Second, FlexMotion uses the algorithm shown in Equation 1 to calculate the desired position that the brake should move to.

$$DesiredBrakePosition = a * (f - n) + n \qquad (1)$$

In this equation, *a* is the desired brake percentage, *f* is the full brake position in counts, and *n* is the no brake position in counts. This algorithm is a function of the maximum full brake position, or *f*, which is recorded experimentally for the position of the brake when the brake is fully actuated. Conversely, n is the no brake position where the brake actuator position is recorded with only slight tension on the steel cable. Thus we recorded the position of the actuator at maximum brake (100% braking) and zero brake (0% braking).

Since the potentiometer measures position in counts and the game controller reports the amount of braking as a percentage, it became necessary to use a conversion. When a percentage is requested from the game controller, the FlexMotion program converts that percentage to an actuator rod position that the brake will be actuated to.

Figure 8 shows the control panel for the desired throttle, brake, and steering percentages. This screen shows the software that is the interface that we can view and control the SRX with. Furthermore, the driver can get feedback on what he or she is asking the SRX to do. Once again, this screen is a great interface for experimentation because it allows the driver to see everything that is being asked of the system in real time (as it occurs).

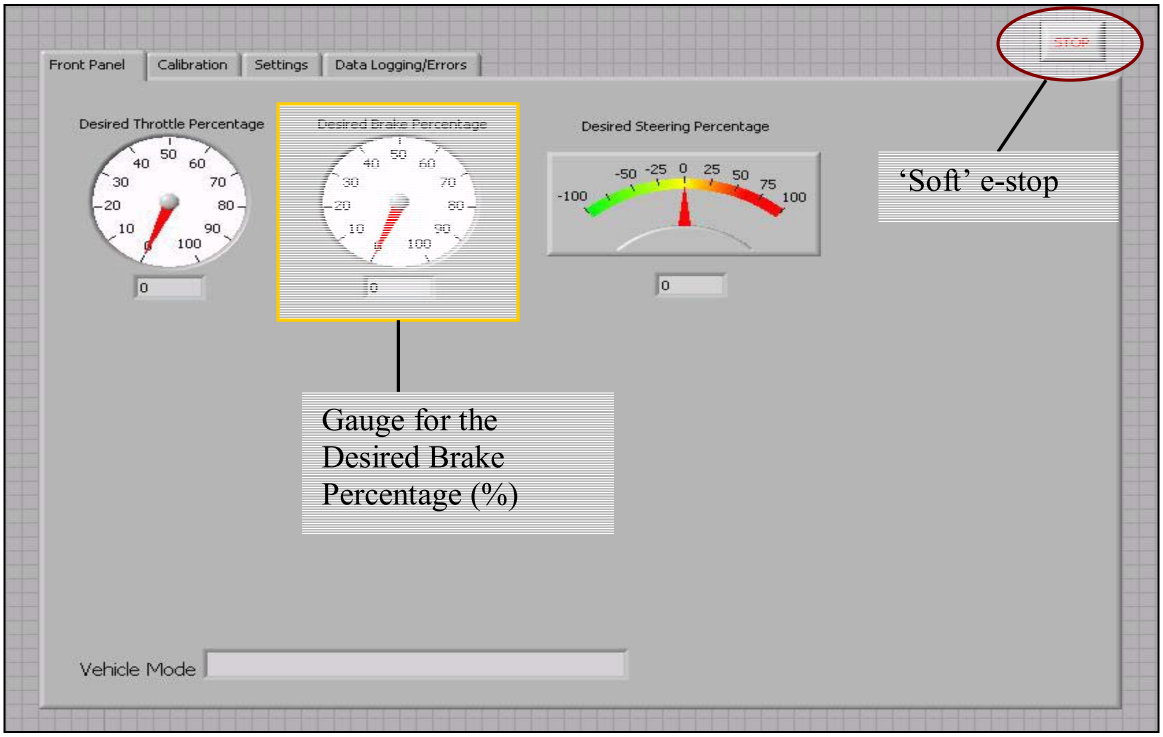

Figure 9: The LabVIEW control panel for throttle, brake, and steering

Another advantage of the Flex Motion program is that it allows us to control the PID constants of the motor during testing. The brake actuator had a tendency to bounce a great deal before we tuned the PID controls of the motor. PID constants were chosen using the trial and error method to smooth out the response of the actuator. Figure 10 shows the program used to tune these constants. The proportional gain K_c, was adjusted in order to increase the speed of the signal while the integral and derivative gains were set to zero. A proportional gain was chosen which allowed for the signal speed to be increased but not unstable. Then, the integral gain was adjusted in order to reduce the steady state error. Increasing the integral gain though also increases overshoot. Once the integral gain was chosen to decrease the steady state error (the difference between the steady state value and the largest amplitude value), the derivative gain was changed. The derivative gain decreases the overshoot and also increases the sensitivity of the system.

This system was used in order to tune the brake motor however the Ziegler-Nichols 'guess and check' method was considered.

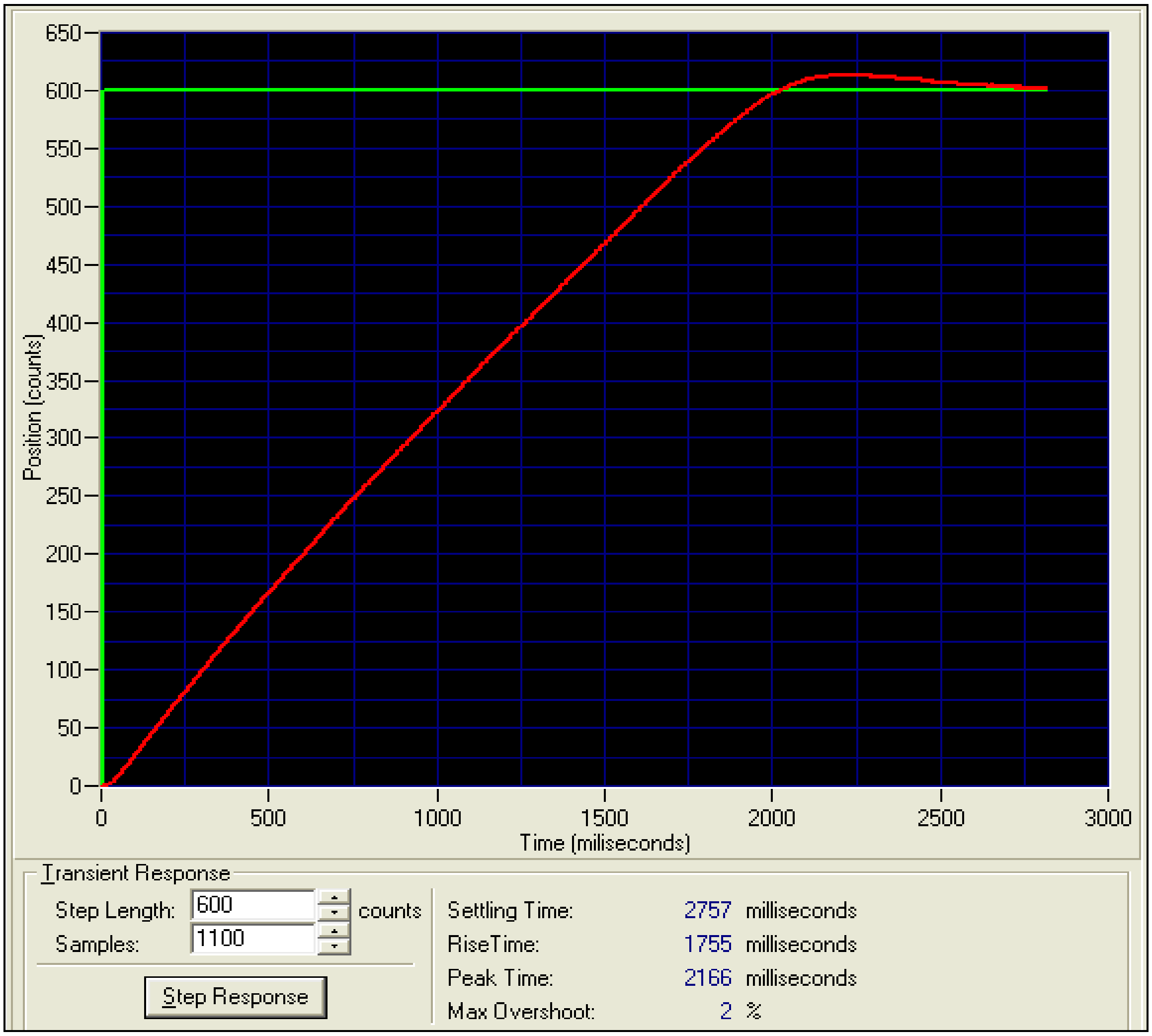

Figure 10: PID tuning for the brake motor using Measurement and Automation Explorer

The last aspect of motor control is motor calibration and motor feedback. Calibration is part of the system initialization process that is started at the beginning of every test. For the braking system, initialization is controlled by the Flex Motion software. The purpose of initialization is to calibrate and restart all of the controls hardware (UMI, DAQ, etc). This initialization program is also used to calibrate the brake positions and to ensure accuracy. This is especially important since there are several conversions that are performed between the game controller and the brake actuator. In order to initiate the process, the initialization program button is pushed. Once those steps are completed, the program signals the brake motor to fully extend the actuator rod. Once the actuator rod is fully extended, this position is recorded as the zero position. Now all of the hardware has been initialized and is ready for testing.

As was discussed earlier in this section, feedback for the brake actuator comes directly from the brake potentiometer. Feedback is one of the most important components for a drive by wire system because it allows us to know exactly where the actuator is. This information supplied by the motor lets us know how much braking is actually occurring. Feedback is also valuable for data logging during tests. The steering mechanism also has a form of feedback but that will be discussed in Chapter 6.

The potentiometer is located inside the actuator housing and measures how far the actuator rod retracts (in counts). The zero position corresponds to the position of the actuator rod while it is fully extended. From the zero count, or 0% braking, the potentiometer measures how many counts the actuator rod moves. As the actuator moves back and forth (thus actuating the brakes), the potentiometer sends the corresponding counts through the UMI to the PC where the data is recorded. Within LabVIEW, position (in counts) is converted to a brake percentage. This data is recorded to the data log where we can see the brake response after testing is completed.

Chapter 4

Results and Recommendations for the Brake-By-Wire System

This section will present the results of testing the brake-by-wire system. In addition, this section will present recommendations to improve future projects.

The HSAVT brake-by-wire system complied with each of the requirements that were defined for the brake-by-wire system. The main goal of the brake-by-wire system was to develop a fully by-wire braking system. The system that was developed also had to be reliable and effective. Furthermore, the brake system had to be hidden and non-intrusive to the driver.

The goals for the brake system were generally broad and subjective in nature. In order to adequately quantify the level of compliance of the braking system with the project goals, the need for quantitative specifications became apparent. The underlying goal for this project was to develop a drive-by-wire vehicle that is as responsive as a conventional vehicle. Therefore, it is important for future teams to define specific requirements at the beginning of the project. General Motors publishes braking characteristics for the Cadillac SRX which should be used as a benchmark for the team to shoot for. The benefits of using the GM specs as a benchmark are twofold since it gives the team a specific goal for the team to work towards as well as providing a basis for comparison.

On May 5th, 2005, the HSAVT demonstrated that the SRX was successfully converted to drive-by-wire status. On this day, the SRX went through testing to demonstrate compliance of the SRX to the project goals. Testing included a 360 degrees turn and several turns left, right, and straight forward. Braking was also tested including soft, slow braking as well as quick braking. All testing was performed less than 10 miles per hour. Figure 11 shows one of the team members driving the SRX using the game controller only.

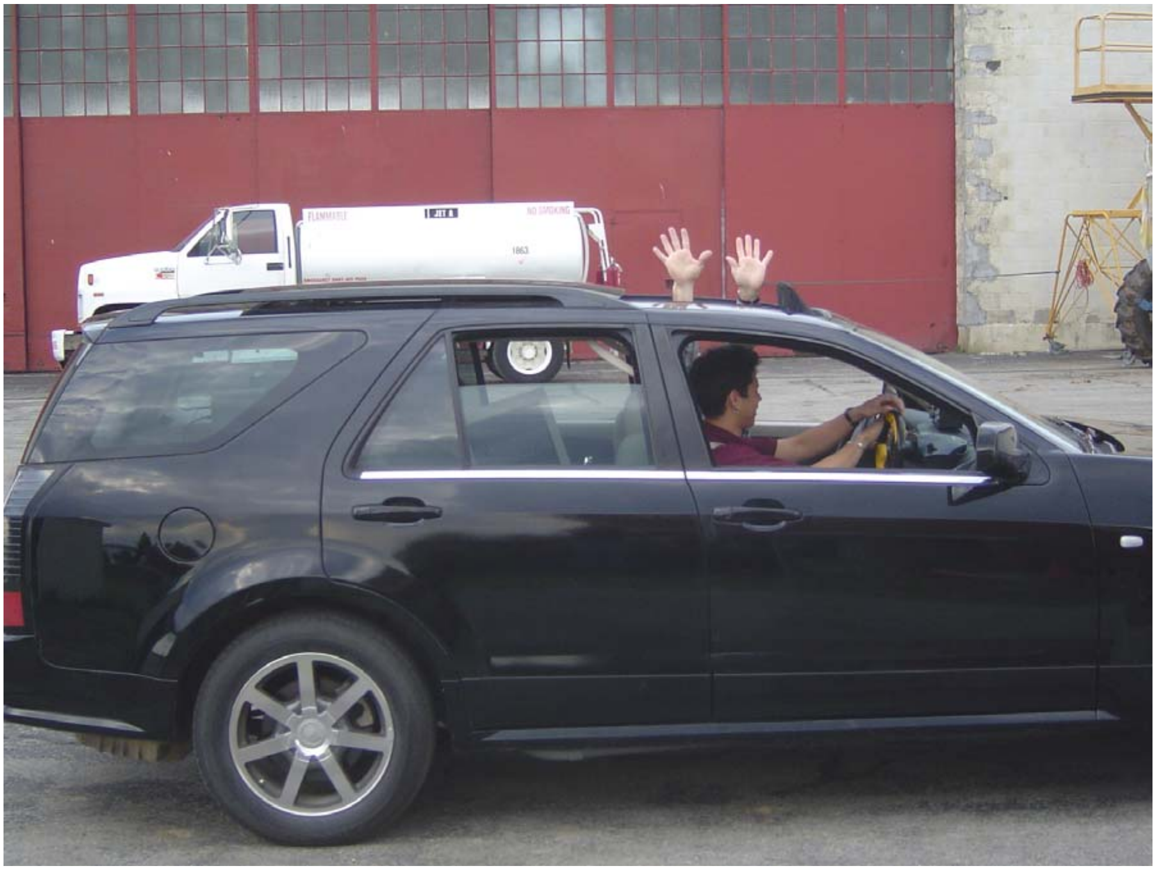

Figure 11: Testing of the fully drive-by-wire GM Cadillac SRX

For safety reasons, a second team member sat in the driver's seat to act as a second emergency stop. The second team member sitting in the driver's seat was there to act as a 'human emergency stop'. If the SRX went out of control for instance, the human emergency stop was there to depress the brake petal. Fortunately, the emergency procedures (human or software based) were not used. The brake responded to all commands from the game controller. The HSAVT braking system complied with all of the general requirements. The brake responded consistently to the game controller commands. Furthermore, the brake system was completely hidden and non-intrusive to passengers. Lastly, the brake-by-wire system in fact did replace traditional mechanical braking operations and was actuated electronically. Therefore, the HSAVT demonstrated full compliance with the project goals and was a complete success

The remainder of this chapter will focus on ways to improve the brake-by-wire system. The purpose for these recommendations is for later teams to learn from the experiences of prior teams. Since the HSAVT was the first to start developing a by-wire vehicle capable of high speed applications at Virginia Tech, this project was a challenge. That said, there are a few changes that would improve future by-wire projects.

There are two main changes that should be made to the HSAVT brake-by-wire system. First, a completely different method for actuating the brake should be implemented. Secondly, a faster brake actuator should be used. There are many advantages of using a more direct method of braking. However, the most important benefit of using another actuation technique would be an improvement in the responsiveness and controllability of braking. In the introduction, two types of brake-by-wire techniques are discussed: electromechanical and electrohydraulic braking. Electrohydraulic braking taps directly into the hydraulic lines to control braking. In contrast, electromechanical braking actuates the brakes by placing an electromechanical disc brake at each wheel. Both of these techniques should be considered in order to maximize the amount of control and stability that a high speed vehicle will require.

Since the brake actuator had to be installed two feet away from the brake pedal, the cable-actuator had to be added to the brake system. Adding a mechanical system to a by-wire system goes against the principle of by-wire technology. The purpose of a by-wire system is to actuate the brakes more quickly and in a more direct fashion than the typical human being. Through observation, it became clear that this actuator did not actuate the brakes faster than a typical human. This actuator should be replaced with a faster and more responsive actuator.

The brake actuator was very slow with a slow reaction time. The delay in braking is due to the amount of time it takes to retract the actuator rod. Since it takes one *inch per second* to retract the steel cable which depresses the brake pedal, this added to how long it takes to brake the SRX. Thus, when the game controller brake is depressed, it would take a full two seconds for the brake actuator to fully brake the vehicle. High speed applications will require a more responsive and more quickly operating brake actuator.

The brake actuator required 24 *volts* of electricity which is twice the value of every other electrical component in the SRX. Since the actuator needed 24 *volts* a DC-DC power converter had to be included in the power design. Having to add a component for one actuator was not a very efficient use of project funds and time. Therefore, the next actuator power requirements should match the power scheme of the SRX power system (12 *volts*).

In addition, there was a problem with the brake actuator continuing to rotate after it reached the fully extended position. The actuator rod is attached to the steel cable which pulls the brake, the fact that the actuator rod continues to rotate caused concern. To help counteract this problem, the steel cable is connected to the actuator rod by a connector that can rotate. This connector prevents the steel cable from twisting while the actuator rod rotates. Even though the connector reduced twisting of the steel cable, the best way to counteract the problem would be to use an alternative initialization process developed by the software team.

On the software side, future teams should log data for every test. Logging data is important for several reasons. The most important reason is that if something goes wrong during testing, the team can go back after the test and figure out what happened to cause a problem. Additionally, data logging is important to benchmark old and new techniques, programs, and hardware. If a component is replaced, there is no way to tell if the new hardware is better than the old hardware. Without data to support the hardware change, observation is the only way to tell if the new hardware is better and observation is a subjective benchmarking technique. Data is also important for accurate and meaningful documentation. Therefore, future teams should strive to log data on every component and for every test.

Future teams should also expand on the type of data that is logged. In addition to recording the feedback signals of motors, the team should look into recording the velocity of the vehicle, the steering angle of the tires, etc. This may require installing extra sensors and or an Internal Navigation System (INS).

Overall, this system was effective in that it met all of the requirements that were set in the beginning of the project. The brake actuator was a little oversized for its purpose since the thrust specifications were well over what was required to actuate the brake petal with power brakes. In addition, there are several different modes of actuation that would make more sense for another brake-by-wire system. Future teams will be able to benefit from this portion of the project in that they will learn how to make a brake-by-wire system better.

Chapter 5

The Steer-By-Wire Solution

This chapter will focus on describing the steer-by-wire system in the Cadillac SRX. First, the requirements for the steering system will be discussed. Second, this section will present a short background of conventional steering systems and methods of electronic actuation. Third, the HSAVT's steer-by-wire system will be discussed.

To ensure an effective steer-by-wire system, several requirements were defined at the beginning of the project. First, a steer-by-wire system must be reliable and responsive. The game controller must consistently demonstrate complete control of the steering system. Also, a responsive vehicle will be able to change directions on command. If the SRX is not responsive to controller inputs, vehicle control will be compromised and is not safe. The vehicle must also be accurately controlled. Accuracy is a necessity especially for high speed applications and the heading of the vehicle must be reliable and accurate. Furthermore, accurate steering control will help ensure that the vehicle is safe. The next requirement of the steer-by-wire system is that it must be compact and non-intrusive to the driver. If the steering system is hidden and protected, there is less interference of testing from the driver and this will ensure safety.

There are also several requirements for the steering actuator. First, the actuator must be sturdy and compact. A sturdy motor will encourage repeatability and will be able to endure rigorous testing. A compact actuator will also help the steer-by-wire system to be out of the way of the driver during testing. The steering actuator must also have feedback capability to provide information about where the steering is at all times. As was discussed in Chapter 4, feedback ensures that we can monitor the path of the vehicle and can be used with a control algorithm such as PID for smoother and more stable actuation. Torque requirements were found experimentally by attaching different weights to the steering wheel to quantify how much torque is needed to turn the steering wheel. The resulting torque requirement was five foot pounds of torque. All of these requirements had to be met to ensure a stable steer-by-wire system.

The purpose of all steering systems is to control the heading of a vehicle. The Cadillac SRX is outfitted with an all speed variable assist power rack-and-pinion steering system. In order to explain a variable assist power rack-and-pinion steering assembly, a basic explanation of rack-and-pinion steering will be presented.

Rack-and-pinion steering has two purposes: to transfer the rotational motion of the steering wheel to linear motion at the wheels and to serve as a gear reduction to make turning the vehicle easier. Figure 12 shows a diagram of a basic rack-and-pinion steering arrangement.

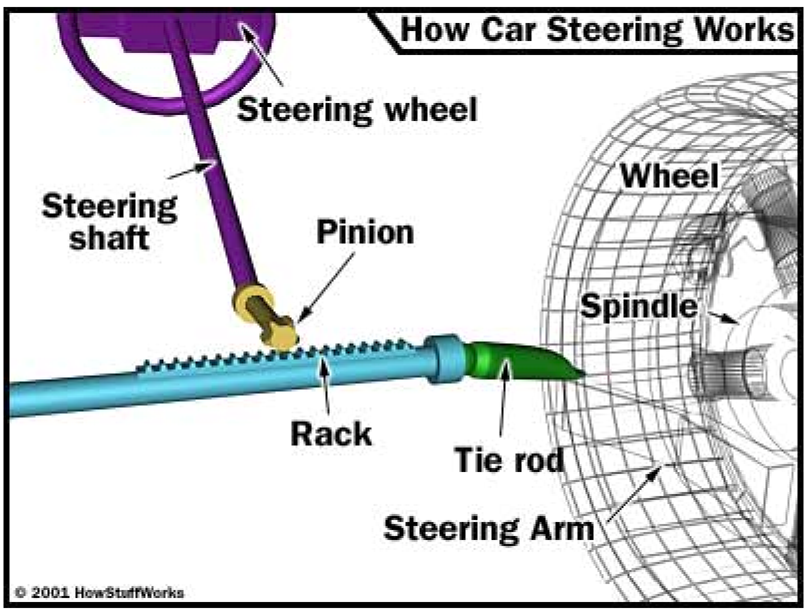

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Figure 12: A diagram of a rack-and-pinion mechanism for turning a vehicle

The principle of this system is quite straight forward. As the driver turns the steering wheel, the steering shaft and the pinion rotates with the wheel. The pinion has teeth that mesh with the teeth of the rack. As the pinion rotates, the pinion teeth move the rack in the same direction. For example, if the steering wheel rotates clockwise (turning right), the pinion moves the rack also to the right. At each end of the rack, a tie rod connects the rack to the steering arm and spindle of each front wheel. So, when the steering wheel turns right, the pinion moves the rack to the right and the steering arms turn the wheels in the same direction.

The entire steering assembly is located underneath of the car in between the front tires. Figure 13 illustrates the layout of the steering assembly.

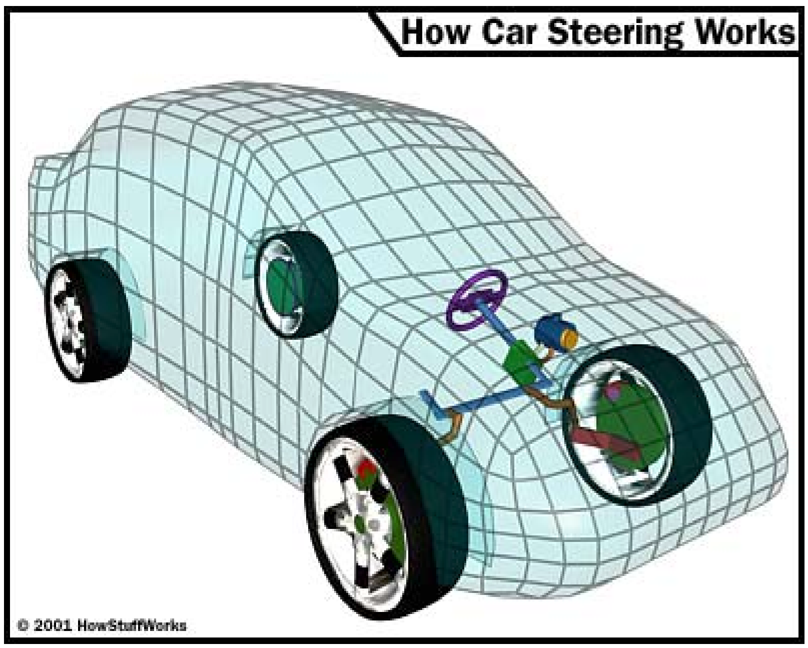

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Figure 13: An overview of the steering assembly

To make steering the vehicle easier, the Cadillac SRX is outfitted with power steering. Without power steering it takes a lot more effort to turn the vehicle since the SRX is over 4,000 pounds.

There are several components that make up the power steering assembly: a pump, a rotary valve, and a hydraulic system. In rack-and-pinion steering, the hydraulic system is installed at the rack. A power rack-and-pinion arrangement is shown in Figure 14.

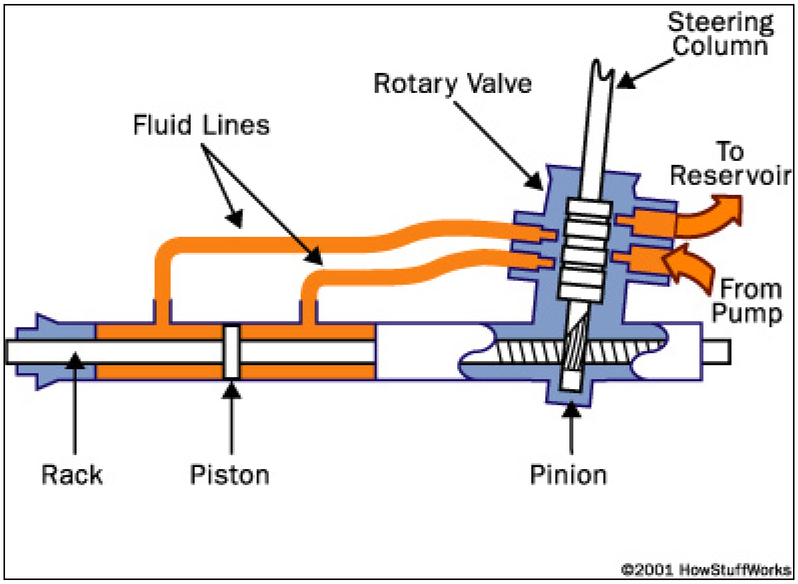

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Figure 14: A power rack-and-pinion system

Surrounding the rack is a cylinder-shaped metal sheath. The compartment between the rack and the cylinder is filled with hydraulic fluid. Attached to the rack is a piston which is located between two fluid lines. When the steering wheel is turned, the rotary valve lets in hydraulic fluid into the corresponding fluid line and into the cylinder. If the steering wheel is turned right, the rotary valve lets more fluid into the right side of the piston. This addition of fluid to the right side creates a high pressure and pushes the rack to the right as well. An important distinction though is that power steering simply assists the pinion-and-rack mechanism and makes turning the wheels easier.

The pump is located along the steering shaft and is run by the engine. The pump simply pumps the hydraulic fluid though the fluid lines.

> "The amount of flow provided by the pump depends on the car's engine speed. The pump must be designed to provide adequate flow when the engine is idling. As a result, the pump moves much more fluid than necessary when the engine is running at faster speeds."
> www.howstuffworks.com

Continuously running a pump for power steering is an inefficient process. Therefore, steer-by-wire is a technology sought to replace the pump and drive the rack electronically.

With a clear background of the SRX steering assembly, HSAVT was able to make an educated decision on how to turn the wheels electronically. The first step in the design for a steer-by-wire design was to choose the method of steering control. In the introduction, two steer-by-wire technologies were discussed, electromechanical steering and all wheel actuation. All wheel actuation is where each wheel has its own steering mechanism. This method was considered but was eliminated because of the complexity and expense associated with an all wheel drive vehicle. That said electromechanical actuation was chosen as the form of steer-by-wire technology. Electromechanical actuation is where a motor is installed in the steering assembly in order to control the direction of the vehicle. Typically in electromechanical steering, actuators are installed on the steering shaft or at the rack and pinion configuration underneath the vehicle. This approach makes use of the power steering that is explained above and utilizes the steering assembly that is already in the vehicle. For these reasons, electromechanical actuation was chosen for by-wire steering in the SRX.

Now that we choose the method for steering the SRX, the next step was to decide where to actuate the steering. As was stated before, electromechanical actuation involves using an actuator to turn the wheels. There are two common places to mount an actuator for steer-by-wire actuation: on the steering shaft or at the rack-and-pinion gearset. Installing an actuator in the rack-and-pinion gearset would involve replacing the hydraulics in the rack with an actuator. The hydraulic system is the means for power steering. Therefore, mounting an actuator at the rack would most likely mean disengaging the power steering. Conversely, mounting an actuator on the steering shaft would utilize power steering of the SRX. Thus in order to take advantage of power steering, the team decided to mount the actuator at the steering shaft.

The next step was to choose the method for turning the steering wheel electronically. Several options were considered such as using a linear actuator to move the steering wheel, a harmonic drive, and an electric motor. Both the linear actuator and the harmonic drive were eliminated as valid choices due to space limitations around the steering shaft. So clearly a method had to be chosen that would fit within the space available around the steering wheel. Considering the space limitations, the end decision was to actuate the steering wheel using an electric motor.

Several electric motors were considered but the one that matched our specifications was the Smart Motor by QuickSilver. This motor is known for its compact design and includes a controller called an encoder. The encoder is engineered to provide 8000 counts per revolution of feedback. Additionally, the motor can provide five foot pounds of torque that is needed to turn the steering wheel with power steering assistance. Figure 15 shows the Smart Motor and Controller[1].

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[1] * The SilverMax® series is no longer offered for sale, it has been superseded by the SilverNugget™ and SilverDust™ series. SilverMax®, SilverNugget™, and SilverDust™ are trademarks of QuickSilver Controls, Inc., which has also granted limited use of their copyrighted materials for inclusion in this thesis.

Figure 15: The QuickSilver Smart Motor and controller

To serve as a gear reduction, a gearhead provided by GAM, was coupled with the motor. This gearhead is able to provide a 16 to 1 gear reduction. That is, for every 16 revolutions the motor makes at the output shaft, the gearhead takes in those 16 revolutions and outputs 1 revolution. This reduces the rate at which the steering wheel can be turned. Figure 16 shows a CAD drawing of the GAM gearhead that was used.

Figure 16: A CAD drawing of the GAM gearhead

In order to transfer the energy from the motor to the gearhead and then to the steering wheel, a belt drive assembly was developed. The belt drive assembly consists of two pulleys and one timing belt. The driving pulley (pulley 1) was mounted to the output shaft of the GAM gearhead. Wrapped around pulley 1 was the timing belt. Figure 17 shows the driving pulley (pulley 1) and the timing belt respectively. From the CAD model shown in Figure 17, pulley 1 and the timing belt have notches where the belt and pulley line up. The second pulley (pulley 2) was then be mounted on the steering shaft of the steering wheel and the timing belt was wrapped around pulley 2. Thus, the motor rotates pulley 1 and transfers that motion to the timing belt which turns pulley 2 thus turns the steering wheel.

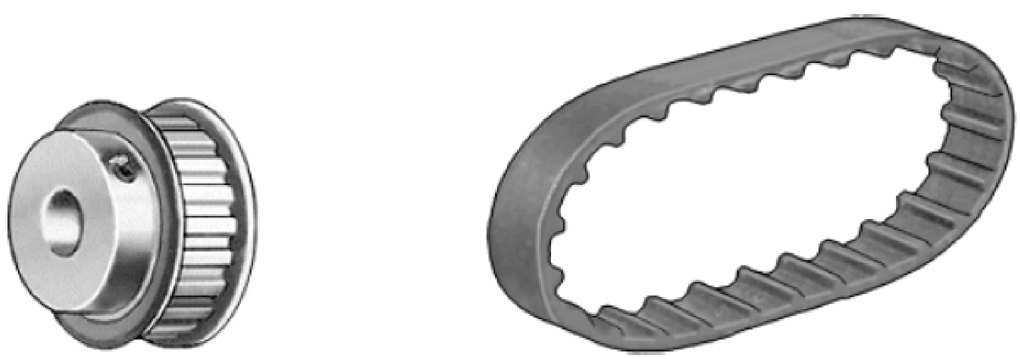

Figure 17: CAD drawings of the McMaster pulley and timing belt

The belt drive assembly was a design developed specifically for the SRX, so in order to install the assembly, several parts had to be machined. The first step was to find out how to mount pulley 2 on the steering column. In order to find out the dimensions of the steering column, the entire steering shaft was taken out of the SRX. Observation of the steering column revealed that the steering shaft is not a uniform shape. In fact, the steering column was flat on two sides with two rounded sides as shown in Figure 18.

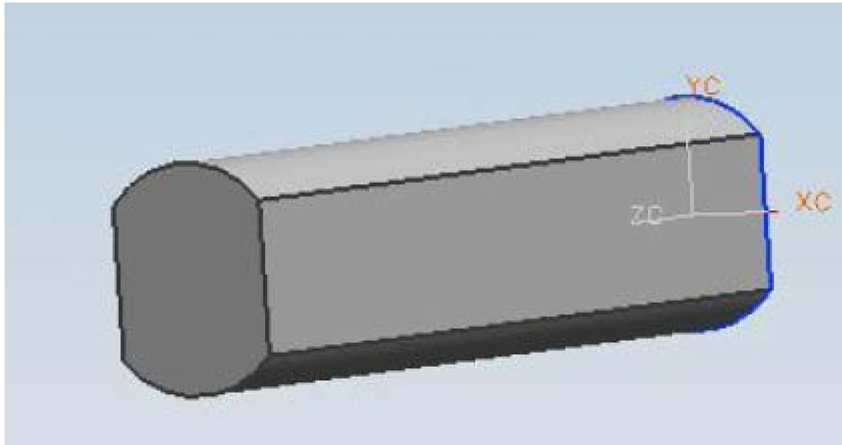

Figure 18: A cross sectional diagram of the steering column in the SRX

The fact that the steering column was noncircular proved to be an obstacle for the team. In addition, there was no advantageous place to slip pulley 2 onto the steering shaft because each end of the steering column was too large for pulley 2 to fit. Therefore, an alternative design was developed for pulley 2 in order to mount it securely to the steering shaft. The maximum diameter of the steering column is 1.055 *inches*. So in order to fit pulley 2 on the steering shaft, a hole was bored through pulley 2. The original diameter of pulleys 1 and 2 were 1 *inch*. So, for pulley 2 to fit on the steering shaft, a 1/16 *inch* hole using a lathe was machined.

Once the necessary sized hole was machined in pulley 2, an adapter had to be designed and installed to make pulley 2 mate with the steering column. The purpose of the adapter was to securely fix pulley 2 to the steering shaft. The adapter designed was made of ¼ inch steel in the shape of a rectangle. The concept was for the adapter to be cut into two pieces. These pieces were then placed around the steering column which fit snugly on the two flat sides. An overview of the design for the adapter is shown in Figure 19. Also pictured in Figure 19 is the machined version of pulley 2 and an un-machined pulley 1.

Figure 19: The adapter, pulley 2, and pulley 1

As is illustrated in Figure 19, the adapter was made to slip onto the steering shaft and four 4-40 machine screws were machined to fix the adapter to pulley 2. To aid in fixing pulley 2 more snugly to the steering shaft, a wooden plug was also machined. This plug is shown in Figure 20. This wooden plug fills in the space between the pulley and the steering shaft.

Figure 20: The two methods used to fix pulley 2 to the steering column; the adapter and the wooden plug

There are several components that support and protect the steering column. The main protecting component is the C-Channel shown in Figure 21. The C-Channel is a metal housing in the shape of a C that the steering column passes through. The C-Channel is located close enough to the steering column that a slot had to be cut where the pulley and timing belt could fit through. So, the C-Channel was removed and a slot was cut out of the channel to make room for the pulley and belt. Figure 21 shows orientation of the steering column and the C-Channel on the left. The picture on the right shows the C-Channel with a slot cut in it to make room for the pulley and belt system.

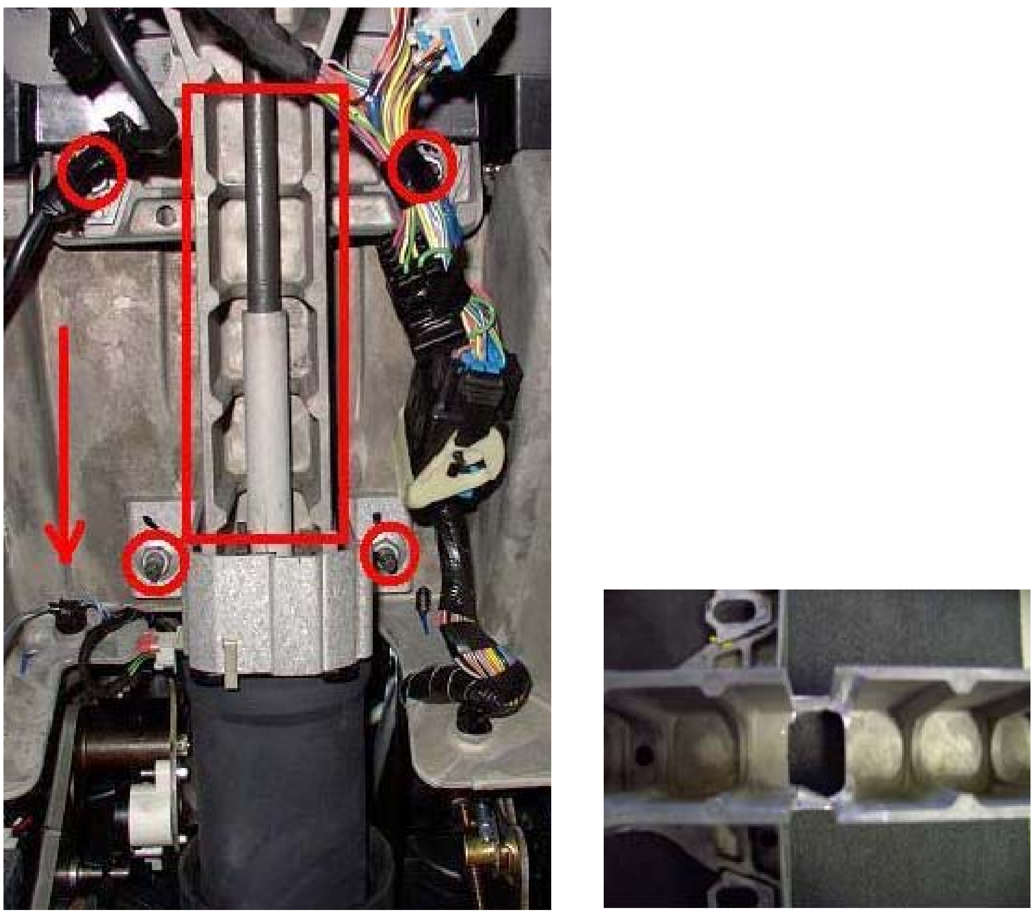

Figure 21: The steering column and the c-channel

One of the drawbacks of cutting a slot in the C-Channel was that the strength of the C-Channel as now compromised. Therefore aluminum support 'wings' were machined to further support the C-Channel. Two aluminum wings were machined which were attached to each lateral part of each side of the C-Channel. Each wing was attached with eight, 7 ½ *inch* Phillips head machine screws. Furthermore, the wings served as a mounting block for the motor and gearhead. Two U-bolt clamps were used to attach the motor to the wings. Also, two holes were drilled into each wing so the clamp could be fixed to the wing.

In order to fix pulley 1 to the gearhead, a 9/16 *inch* diameter hole was bored through. This allowed the pulley to befixed to the gearhead and then the belt was mated to pulley 1. Figure 22 shows the layout of the motor and belt drive system from two different orientations.

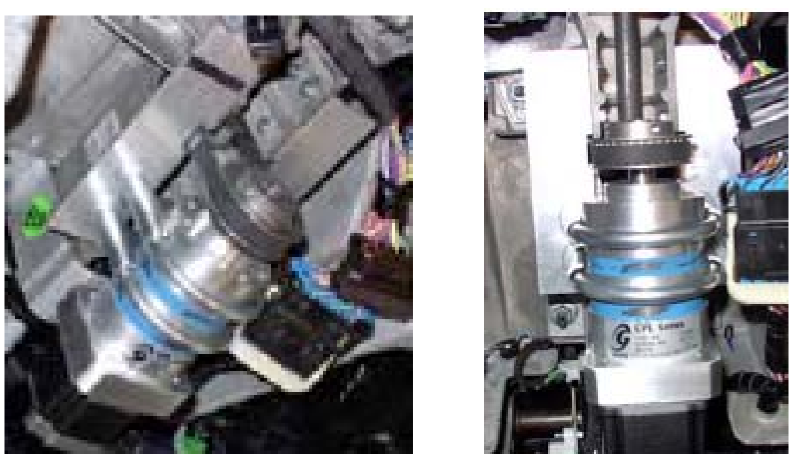

Figure 22: Two views of the motor attached to the wings with U-bolt style clamps

The GAM gearhead reduces the angular velocity from the QuickSilver motor's shaft by a ratio of 16:1. Pulley 1 was attached to the GAM gear reducer in order to transfer the angular velocity to the timing belt. From this point, the timing belt rotated pulley 2 thus turning the stock SRX steering wheel. The final steer-by-wire design is shown in Figure 23.

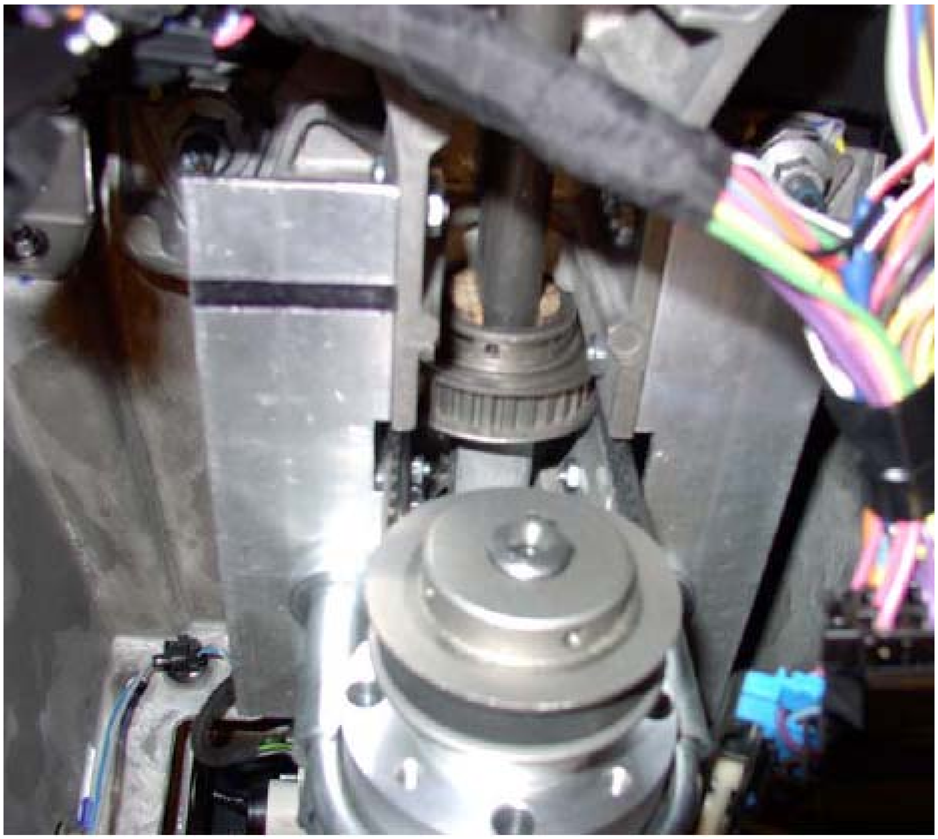

Figure 23: The final steer-by-wire motor and belt drive system

Chapter 6

Control of the Steer-By-Wire System

This section will explain how the steering motor is controlled. First, how the signals flow through the control architecture will be explained. Second, an overview of the software programs that were used for the project will be presented. Third, all other control considerations such as calibration of the steering motor and motor feedback will be discussed.

There are five components that were needed in order to control the Smart Motor: the game controller, the PC, the QuickSilver Controller Interface, the SilverNugget, and of course the steering motor. The flow of the signals for these components is displayed in the block diagram in Figure 24.

A steering wheel game controller serves as the interface for the steering. Data for the desired position for the steering wheel is then sent from the game controller to the personal computer (PC). The PC receives the data from the game controller and processes these signals in the LabVIEW software program. The PC also served as an interface to control the smart motor directly from the PC using LabVIEW (this function will be described more in depth later). From the PC, data is sent to the steering motor through the breakout board otherwise known as the QuickSilver Controller Interface. The breakout board is a platform that relays signals from the motor to the PC and from the PC to the motor. From the breakout board, data is then sent to the SilverNugget. The SilverNugget serves as the controller and amplifier.

The SilverNugget sends data to the smart motor to start actuating the steering wheel and thus turning the wheels of the SRX. Inside the motor is an encoder which reports the position of the output shaft of the motor as it rotates. This feedback data is sent through the controller to the breakout board and then to the PC for data logging.

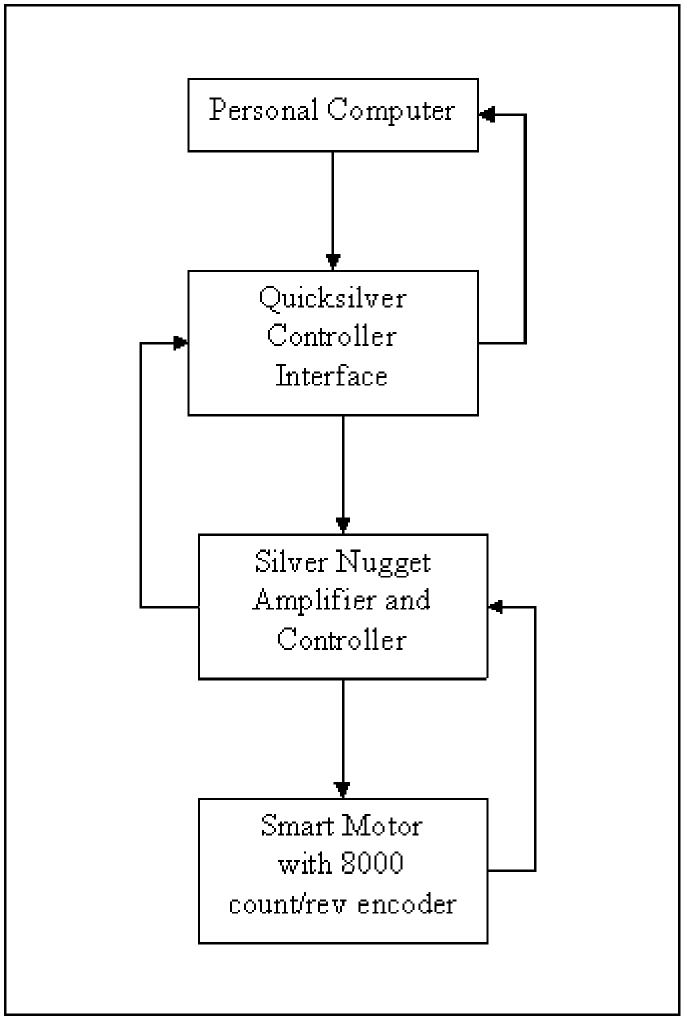

Figure 24: A block diagram showing the flow of the signals for steering

To review, the signal starts with the game controller and is sent to the PC. From the PC, a signal is then sent through the QuickSilver Controller Interface otherwise known as the breakout board to the SilverNugget controller and amplifier. From the SilverNugget, a voltage signal is then sent to the smart motor. The smart motor then moves to the position corresponding to the signal that was sent. As the motor rotates, an encoder inside the motor sends feedback through the SilverNugget and the breakout board straight to the PC.

The smart motor encoder reads 8000 counts per revolution of its output shaft. On the other hand, the PC shows the desired braking in terms of a percentage. When the steering wheel is turned all the way to the left, that is -100 % steering, when the steering wheel is turned all the way to the right, that corresponds to 100 % steering, and straight ahead is 0 % steering. This convention is more user friendly and unambiguous for the operators of the vehicle. Furthermore, communicating the amount of steering in terms of counts would not be very clear and easy to communicate during testing. Figure 25 shows the most commonly used software screen where steering can be controlled via the game controller or the PC directly.

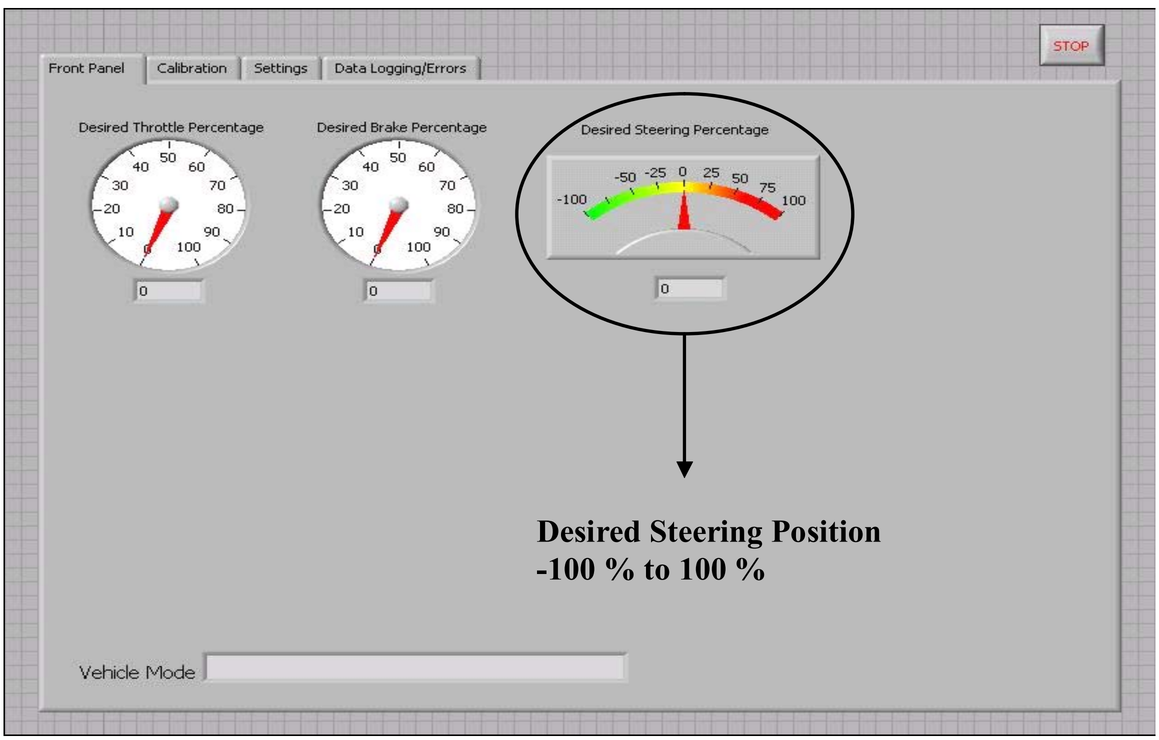

Figure 25: The computer control panel with steering gage circled in black

As was mentioned earlier, the software in the PC converts any data from the game controller to a corresponding -100 % to 100 % steering position. However, in order to communicate with the motor, the PC had to be programmed to convert the desired percentage of steering position. Since the motor encoder makes 8000 counts per revolution, that is 22.2 counts per degree that the output shaft moves. Thus the motor has the capability to be quite exact with the position that it moves to. Since the motor reads the number of counts per revolution, the software in the PC had to convert the steering position from a percentage to the number of counts that the motor had to move.

The flow of the data sent from the game controller to the PC is a string of steering commands. Starting at the game controller, steering commands are sent to the PC. Within the PC, the LabVIEW software converts the commands to a desired percentage of steering. Similar to braking, the PC converts the desired position to -100 % to 100%, which corresponds to the steering wheel turned all the way left and the steering wheel turned all the way right respectively. Within the software in the PC, the desired steering position in counts is sent through the breakout board to the motor controller and amplifier. Then, the motor moves to the desired count position and then the motor sends feedback to the motor controller. The feedback position continues through the breakout board or the QCI, and is received at the PC. Once again, in the PC the position is converted to a corresponding -100 % steering to 100 % steering and is recorded in the data logger. The frequency that the PC samples the position is 5 *hertz*.

In order to know exactly where the motor was at any time, the steering motor had to be calibrated. This calibration occurs within the initialization procedures. The initialization process initializes the hardware and calibrates the steering motor position. Without the initialization process, the PC has no idea what position the motor is starting from. Thus, if the motor does not know where the beginning position is, it cannot know where to rotate the steering wheel to. So, the initialization process is a very important step for testing.

Initialization procedures occur as follows. First, the PC and all hardware shown in Figure 26 must be turned on. Second, once the necessary Labview programs are started, the steering wheel is turned all the way to the left manually. At this point, the software program records this position as the new zero position (in counts). This is the position that corresponds to the starting position for the steering. So, in the software program, -100 % corresponds to the steering wheel turned all the way to the left, 100% steering corresponds to the steering wheel turned all the way to the right, and 0% steering corresponds to no turning. For the steering motor, the zero position corresponds to the steering wheel turned all the way to the left.

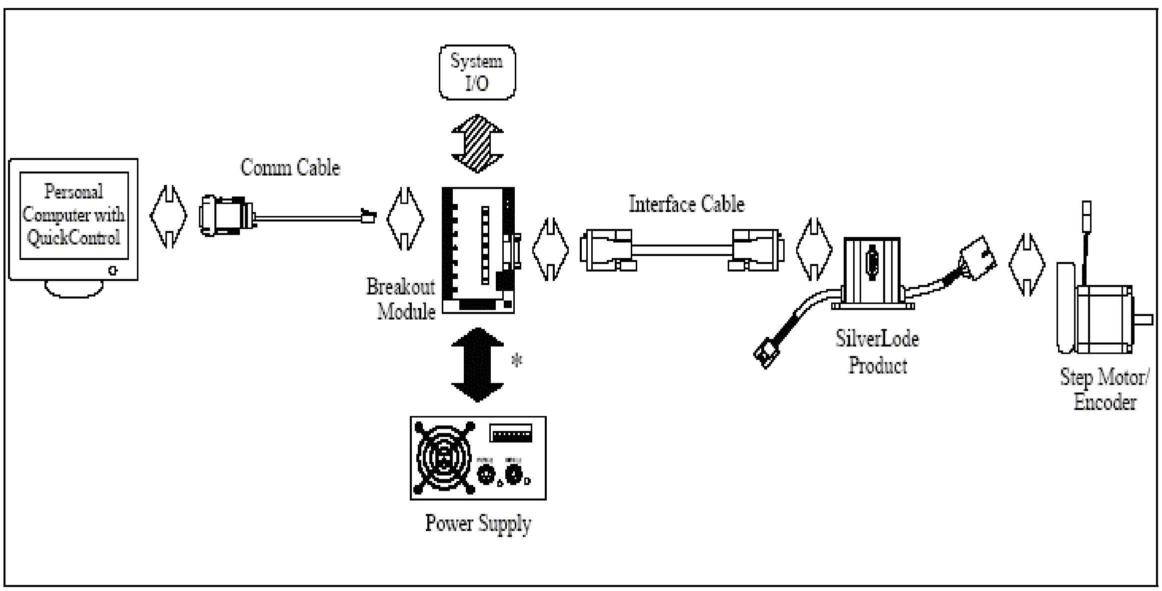

Figure 26: A block diagram showing the flow of signals for the smart motor

The last topic of discussion for the steering motor is the feedback that is sent from the steering motor. In order to update the PC on the position of the steering wheel, the motor continuously sends data to the PC. Data logging is important for a number of reasons, but most noteworthy of those is the need to be able to look at tests after they have occurred. The feedback that is sent comes from the encoder installed inside of the motor. The PC logs the data at a rate of 5 *hertz*.

Chapter 7

Results and Recommendations for the Steer-By-Wire System

This section will present the results of the steer-by-wire system. First, a recap of the requirements for a satisfactory steer-by-wire system will be presented. Second, a qualitative account of how well the specifications were met is shown for the overall steering system as well as for the motor. Third, this section will offer recommendations based on the results in testing.

To ensure an effective steer-by-wire system, several requirements were defined at the beginning of the project. First, a steer-by-wire system had to be reliable and responsive. In addition, the game controller had to consistently demonstrate complete control of the steering system. The steering also had to be accurate. Since this is the High Speed Autonomous Vehicle Team, accuracy was a necessity. The vehicle also had to be deemed safe by being responsive, accurate and reliable. The steer-by-wire system also had to be compact and non-intrusive.

On May 5th, 2005, the Cadillac SRX endured testing to determine if the steer-by-wire system satisfied the specifications outlined above. The SRX performed several maneuvers in order to demonstrate that the steering was electronically controlled. Figure 27 shows the set-up for the game controller steering wheel. Testing included a full 360 degrees turn as well as several turns left and right and straight forward. To ensure safety since testing was performed in a small space, all driving maneuvers were performed at speeds less than 10 mph.

Figure 27: The set-up for the SRX on the final day of testing

To conduct testing, several steps had to be performed. First, the vehicle was manually driven to the test site in the Virginia Tech Airport hanger parking lot. Next, the power had to be turned on to start all of the hardware components. Next, the steering components had to be initialized through the process outlined in the software section. Lastly, a team member sat in the passenger's seat to drive the vehicle. As a safety precaution, two other people were in the vehicle during testing; one in the driver's seat and one in the back seat. The job of the person in the passenger's seat was to drive the vehicle by-wire. The person in the driver's seat served as an emergency brake in case something went wrong. Lastly, in the back seat, a person was there to perform initialization procedures for the hardware and to oversee software programs displayed on the PC.

Since all maneuvers were performed several times, the steer-by-wire system proved to be reliable. In addition, the vehicle turned when the game controller steering wheel turned, at similar rates, and without a delay, thus proving that the vehicle was responsive and accurate. The steer-by-wire capability never had problems during testing thus proving that the SRX was under full by-wire control. The last requirement of the overall by-wire system was for the steering components to be compact and non-intrusive. Through testing, the HSAVT proved that the system was not in the way of any passengers or vehicle operators.

In addition to overall steer-by-wire requirements, there were also several requirements for the steering actuator. First, the actuator had to be sturdy and compact. The steering actuator also had to have feedback capability to provide information about where the steering is at all times. Torque requirements were found experimentally so the motor had to be able to provide a minimum of 5 foot pounds of torque.

Since the encoder of the motor had the capability to measure the position of the output shaft 22.2 counts per revolution, the steering system proved to be fairly accurate. The accuracy of the motor contributed to the safety of the steering and of the overall system. Thanks to the mechanical team's ingenuity, the steer-by-wire system was compact and non-intrusive to the driver. The entire steering system ended up being completely hidden from the driver since it was located underneath the steering console of the SRX. Figure 28 shows the final steering assembly which is tucked up underneath of the steering column.

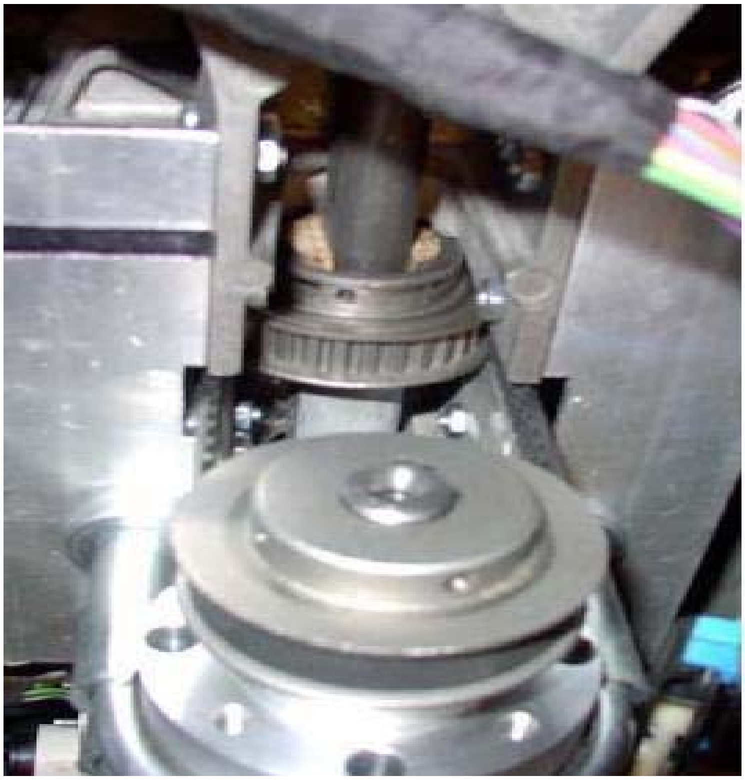

Figure 28: The final steer-by-wire belt drive system driven by the QuickSilver smart motor and a belt drive system

In addition, the steering motor itself was sturdy and compact. The motor's compact design also demonstrated throughout testing that it was sturdy and produced reliable feedback to the PC. Since the encoder was rated at such a high level for feedback at 8000 counts per revolution, the motor was able to provide excellent feedback to the PC. Through proper gear reduction and experimentation we found that the torque provided to the steering column worked for the SRX power steering system. Furthermore, the motor provided a minimum of 5 foot pounds of torque to make control the motion of the steering wheel.

There are several ways in improve future steer-by-wire systems and testing procedures. The rest of this section will present the good qualities of the current steering system as well as recommendations based on testing and research presented in the introduction. Lastly, some recommendations on how to improve testing procedures is presented.

The method of steering used for this project was satisfactory. In the introduction, the two actuation systems were presented for steer-by-wire systems: Electromechanical, and fully electronic. Within electromechanical actuation, the actuator can be mounted at two different places within the vehicle. An actuator can be mounted at the rack-and-pinion gearset in order to initiate wheel turn. The advantages of this system are that the connection between the actuator and the wheels is more direct than the HSAVT mode of actuation. The second system which has been discussed at length in this paper is where the actuator is mounted on the steering column. The other form of steer-by-wire actuation is where motors are place directly at the wheels. This option is by far the most direct since all mechanical elements are taken out of the steering system completely. For further projects, I would suggest any one of these three modes of by-wire control. All of them, actuator at the steering column (HSAVT solution), an actuator mounted at the rack-and-pinion gearset, or motors mounted directly at the wheels are all effective forms of by-wire actuation. Based on the performance of the steering system, the HSAVT solution of mounting the motor on the steering column seems to be an effective form of wheel acutation. Therefore, future teams should stick with this method of steering.

In addition, the motor was clearly a good choice for this project. During testing, the motor was responsive and could turn at variable rates. The motor is compact and completely hidden from the driver as well as being sturdy. The QuickSilver system as a whole is also a robust system. The motor controller and amplifier are combined together in the compact SilverNugget found in the back of the vehicle.

The gear reduction seemed to be effective for our purposes and proved to be a sturdy assembly. Therefore, future teams should leave the gearhead the same for this particular steering arrangement.

Based on the performance of the steering system, the only adjustment should be to modify the current belt drive system between the motor and the steering column. Since high torques was required to turn the steering column, the pulleys and the belt were under high stress. Due to the high torque requirements to turn the steering column, slipping occurred between the pulleys and the belt. Therefore, each time slipping occurred, which could be heard audibly, steering had to be recalibrated each time the slipping occurred. Thus, future teams should modify the belt drive system to eliminate slipping.

For the testing procedures, future teams and advisors should better define the requirements for performance of the steering system. The requirements set in the beginning of the project should include specifics on how the steering system has to perform. Perhaps a checklist of routes that the SRX has to complete in order to pass inspection would be a good starting point. As another example, given that we had a fairly small space in which to test the vehicle legally, the SRX should go through rigorous testing for the steering: hairpin turns left and right, full circles left and right, turning while accelerating, braking while turning, backing up while turning, etc. Deciding these routines in the beginning of the project is important for benchmarking to make sure progress has been made and to help measure performance.

In addition, more data should be logged. Any time the vehicle is operated, data should be recorded. Logging data can help the team to measure the performance and makes it possible for problems to be analyzed after testing is through.

Overall, the steer-by-wire system was an effective design. All requirements that were initially set were demonstrated on the last day of testing. Figure 29 shows the vehicle being driven by the person in the passenger's seat with the game controller. From the picture it is evident that the person in the drier's seat was not in control of the steering or the pedals since his hands were out of the vehicle.

Figure 29: The fully drive-by-wire GM Cadillac SRX.

Chapter 8

Final Results and Recommendations

This thesis has presented the design and the results for the conversion of a fully drive-by-wire General Motors Cadillac SRX. The systems that were described in depth include the brake-by-wire system and the steer-by-wire system that were implemented by the High Speed Autonomous Vehicle Team. In addition, the controls of the motors that were used for brake and steering actuation were also addressed.

Chapter 1 served as a forum to discuss the history of by-wire systems and presented a background on successful by-wire technologies. In Chapter 2, the HSAVT solution for the brake-by-wire system was presented. Additionally, a short background on current hydraulic braking systems was discussed. In Chapter 3, motor control was addressed touching on the basics of the software and the electronic components that drive the brake motor. Chapter 4 presents the results and recommendations for the brake-by-wire system. In Chapter 5, the HSAVT steer-by-wire system was presented with an in depth technical background on conventional steering configurations. Chapter 6 goes on to briefly explain the controls of the steering motor. In Chapter 7, results and recommendations were offered for the steer-by-wire system.

In conclusion, the HSAVT project was a success. All requirements were met for both the brake and steer-by-wire systems. In addition, motor control was demonstrated with good control of the brake actuator as well as the steering motor.

Recommendations for future projects include more detailed requirements for final testing and more data logging to provide information to analyze. In addition, a new form of brake actuation should be implemented into later iterations of this project. The steering system is exceptional as it is though a new belt drive system may be in order to reduce belt slip. More safety systems such as mechanically actuated emergency stops should be incorporated into future projects as to ensure safety. Also when choosing a motor, future teams should make sure to clearly define the specifications that they expect the motor to satisfy.

Future teams should also incorporate more sensors to make analysis more meaningful. Suggestions for sensors include an internal navigation system and global positioning sensors. With these sensors included in the controls scheme, the ability to make the vehicle drive autonomously will also be a possibility. Furthermore, incorporating these sensors will make data logging more meaningful. Installing sensors at the wheels, steering shaft, and brakes for instance will also make it possible to quantify how much turning and braking is occurring in the vehicle. Thus, there will be a basis for comparison to measure exactly how effective the drive-by-wire system is. By comparing the data of what was requested by the controller to data provided by said sensors during testing, a quantifiable number can then be assigned to each by-wire system. It is important to develop quantitative values for to measure just how much each system complies with that which is requested by the driver. This is especially important since the vehicle eventually will be driven completely autonomously. With numerical measures of system compliance, results can be communicated without being vague and subjective.

Overall, this project was a complete success and was a pleasure to be a part of.

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