The 24th Conference of the Mechanical Engineering Network of Thailand
October 20 – 22, 2010, Ubon Ratchathani

Design of Steer by Wire Control Unit

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Abstract

The project presents a control unit of a steer by wire system. Its main functions are to generate the command signal to drive the steering mechanism and to generate the feedback force to simulate the driving conditions. The steering wheel feedback force is mainly a function of vehicle's speed and frontal wheels angle. The steering wheel is directly connected to the permanent magnet DC motor with encoder and thus the torque can be generated and its position can be sensed. The processors of the control unit are coprocessor Arm7 and FPGA in order to handle high speed signal processing and high level arithmetic operations effectively. FPGA receives the quadrature signal from the encoder and decodes it to 16 bit data before sending to Arm7. The Arm7 interprets and processes the data and then it controls the angular position of the modeled vehicle's frontal wheels accordingly. It also calculates and simulates a virtual force feedback to the steering wheel through the permanent magnet DC motor. Furthermore, the control unit can also generate several of command signals including throttle opening.

***Keywords**:* Steer by wire, intelligent control unit, and force feedback.

1. Introduction

Steer-by-Wire system is the main part of the Drive-by-Wire system. By replacing the conventional mechanical and hydraulic systems with the new drive-by-wire system, the overall vehicle safety, driving convenience and functionality can be improved significantly. In the Steer-by-Wire system, the mechanical linkages between the steering wheel and the front wheel are removed and the system was operated by the electrical actuators. Therefore, the Steer-by-Wire system has many advantages compared to its conventional side.

To begin with, the Steer-by-Wire system can reduce a vehicle's weight by reducing the number of necessary mechanical parts which can lead to energy reduction effectiveness. Furthermore, it ensures more safety to the vehicle by eliminating the dangers of a driver being crushed when there is front-end collision as there is no steering column. Lastly, the most valuable advantage is that it permits automatic steering and vehicle stability control to be free.

Even though the mechanical linkages have been removed, the Steer-by-Wire system still needs to retain the feeling of the conventional system. By connecting the reactive motor to the end of the steering wheel, the force feedback can be generated, and the driver will be able to obtain the real vehicle's steering feeling. The torque map for force feedback can be freely designed using the control algorithm which depends on the two factors, the steer wheel angle and the vehicle speed. The front wheel can be controlled by using another motor connected to the wheel axle. The vehicle's maneuverability and stability can be improved by using the understeer and oversteer propensity of the vehicle. All these functions have to be calculated and actualized using a steer by wire control unit.

1.1 Literacy Review

1.1.1 Vehicle state estimation and control

From US patent topic on Steer-by-wire for Vehicle State Estimation and Control (web-based article [2]), Paul Yih and J. Christian from Stanford University present an approach to estimate vehicle sideslip angle using steering torque information. Their method suits with all vehicles using steer-by-wire system since the steering torque can easily be obtained from the current apply to the steering motor. By combining a linear vehicle model with the steering system model, a simple observer may be devised to estimate sideslip when yaw rate and steering angle are measured. Based on this estimate of sideslip angle, a type of state feedback control has been developed to effectively alter the handling characteristics of a vehicle through active steering intervention. Both the observer and its application to vehicle handling modification are demonstrated on an experimental vehicle equipped with steer-by-wire capability.

1.1.2 Factors Affect Steering Torque

The research done by Se-Wook Oh, Ho-Chol Chae, Seok-Chan Yun, and Chang-soo HAN on "The Design of a Controller for the Steer-by-Wire System" was experimenting on how to verify the control algorithm. They come up with the equations to identify the steering torque feedback based on the steering wheel angle and vehicle speed. With only a little error, their result corresponds to the real vehicle graph.

2. Objectives

The overall objective of the project is to create an actual working and fail safe prototype of the steer by wire control unit within the low cost budget of 25,000 Bath. This also includes designing a computational model, calculating various mechanical parts, and working out the hardware for the system implementation. They can be divided into following categories:

2.1 Control Vehicle Wheels Angle

The modeled front wheels' rack is connected to a servo motor. The steering control unit has to send pulse width modulation to control the servo motor's position and thereby the front wheels' angle.

2.2 Control Vehicle Cruise Control

The steering control unit has to receive the input signals from the vehicle cruise control. These acceleration, deceleration and brake input signals must vary the modeled vehicle speed accordingly.

2.3 Simulate Steering Wheel's Feedback

The steering wheel feedback is determined by combination of steering angle signal and steering velocity signal. The steering control unit then has to compute instantaneous signals input and actuate variable feedback torques accordingly

2.4 Simulate Vehicle Gear

The modeled vehicle must also be able to travel backward or forward.

Therefore, the steering control unit has to be able to create an H-bridge motor driver for the rear wheels.

2.5 Intelligent Control

Use of coprocessor Arm7 and FPGA in order to handle high speed signal processing and high level arithmetic operations effectively.

2.5.1 Increase Safety

Normally, the steering wheel becomes easier to turn as the vehicle speed increase. Therefore, at high speed a slight turn of the steering wheel can cause the vehicle to lose control, which can be very dangerous for the driver. So, the steering control unit has to reduce this possibility by making it harder to turn at high speed.

2.5.2 Ease of Parking

Normally, the steering wheel becomes harder to turn as the vehicle speed decrease. So, the steering control unit has to decrease the reactive torque at low speed, thereby making steering easier to turn when parking.

3. Methodology

The project can be divided into two parts: the control unit and the mechanical interface.

3.1 Steer by Wire's mechanical Interface

The design is done in a CAD computer program named CATIA V5 R15; a virtual 3D prototype was created and then built, "Fig. 1". It generates actual signals from the steering wheel's encoder and various other functions for the steering control unit.

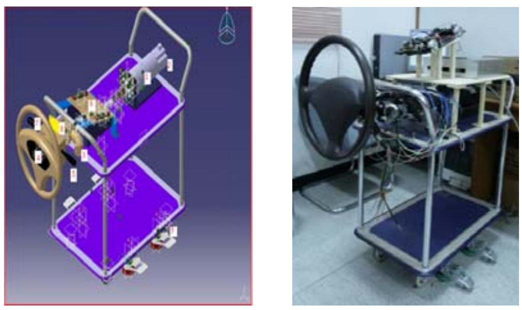

Fig. 1 CATIA Design and actual prototype of steer by wire mechanical interface.

3.2 Steer by Wire Control Unit

The main functions are to generate torque feedback to the steering wheel, and to rotate the wheels when the driver steers. For the torque feedback, we have to receive the signals from the encoder and calculated it to torque. So we need a programmable microcontroller that has a counter. The more precise it is, the better results we get. Both of the functions are to be controlled by the motors, therefore, the microcontroller need to be able to interact with the motor driver, dealing with both analog/digital signal and pulse width.

3.2.1 FPGA Discovery III

FPGA Discovery III is used to process quadrature signals to 16 bit data from the steering wheel to determine its position. Its advantage is the simultaneous signal processing using 200,000 logic gates, which includes simple flip-flops to more complete blocks of memory. As a result, we used FPGA board for receiving the signals from the encoder and send the data to ARM7. Its program, "Fig. 2," includes set zero and home position of the steering wheel. As a result, the counter resets itself to the initial zero position every time the steering wheel does a complete revolution and thereby minimize the potential of counting error.

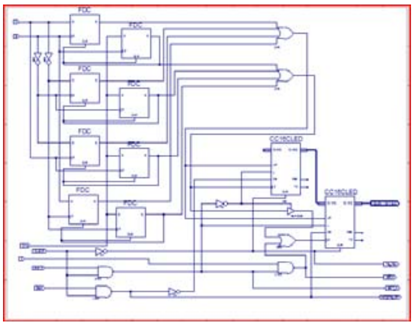

Fig. 2 FPGA Discovery III Program using VHDL language

3.2.2 ARM7 LPC2214

The LPC2214 is an ARM7TDMI-S based high-performance 32-bit RISC Microcontroller with In-System Programming. It also contains PWM, SPI, DAC and 16KB RAM which are perfect for controlling servo motor (front wheel angle), UND2916 (rear wheel speed), XSL motor driver (steering wheel force feedback) and high arithmetic calculations respectively.

4. Arithmetic calculations

The purpose of the steering wheel feedback torque is to generate reactive torque like a real commercial vehicle when the drivers steer. The drivers will be able to get the feeling of the road while steering. The reactive torque can be adjusted freely by varying the constant. In real commercial vehicle, the reactive torque vary depending on the three most significant factors, that is, the vehicle speed, the steering wheel angle, and the road surface condition. The control algorithms for the torque map are calculated by the following equations from journal article [1]:

4.1. Vehicle speed

$$y_v = -K_\beta x^2\left(\frac{1}{3}x-\frac{1}{2}V_{max}\right)+T_{in}$$

where,

y_v = component of steering reactive torque corresponding to vehicle velocity

K_β = velocity gain constant

x = vehicle velocity

V_{max} = maximum velocity

T_{in} = initial torque

4.2 Steering wheel angle

$$y_{sw} = K_\alpha \sqrt{\theta}$$

where,

y_{sw} = component of steering reactive torque corresponding to steering wheel angle

K_α = angle gain constant

θ = steering wheel angle

4.3 Total torque

$$T_{total} = y_v + y_{sw}$$

where,

T_{total} = Total reactive torque from both vehicle speed and steering wheel angle

4.4 Road surface condition

$$T_{total,wet} = \frac{1}{2} T_{total,dry}$$

where,

$T_{total,wet}$ = Total reactive torque in **wet** road surface condition

$T_{total,dry}$ = Total reactive torque in **dry** road surface condition

5. Steer by Wire System

From the analyzing existing steer by wire control unit, we have been able isolate the best core computing boards for our steering control unit, the FPGA Discovery III and the ET-JR Arm7.

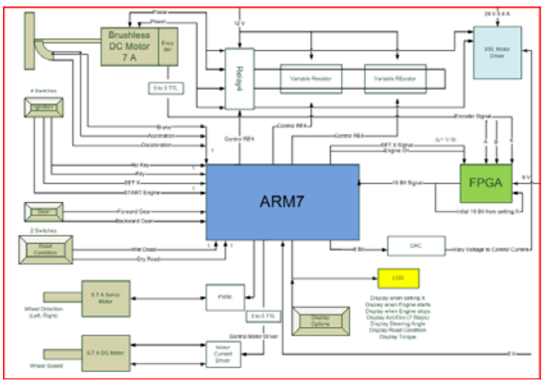

Fig. 3 Wire Diagram of steer by wire system

The Fig. 3 shows the complete flow chart of the core components, FPGA & Arm7, and subcomponents, relays, motor drivers, DAC boards, TTL converter board and LCD display.

The Fig. 4, diagram shows how each components are connected together to form a complete system with various inputs from the steering wheel and feedback to steering wheel brushes DC motor, front wheel servo motor and rear wheel DC motor.

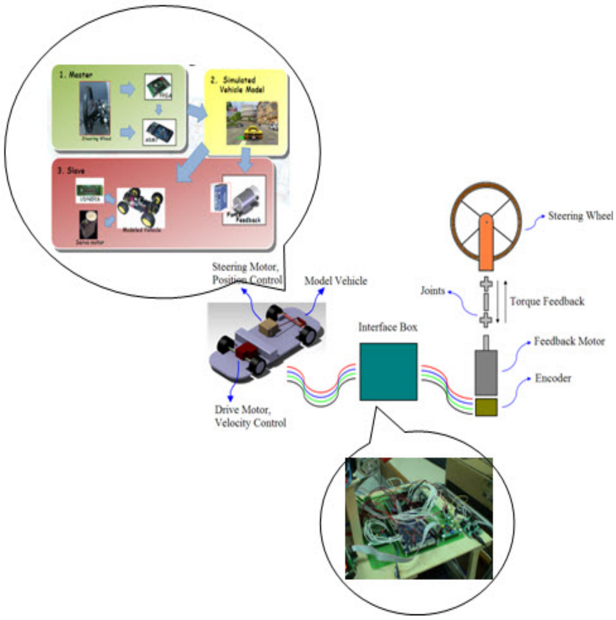

Fig. 4 Steer by Wire Signals Flow Diagram

5. Result

5.1 Steer by Wire System

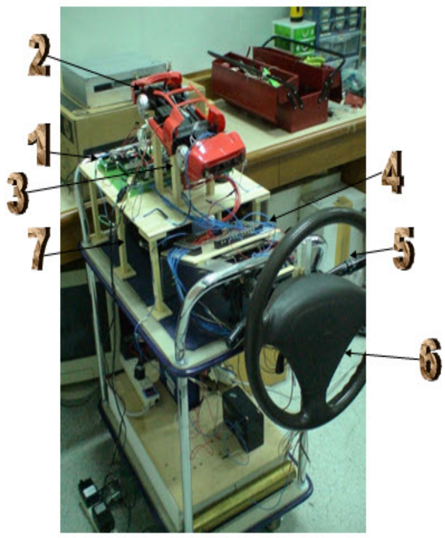

Fig. 5 Completed Steer by Wire System

We have been able to complete the whole steer by wire system, Fig. 5. The steering wheel (6) and switches (5) provides digital signals to the junction box (4) before going to the steering control unit (1). The steering control unit processes the digital signal: steering angle (6), road condition (5), and cruise control (5), and LCD display options (5). After that, the steering control unit then simulates the torque feedback according to the steering angle, vehicle speed from cruise control, and road condition. Next, it generated signal to control torque feedback though brush DC motor (7), modeled car's speed (3), and modeled car's angle (2).

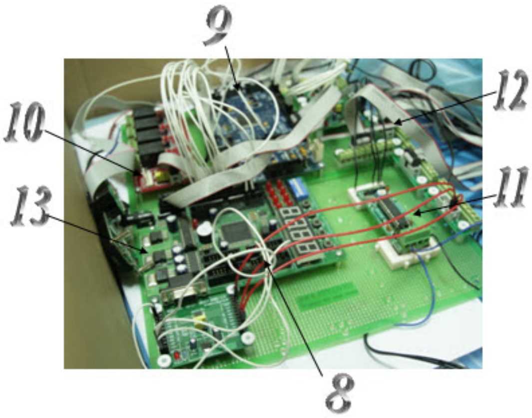

Fig. 6 Completed Steer by Wire Control Unit

Fig. 6 is the steering control unit hardware. The FPGA (8) received the encoder signal and processes it to 16 bit digital data to Arm7 (9). Arm 7 controls the motor's driver (11), servo motor PWM (12), XSL motor driver (12), relay (10), and LCD display (13).

5.2 Steering Feedback Force

Here are the plotted graphs showing all the torque at each steering wheel angle and vehicle speed in both dry and wet condition. We range the angle from -600° to 600°, and vehicle speed from 0 m/s to the max speed of 50 m/s.

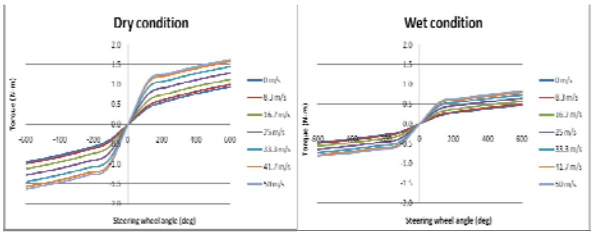

Fig. 7 Steering wheel Torque feedback

Comparing the two graphs from Fig. 7 you can see that when the road is in the wet condition, the torque feedback to the steering wheel is reduced by half of when the road is in the dry condition. For both graphs, the torque is zero no matter what the vehicle speed is.

5.3. Modeled Vehicle Angle

By using the protractor to measure the angle, and stroboscope to measure the speed of the modeled vehicle, we obtained the results which are plotted in the below graphs. Fig. 8 shows that the degree of each wheel rotates at different angle when turned with maximum difference of 10 degree. Fig. 9 shows how the cruise control speed related to the vehicle speed. Since the motor driver has only two outputs, half and full, there are only two speeds for the modeled vehicle which is 5km/hr and 10km/hr.

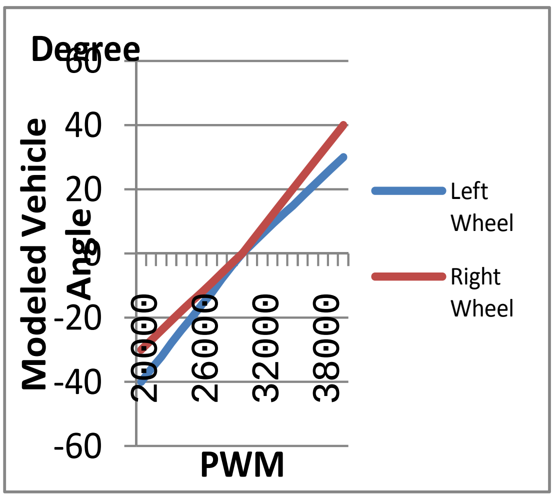

Fig. 8 Modeled vehicle angle

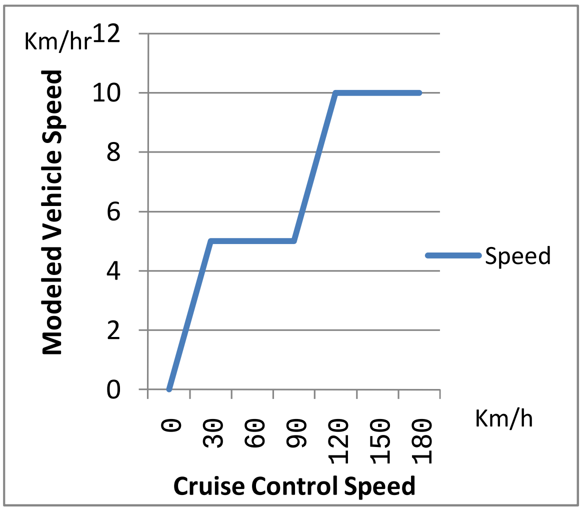

Fig. 9 Modeled vehicle speed

5.4. Safety Concern

In reality, the steering reactive torque will be decreases as the vehicle speed increases. This is due to the friction between the tire and the road surface. Since static friction is higher than kinetic friction, turning the steering wheel while the vehicle stops will generate more friction force and it will be harder for the drivers to turn the wheels. As the vehicle's velocity increases, the friction force drops lesser and the reactive torque decreases.

In our project, the torque feedback is opposite. The equation that we used gives an increase in torque as the vehicle speed increases. This is to ensure more safety to the drivers. By reversing the feedback, the drivers will feel more reactive torque at high vehicle's velocity which it will be harder to lose control of the vehicle. In addition, having low reactive torque at low speed makes steering easier when parking.

The two graphs below from Fig.10 and 11 compare the real vehicle with our Steer-by-Wire system.

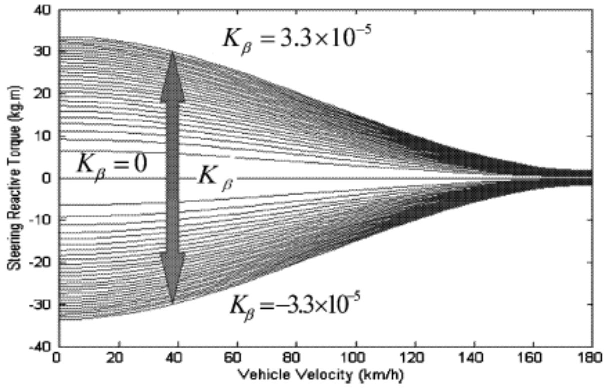

Fig. 10 Real car steering torque feedback

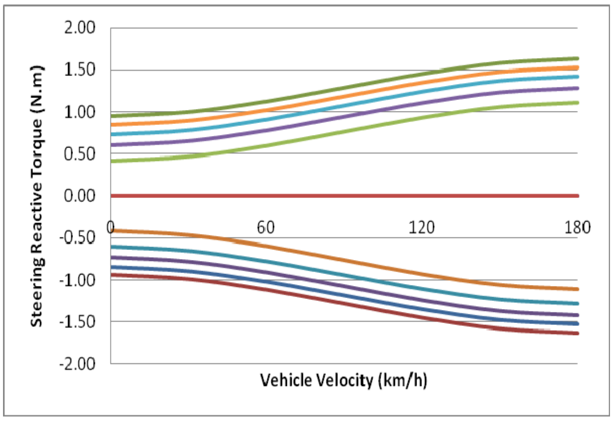

Fig. 11 Our Steer by Wire torque feedback

6. Conclusion

We have been able to create a feedback torque on the steering wheel according to steering angle and vehicle speed. From calculation, we have obtained two feedback graphs for the two road condition, dry and wet roads. (See calculation for the two graphs) The two graphs show the maximum and minimum torque feedback to be between 0 to 2 Nm. This feedback torque is within the human comfort zone that doesn't exceed 4 NM. In addition, the lock to lock angle of the steering wheel is one and a half turn, which agrees with normal passenger car regulation. Moreover, the tested drivers give positive feedback about steer by wire system with safety over steer prevention at high speed driving. Lastly, the molded vehicle responds accordingly with the steering angle and cruise speed control.

In short, the steering control unit performs within all our objective criteria. Moreover the steering control unit can function as a real car ECU since it contains almost all the basic ECU functions; acceleration, deceleration, brake, steering angle, vehicle status display, torque feedback calculation and road condition calculation. Therefore, it will be easy for further development and implementation in a real car.

7. Acknowledgement

Special Thanks to Prof. Ratchatin Chancharoen from the Department of Mechanical Engineering, Chulalongkorn University for his guidance throughout the project.

8. References

8.1 Article in Journals

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[1] Leiann K. Leppan (2005). The Conversion of General Motors Cadillac SRX to Drive by Wire System, p. 54-57

8.3 Books

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8.4 Web-Based Articles

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[2] Paul Yih and J. Christian Gerdes. Steer-by-Wire for Vehicle State Estimation and Control
URL: http://www-cdr.stanford.edu/dynamic/bywire/avec2004_v2.pdf