Comparison of Three Control Methods for an Autonomous Vehicle

Anup Deshpande, Kovid Mathur and Ernest Hall
Center for Robotics Research
University of Cincinnati
Cincinnati, OH 45221-0072 USA
Phone: 513-556-2730
Fax: 513-556-3390
www.robotics.uc.edu

ABSTRACT

The desirability and challenge of developing a completely autonomous vehicle and the rising need for more efficient use of energy by automobiles motivate the search for an optimum solution to computer control of energy efficient vehicles. The purpose of this paper is to compare three control methods - mechanical, hydraulic and electric that have been used to convert an experimental all terrain vehicle to drive by wire which would eventually act as a test bed for conducting research on various technologies for autonomous operation. Computer control of basic operations in a vehicle namely steering, braking and speed control have been implemented and will be described in this paper. The output from a 3 axis motion controller is used for this purpose. The motion controller is interfaced with a software program and WSDK (Windows Servo Design Kit) serves as an intermediate tuning layer for tuning and parameter settings in autonomous operation. The software program is developed in C++. The voltage signal sent to the motion controller can be varied through the control program for desired results in controlling the steering motor, activating the hydraulic brakes and varying the vehicle's speed.

The vehicle has been tested for its basic functionality which includes testing of street legal operations and also a 1000 mile test while running in a hybrid mode. The vehicle has also been tested for control when it is interfaced with devices such as a keyboard, joystick and sensors under full autonomous operation. The vehicle is currently being tested in various safety studies and is being used as a test bed for experiments in control courses and research studies. The significance of this research is in providing a greater understanding of conventional driving controls and the possibility of improving automobile safety skills.

Keywords: Intelligent autonomous vehicle, electrical control, hydraulic control, mechanical control, human interface.

1. INTRODUCTION

An experimental all terrain vehicle was made street legal and modified to drive by wire for the 2007 DARPA Urban Challenge which would also serve as a test bed for further studies in energy efficiency, safety and educational purposes. In order for the experimental vehicle to be street legal it was required to have head/indicator lights, a safety glass windshield followed by an inspection by the State Patrol. The successful inspection then permitted the registration, license and insurance of the vehicle. The conversion of the vehicle to drive by wire mode required several design changes in the steering, speed control and brake system. Since this 2100 pound vehicle can reach speeds of 45 mph with its two 7.5HP electric motors, safety was of primary concern. For this reason, an emergency stop and a back up signal were added. A wireless remote emergency stop was also made available and a chase vehicle was always used for street testing.

The reasons for performing this study and conducting further research in the field of autonomous vehicle control are as follows.
1) A fully electric vehicle is a step towards energy efficiency.

2) Implementation of computer control of basic automobile operations like speed, steering, and braking control permits the exploration of new ways for computer control of automotive operations.

3) The computer control and further research work to address existing unresolved problems can eliminate the need or augment the actual physical control by the user, which can be helpful to people with physical limitations.

4) Implementation of the modern tools like artificial neural networks and computer vision can also be used to detect faults and assist users with obstacle avoidance as collisions cause most injuries to humans.

5) Electric and hybrid vehicles are now available for transportation and robotics is the modern tool for automation. The combination of these technologies can results in new solutions to a variety of applications.

The study of autonomous operation of automobiles can improve the reliability both in terms of the safety of its operation as well as minimal consumption of energy. The problem of autonomous vehicle control may be modeled as a dynamic programming problem.[1] However, the gap between theory and practice is still rather large. It has been made smaller by experimental studies conducted at the Intelligent Ground Vehicle Contest (www.igvc.org) that has been conducted since 1993 which has resulted in many technical advances on small sized unmanned ground vehicles. Larger experimental vehicles have been motivated by the DARPA Grand Challenges in 2004 and 2005 and the Urban Challenge in 2007. Thrun [2] describes the winning vehicle for the 2005 Grand Challenge. Urmson, el al. [3] describe the 2007 winning team and vehicle. Most of the vehicles in the Urban Challenge were "production vehicles." However, various "self constructed" vehicles were also eligible with additional qualifications.

The purpose of this paper is to compare and contrast three methods for vehicle control – mechanical, hydraulic and electrical. For definiteness, an example of an experimental "self constructed" vehicle is used which was modified for various needs at the University of Cincinnati.

The steering control will be described in Section 2, brake control in Section 3 and vehicle speed control in Section 4. Finally, a comparison of the methods and experimental results are given in Sections 5 and 6.

2. STEERING CONTROL

A servo control system is used in the electric ATV (All terrain vehicles) to steer the wheels. It comprises of a motor, an encoder and an amplifier. A gearbox with gear ratio 10:1 is used to be able to turn the wheels from full left to full right in 100 motor turns which would give us an acceptable response time for real time operations.
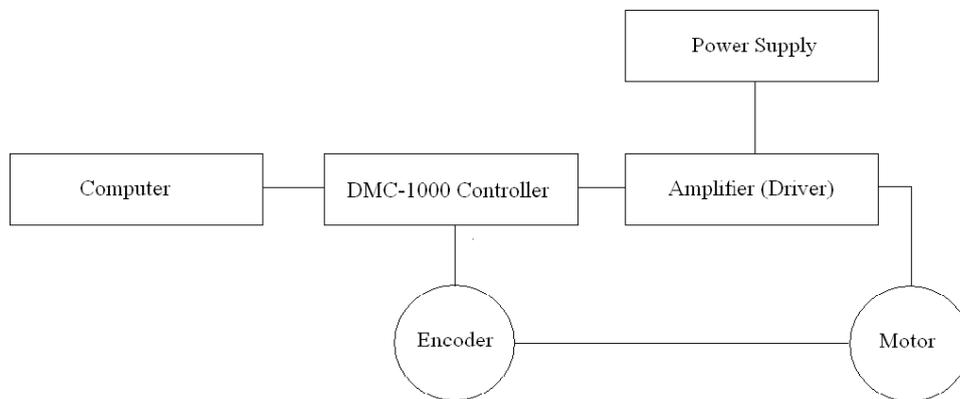

Figure 1. Elements of servo system

1.1 Servo control system elements

Motor: A motor converts current into torque which produces motion. The desired motion in our case is the steering of the wheels with its extremes being a full left or full right turn. In a motion controller, each axis of motion requires a motor sized properly to move the desired load at the desired speed and acceleration. The motor may be a step or servo motor and can be brush type or brushless, rotary or linear. For our application a rotary, brush type DC servomotor is used.

Amplifier: An amplifier is a device that modifies (usually increases) the amplitude of an incoming signal. In our circuit, the power amplifiers convert input voltage signals from the controller into current required to drive the motor. For best performance the amplifier should be configured for a current mode of operation with PID compensation.

Encoder: An encoder translates motion into electrical pulses which are fed back into the controller. Encoders typically provide two channels in quadrature, channel A and channel B. This type of encoder is called a quadrature encoder. The channels A and B are 90 degrees out of phase and due to this relationship, the resolution of the encoder is increased to 4N quadrature counts/rev. (N is the number of pulses generated by the encoder per revolution).

1.2 Digital-controlled servo system

A servo system is a closed loop motor control system that combines various components to automatically and accurately control a machine's operation[4]. It is generally composed of a servo drive, a motor, and a feedback device. The controller receives an outside command signal and a feedback signal from the motor which get summed up and a resultant signal is sent which controls the torque, velocity and position of the motor shaft. The feedback continuously reports the real time status, which is constantly compared with the command value. Differences between the command position and feedback signals are automatically adjusted by the closed-loop servo system. This closed-loop provides the servo system with accurate, high performance control of a machine.
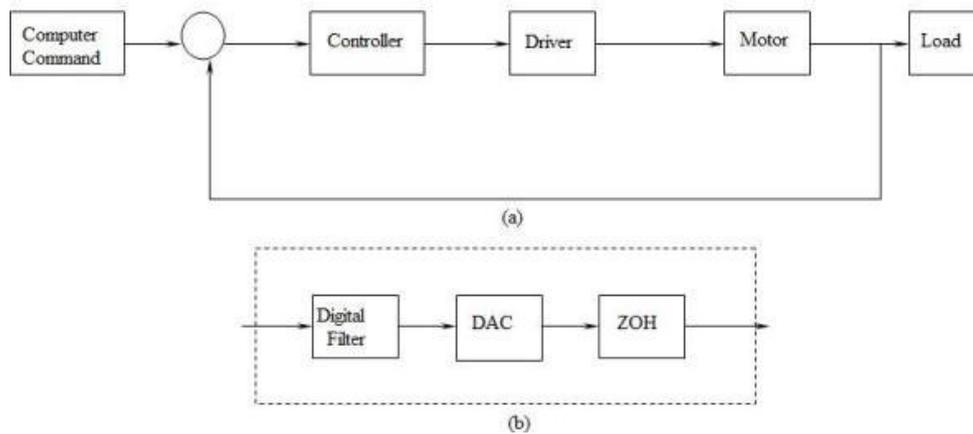

Figure 2. Functional elements of a computer controlled servo system
(a) block diagram (b) the controller[4]

A typical computer-controlled servo system is shown in Figure 2. It has three main elements, a digital controller, an amplifier, and a motor combined with an encoder. The controller is composed of a digital filter, a zero-order-hold (ZOH) and a Digital to Analog Converter (DAC). The purpose of the controller is to compensate for the system to make an unstable system become stable. This is usually achieved by adjusting the parameters of the filter. The controller accepts both encoder feedback and commands from the computer and finds the error between them. The error signal then passes through the digital filter, ZOH and DAC to generate control signals to control the amplifier (AMP). The amplifier amplifies the control signals from the controller to drive the motor. The encoder is usually mounted on the motor shaft. When the shaft moves, it generates electrical impulses, which are processed into digital position information. This position information is then fed back directly into the controller. The mathematical model of the above components could be varied among different products.

1.3 Computer control of the steering mechanism

Figure 3 shows the computer control of the steering mechanism. It involves a servo system and a motion controller. The motion controller serves as an interface between the computer program (to provide command signals) and the servo system.
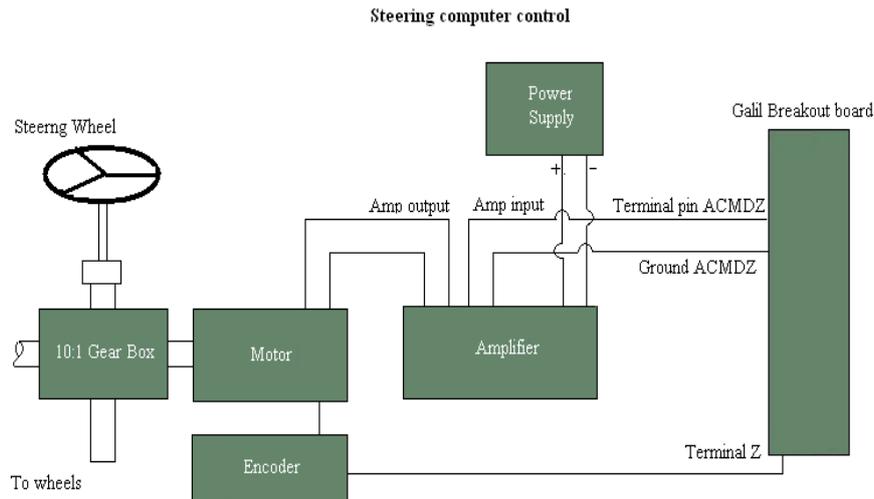
Figure 3. Computer control of steering mechanism

As discussed earlier, the controller has three elements, namely the Digital-to-Analog Converter (DAC), the Digital Filter and the Zero Order Hold (ZOH). The Digital-to-Analog Converter (DAC) converts a 14-bit number to an analog voltage. The input range of numbers is 16384 and the output voltage is $\pm10V$. From system analysis, it is found that the voltage required to generate a torque to turn the steering motor is $\pm10V$ with desirable response time. The computer program is designed to provide signals for generating this voltage output. The input device for the computer program can be either a keyboard or a joystick. The joystick axis can offer better and precise control of the steering mechanism.

The power amplifiers amplify the voltage signal from the controller to drive the steering motor. The encoder, which is an integral part of the motor, generates electrical pulses on the movement of the shaft. These pulses are processed into digital position information. This position information is then fed directly into the controller. The controller thus accepts the encoder feedback and the computer command on the basis of which it calculates any error between the two. This error signal then passes through the digital filter, ZOH and DAC to generate control signals to control the amplifier. Power amplifier then provides with a signal to generate the required torque. The motor output is geared down to be able to turn the jeep wheels from extreme left to extreme right in 100 rotations of the motor shaft. For our purpose we use a gearbox with a gear ratio of 10:1.The gearbox is connected to the steering column as shown in Figure 4 which also shows the motor, and the steering column.
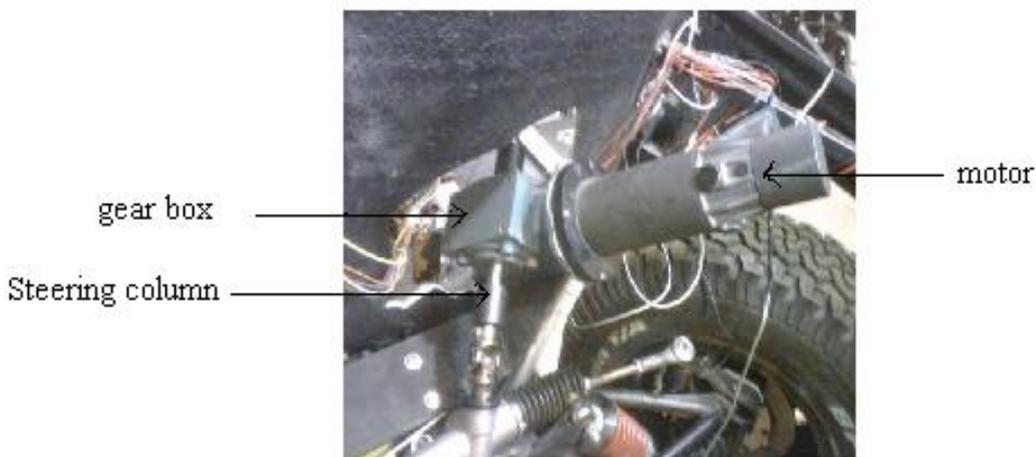

Figure 4. Photo showing the motor, gearbox and the steering column attached
to the rack and pinion steering mechanism.

A major challenge for any closed loop system is tuning for stability. The tuning of this system was done experimentally and simulated to check for errors. The analytical values of K_p, K_i and K_d which are the proportional, integral and derivative gains respectively, of the PID controller, were tested for stability in the real system with the help of Galil Motion Control's – Windows Servo Design Kit Version 4.04[5]. A typical step response plot is shown in Figure 5.
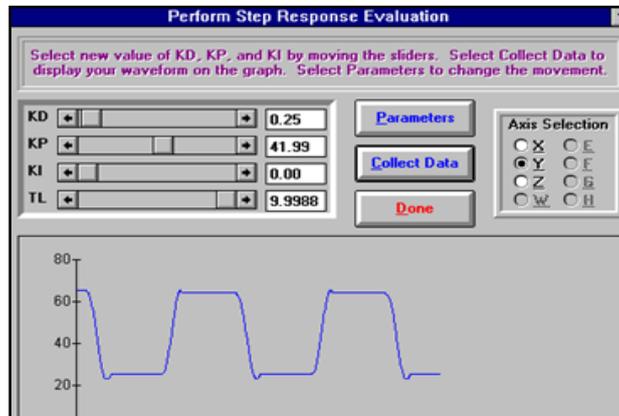

Figure 5. Step response from the PID tuning procedure

3. BRAKE ASSEMBLY

Since the ATV was being prepared to work for all speed conditions, it necessitated the vehicle to have a robust and dependable braking system. The vehicle already had a mechanical hydraulic braking system which worked effectively for manual control. To activate the brakes under computer control, a trailer brake assembly was used. The hydraulic brakes could thus be triggered by an electric signal which can be controlled by a computer command.

Figure 6. Hydraulic control cylinders

3.1 Hydrodynamic brake system

The existing brake system on the jeep comprises of a typical hydro-mechanical system with disc brakes on both the front and rear wheels. Figure 7 shows a schematic of the existing brake system on the vehicle.
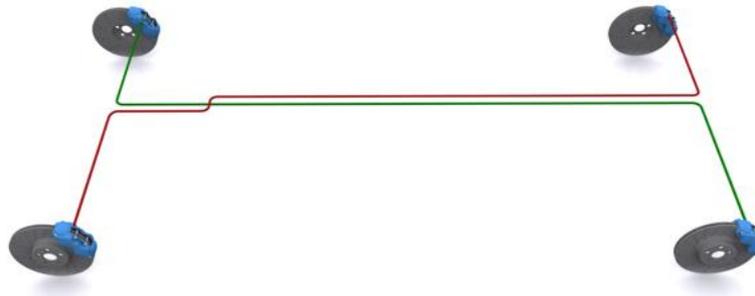

Figure 7. Schematic diagram of a disc brake system (http://www.carbibles.com/brake_bible.html)

Instead of a single master cylinder for all four wheels, the jeep has two master cylinders which were both connected to the brake pedal by the same connecting rod. Each cylinder pumps the brake fluid to either the two front wheels or the rear wheels individually. The advantage of this system lies in the independent front and rear brake lining. If the rear wheel's brake line malfunctions, control of the front wheels will still be possible as they are not interdependent and vice versa.
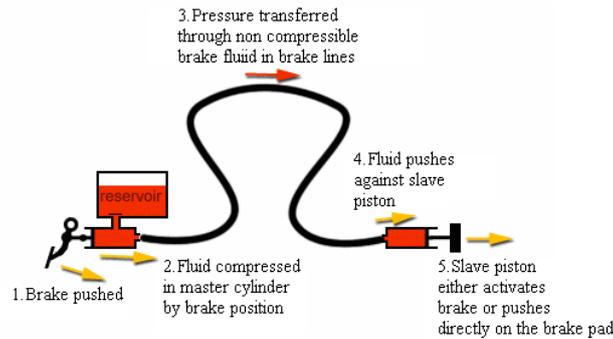

Figure 8. Activation of the hydraulic brake system (http://www.carbibles.com/brake_bible.html)

3.2 Brake by wire solution

For effective computer control of the brakes we had an option of introducing an electro- mechanical braking system. We chose the electro- hydraulic system for two reasons. First, a functional hydraulic braking system already exists on the vehicle and second, the technology of electro mechanical braking is expensive to implement. In order to have computer control over the brakes we needed to introduce certain components into the system. These are described as follows:

1. Brake Actuator: A Dexter DX series brake actuator is used with a 1600 psi rating which works on a 12V DC power supply.
2. Brake Controller: A Dexter Predator DX2 electric controller is used. It comprises of an inbuilt manually operated lever which allows variable braking effort if required. It works on a 12V electrical system.
3. Motion Controller: A Galil DMC1000 motion controller with 4 axes is introduced, one of which is used for brake control.

Since the Jeep is a test bed for ongoing and future testing of various autonomous algorithms, one of the biggest concerns is for safety. The idea was to have manual control over the brakes at all times even if the vehicle is running in a computer control mode. For this reason a unique idea is introduced in which the front wheel brakes would be electronically controlled at all times whereas the rear wheels would continue to be a manually operated. This would give us an additional safety measure in case the computer algorithm does not work the way it is designed during testing.

To accomplish this goal the two master cylinders designed to initially actuate the front and rear wheels separately were modified to be working in union with each other. The brake line's output from each were combined together and fed to the rear wheels. This would make the rear wheels work independent of any electronics and would rely on mechanical linkages and human response time for the safety of the vehicle.

The front brakes are operated by the computer. As mentioned earlier, for this operation a motion controller, a brake actuator and a brake controller are introduced which work together for effective front wheel braking. An "Offset" command to the Galil Motion controller dispatches a defined voltage signal via the break out board to the brake controller which is then forwarded to the actuator. The actuator in turn pumps the brake fluid from a reservoir into the front brake lining thereby causing the hydraulic braking action. The intensity of braking will be governed by the vision, line following and obstacle avoidance algorithms for the autonomous operation. A central server can be introduced later which makes use of the virtual force field[6] method to calculate a combined decision from all the algorithms and translates it in terms of voltage. This voltage can be used as an input command to the Galil eventually. The process is explained in the following flowchart.
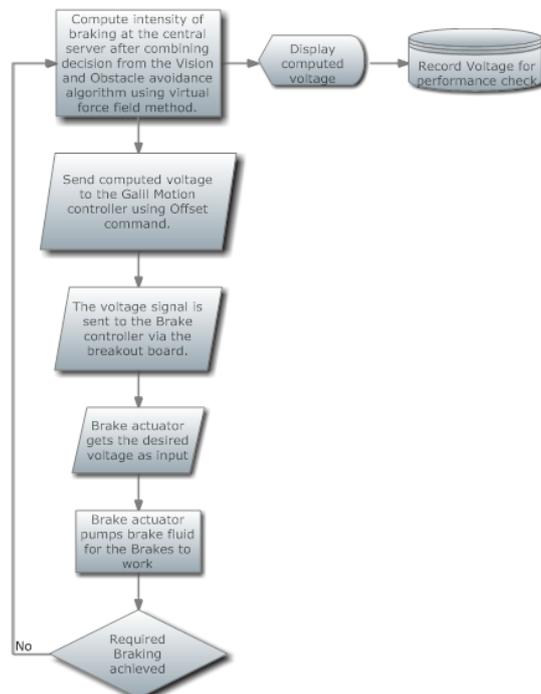

Figure 9. Flowchart to show path of braking signal from calculation to execution

The brake controller is modified to accept the input from the Galil motion controller and send an amplified voltage signal to the actuator.

While designing the computer control of brake system, hardware and electrical system failure are also taken into account. To cope with such unforeseen circumstances, an additional brake controller is introduced on the dashboard of the ATV. This brake controller runs on a 12V electrical system and is connected to the brake actuator directly without any computer control in the middle which in turn connects to the front wheel brakes. A schematic of this arrangement is shown in Figure 10.
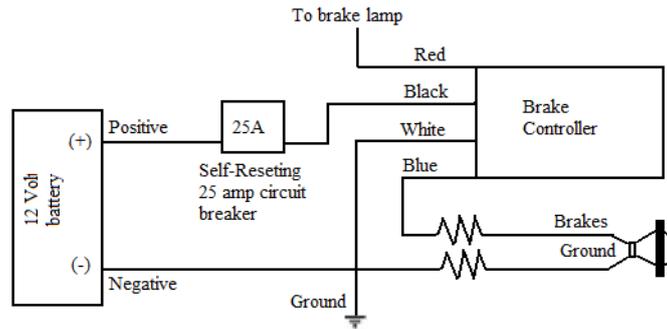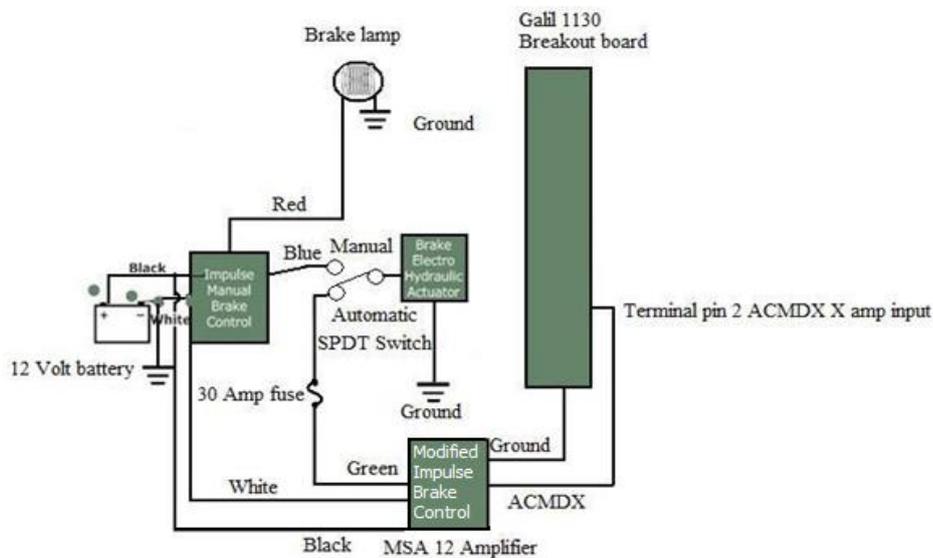
Figure 10. Wiring diagram showing manual brake controller operation

This design provides manual control over the front wheel brakes electronically at all times independent of the computer control. This idea gives an additional level of braking safety for a case when the computer control of brakes ceases to work.

Figure 11 shows the circuit for computer and manual control of the front wheel brakes. Terminal ACMDX of the Galil provides the required input voltage to the modified impulse brake controller. The brake controller amplifies this signal and sends a voltage ranging from 0-10V to the brake actuator which in turn activates the hydraulic pump. The pump provides necessary hydraulic force via the brake lining to the brake calipers. The manual brake controller as described in the previous section also works in the same way except that the voltage required to activate the brake actuator is governed by manual operation of a lever.

The output from the modified brake controller and the manual brake controller are routed to the brake actuator through a single pole double throw switch (SPDT). This facilitates the toggling between the two types of control. When the switch is on the automatic side, the circuit for Galil voltage signals gets completed and the brakes can be operated in computer control mode with the help of an input device. When the switch is on manual side, the brakes can be operated manually.

Figure 11. Wiring diagram for brake control

4. SPEED CONTROL

The jeep vehicle is powered by two 7.5HP electric motors each of which is controlled by a GE SX speed controller[7]. A schematic diagram of the speed control circuit is shown in Figure 12. The OSC card in the SX speeds controller receives connection from various circuits like the forward-reverse motion (P4 &P5), the seat switch (P6), Accelerator start switch (P3), and the regenerative braking potentiometer input (P13). The pins P7 and P9 control the speed of the two motors. Interfacing the GE SX control with the Galil system requires disconnecting the manual throttle and replacing it with the output signal from the Z axis of the Galil motion controller. To keep both control modes (manual and computer control) active a single pole double throw (SPDT) switch is introduced to toggle between the two modes.
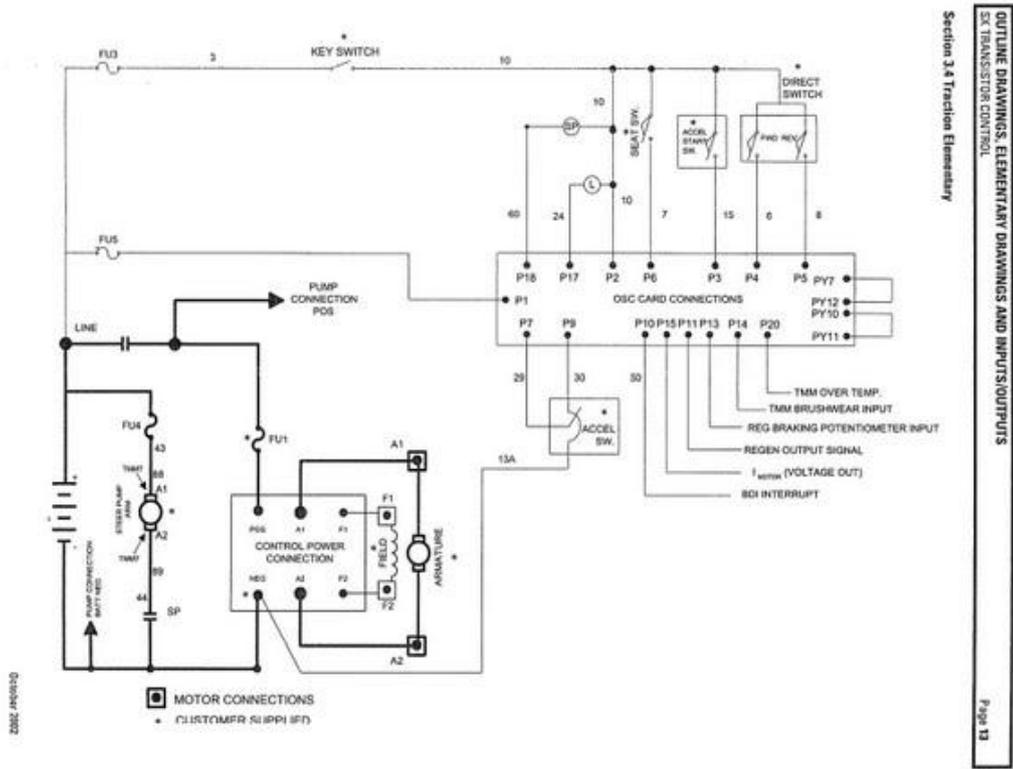

Figure 12. GE SX Speed Controller schematic

In manual mode, the accelerator pedal is connected to a variable resister (potentiometer) between pins P7 and P9. The terminal P9 is attached to the resister, while the other terminal (generally called wiper) P7 is attached to a center tap for the variable resistor .When the wiper slides along the resistor, it varies the resistance from minimum (almost zero) to its maximum value. Pressing of the throttle or accelerator pedal (which is connected to P7) slides the wiper over the resistor decreasing the resistance value. During the computer control mode, the program controls the Galil's voltage signal required to change the speed. Under normal operation, the voltage at P7 should be 3.5V for zero velocity and 0.5V for maximum velocity. The software program values are thus adjusted so that the Galil provides a voltage in the range of 0.5 to 3.5 volts.

Figure 13 shows the circuit for computer and manual control of speed. Terminal ACMDY of Galil provides the voltage required for acceleration in computer control mode. Terminal P7 which is connected to the Accelerator pedal passes the required voltage in manual mode. The two terminals ACMDY and P7 from the throttle are connected to a Single Pole

Double Throw (SPDT) switch. The mode of control can be toggled between automatic and manual mode by changing the SPDT switch position. The output of the SPDT switch is connected to the terminal 4 of a six pin connector. The ground from Galil and the negative terminal from throttle are connected to the pin 6 of the connector. The remaining pins of the 6 pin connector are for various other terminals like reverse forward switch, seat switch etc. The other end of the six pin connector is connected to the OSC card of the GE SX controller circuit.

In manual mode, when the accelerator pedal is pressed the wiper connected to the terminal P7 slides over the resistor and varies the resistance and causes a decrease in the voltage from 3.5V to 0.5V increasing the motor torque which in turn provides the motion to the wheels. In computer control/automatic mode, when the joystick axis is moved, the software program passes the appropriate control signal to the Galil break out board. The Galil then generates voltage value in the range of 0.5 to 3.5V depending upon the joystick axis position. When the joystick axis is in idle position, the Galil passes a voltage of 3.5V to give zero torque to the wheels and a 0.5V when the joystick axis is in extreme position providing maximum torque to the wheels.
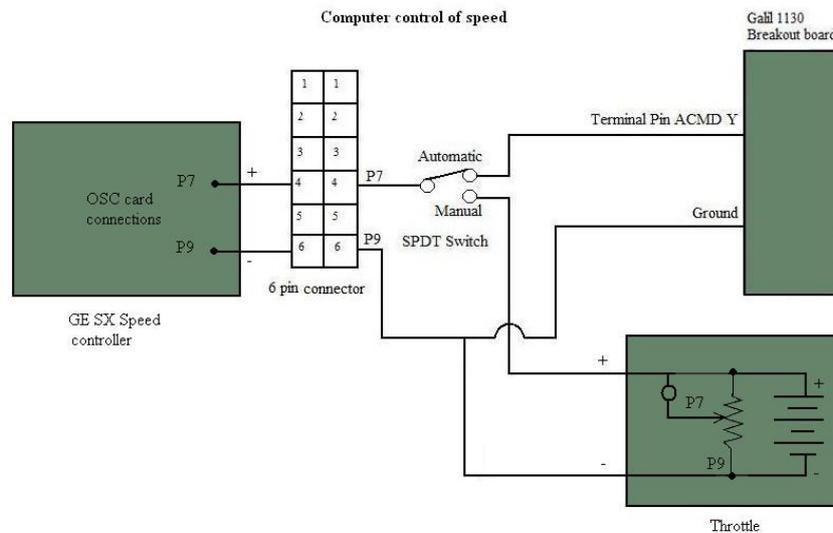

Figure 13. Computer control of speed

5. JOYSTICK CONTROL PROGRAM

The joystick control program used for computer control of the vehicle is the main interface between the mechanism of motion control and human operation. The program is developed in C++ and uses Microsoft DirectX, which is a collection of application programming interfaces (APIs) for handling tasks such as multimedia, game programming etc. DirectX can be used to process data from input device (joystick in our case) .It provides all the classes and functions required to acquire the joystick, update the status, polling the joystick etc. The interfacing with the Galil motion controller is done with the help of APIs provided by Galil which make the communication between the hardware and software possible.

A Logitech dual action gamepad joystick with 4 axes and 12 buttons is used. Figure 14 shows different control axes on the joystick. Out of the four axes X, Y, Z and Z_R i.e. Z - rotation, we are using X axis to control and pass commands to the brake actuator, Y axis for the speed control of the two 7.5 HP motors and Z_R axis for the steering motor. The voltage ranges required to control the Steering, braking and speed are as shown in table 1.

Table 1. Voltage ranges for joystick control

Steering	-10V to 10V
Braking	0V to 10V
Speed	-3.5V to 0.5V

Following is the code snippet of the joystick control program

```
sprintf(str,"PA 0,0,%d",40*js.lX);    //sends steering command
DMCCommand(hDmc, str, szBuffer, sizeof(szBuffer));
float vel=3.5-(js.lY>0?js.lY/333.3:-js.lY/333.3); //sends  velocity command
float brake=5-2.6*(js.lRz>0?js.lRz/1000:-js.lRz/1000);  //sends Brake command
sprintf(str,"OF %f,%f,0",brake,vel);//
DMCCommand(hDmc, str, szBuffer, sizeof(szBuffer)); //sends an offset command to
the Galil
DMCCommand(hDmc, "BG", szBuffer, sizeof(szBuffer)); //commands the galil to begin
motion
```


Figure 14. Joystick and the three control axes (http://www.logitech.com/repository/95/jpg/450.1.0.jpg)

A block diagram of the complete control circuit is shown in Figure.15. It shows the signal flow from the input device to the wheels, steering motor and the brakes through software program via the motion controller.
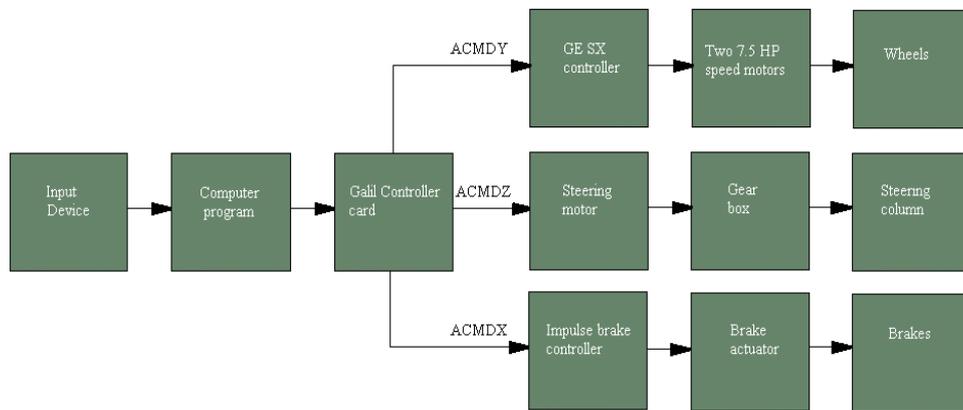.

Figure 15. Block diagram of the computer control

6. RESULTS AND CONCLUSIONS

The vehicle has been tested extensively in electric power mode in which it can travel about a 100 miles per charge. It passed a 1000 mile hybrid test with the help of a gasoline powered generator. The vehicle has also been tested for the drive by wire technology which has been discussed in this paper. To ensure safety, these tests were first performed by

putting the vehicle on jack stands and only when the results were found to be agreeable to the expected results, was the vehicle tested on ground. The vehicle as of now is a perfect test bed for studies related to control theory and also for further research on the autonomous vehicle technologies.

Figure 16. Testing the vehicle

ACKNOWLEDGEMENT

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