PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROL ALGORITHM WITH DELAY COMPENSATION FOR STEER-BY-WIRE UNDER NETWORK CONTROLLED SYSTEM

MOHD SAZLAN BIN ZAINAL

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechatronics & Automatic Control)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

DECEMBER 2015

To my parents, who has been supportive throughout my life, my wife and children, for their love, support, patience, sacrifice and encouragements.

ACKNOWLEDGEMENT

Alhamdullilah. First and foremost, my grateful appreciation goes to Allah s.w.t for His blessing and lending me the strength in the process of completing this project.

In this opportunity, I would like to express my gratitude to my supervisor, Associate Professor Dr. Abdul Rashid bin Husain for the guidance, encouragement, critics, advice and a lot of brilliant ideas. Without his continued support and interest, this thesis would not have been the same as presented here.

I am indebted to the Ministry of Higher Education for funding my studies here in Universiti Teknologi Malaysia.

My sincere appreciation also goes to my fellow postgraduate students for their support, knowledge sharing and assistance at various occasion during my postgraduate experience. Unfortunately, it is not possible to list all of them in this limited space but their friendly faces and gestures will always be remembered.

Last but not least, my special warmest gratitude goes to my parent and family, whom are very supportive to me during the period of my study. Special thanks to my wife, Marjan Mastura binti Mohamad and my three cheeky but kind and adorable children, Muhammad Sofiy, Marissa Sofia and Munira Sofia for being patient and so understanding to me. Their love, sacrifice and support will always be there in a special place in my heart. Thank you.

ABSTRACT

Controller Area Network (CAN) is a popular network commonly used in the automotive industry which is an advanced serial bus system designed for real-time control system. This thesis addresses the modelling and controller design for Steer-by-Wire (SbW) system under the influence of a network controlled system. The analysis of the control performance of the SbW system under several CAN configuration setting is discussed in detail. The mathematical model of the SbW system is adopted from previous research works using both steering rack dynamic and the vehicle system dynamic. Proportional-Integral-Derivative (PID) controller that can compensate delay is designed to achieve the desired control performance of the SbW system. The analysis of the control performance is solely based on the simulation conducted in the Matlab/Simulink software environment with Truetime toolbox to simulate the real time performance of the SbW system. The simulation is performed based on nine different cases in the event of several difference in the CAN network properties such as the network speed, sampling periods, scheduling techniques, rate of data losses, interruption by higher priority data and clock drift to evaluate the control performance of the SbW system. The result is found that the SbW system control performance deteriorates by the selection of low network speed, sensor’s sampling periods and the rate of data losses.

ABSTRAK

Pengawal Rangkaian Kawasan (CAN) adalah rangkaian popular yang biasa digunakan dalam industri automotif iaitu sistem talian rangkaian bersiri canggih yang direka untuk sistem kawalan masa nyata. Laporan tesis ini melaporkan kaedah untuk mendapatkan model dan merekabentuk pengawal untuk sistem Pacuan-melalui-Wayar (SbW) dibawah pengaruh sistem kawalan rangkaian. Analisis prestasi kawalan sistem SbW di bawah beberapa tetapan konfigurasi CAN dibincangkan secara menyeluruh dan terperinci. Model matematik sistem SbW yang diguna pakai dari kajian sebelum ini, menggunakan kedua-dua model dinamik rak roda stereng dan model dinamik sistem kenderaan. Pengawal Berkadar-Kamiran-Terbitan (PID) yang boleh menyelesaikan masalah lengah masa direka untuk mencapai prestasi kawalan yang dikehendaki oleh sistem SbW itu. Analisis prestasi kawalan adalah berasaskan kepada simulasi yang dijalankan menggunakan perisian Matlab/Simulink dengan Truetime untuk mensimulasikan prestasi masa nyata sistem SbW itu. Simulasi ini dijalankan berdasarkan sembilan kes yang berbeza mengikut beberapa perbezaan dalam ciri-ciri rangkaian CAN seperti kelajuan rangkaian, tempoh persampelan, teknik penjadualan, kadar kehilangan data, gangguan oleh data yang lebih utama dan gelinciran waktu untuk menilai prestasi kawalan sistem SbW. Hasilnya didapati bahawa prestasi sistem kawalan SbW merosot dengan pemilihan kelajuan rangkaian yang rendah, tempoh persampelan di pengesan dan kadar kehilangan data.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

τ_p	-	Processing Delay
τ_n	-	Network Delay
τ_s	-	Synchronization Delay
τ_{cl}	-	Closed-Loop Delay
τ_{sc}	-	Delay from Sensor to Controller
τ_{ca}	-	Delay from Controller to Actuator
$\ddot{\theta}_r$	-	Road Wheel Angular Acceleration
b_r	-	Viscous Damping Coefficient
J_r	-	Moment Of Inertia of The Road Wheel
$\dot{\theta}_r$	-	Road Wheel Angular Velocity
η	-	Steering Ratio
K_{tr}	-	Constant
i_r	-	Motor Current
τ_a	-	Self-Aligning Torque
τ_f	-	Friction Torque
$\dot{i}_r$	-	Derivative of Motor Current
K_{er}	-	Constant
L_r	-	Motor Inductance
R_r	-	Motor Resistance
V_r	-	Motor Voltage
$C_{\alpha F}$	-	Front Tire Cornering Coefficient
α_F	-	Front Tire Slip Angle
g	-	Gravity Acceleration
t_p	-	Tire Pneumatic Trail

t_m	-	Tire Mechanical Trail
W_f	-	Front Tire Weight
μ	-	Friction Coefficient
β	-	Vehicle Body Slip Angle
r	-	Yaw Rate
a	-	Distance from the Front Tire to the Vehicle Centre of Gravity
b	-	Distance from the Rear Tire to the Vehicle Centre of Gravity
v	-	Vehicle Longitudinal Velocity
$C_{\alpha R}$	-	Rear Tire Cornering Coefficient
m	-	Vehicle Mass
I_z	-	Vehicle Moment of Inertia
θ_L	-	Left Steering Angles
θ_R	-	Right Steering Angles
α_R	-	Rear Tire Slip Angle
u	-	Control Signal
K_p	-	Proportional Gain
e	-	Error Signal
T_i	-	Integral Time Constant
T_d	-	Derivative Time Constant
u_p	-	Proportional Control Signal
u_i	-	Integral Control Signal
u_d	-	Derivative Control Signal
k	-	time-step
h	-	Sampling Time
N	-	Filter time Constant
θ_r	-	Road Wheel Angle
θ_s	-	Steering Wheel Angle
e_{ss}	-	Steady-State Error

LIST OF ABBREVIATIONS

SbW	-	Steer-by-Wire
ABS	-	Anti-lock Braking System
DbW	-	Drive-by-Wire
PID	-	Proportional-Integral-Derivative
CAN	-	Controller Area Network
DC	-	Direct Current
SLMC	-	Sliding Mode Learning Control
PD	-	Proportional-Derivative
MDPP	-	Minimum-Degree Pole Placement
RCS	-	Robust Control Scheme
NFC	-	Nominal Feedback Controller
SMC	-	Sliding Mode Compensator
NCS	-	Networked Control System
FD-NCS	-	Fully Distributed Networked Control System
SD-NCS	-	Semi Distributed Networked Control System
PI	-	Proportional-Integral
ADS	-	Asynchronous Dynamical System
CoG	-	Centre of Gravity
ECU	-	Electronic Control Unit
CSMA/CD	-	Carrier Sense Multiple Access Protocol with Collision Detection
DM	-	Deadline Monotonic
EDF	-	Earliest Deadline First
EMI	-	Electromagnetic Interference
ISE	-	Integral Squared Error

IAE	-	Integral Absolute Error

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter covers brief introduction of the present scenario of the automotive industry together with the technological advancements that brought benefit to mankind. The conventional steering system and the Steer-by-Wire (SbW) system overview is also presented in the chapter. This chapter provides the framework of the project to be done with the detail explanation of the problem statement, objectives and the scopes of the project. This chapter ends with the outline of the project thesis report that will provides the basic idea on how the project report thesis is presented.

1.1 Introduction

As more than 100 years old industry, the automotive sector has experienced an incredible technological advancement in the past decades. With the development and improvement of control system engineering, a lot of changes has been incurred to the automotive industry. Several advanced control technologies have been integrated into the automotive world such as anti-lock braking system (ABS), vehicle traction control, electronic stability control system, and active suspension system.

Blossoming from the industrial realization and effort to develop green, safe and comfortable version of a vehicle, the drive-by-wire (DbW) technology is attracting a lot of interest from a lot of researchers all over the world. This so-called “drive-by-wire” technology is referring to a new technological advancement in automotive industry which is very much dependent on the electronic actuators, controllers and sensors to replace the conventional mechanical and hydraulic system for braking, suspension, throttle and steering function [1].

1.1.1 Conventional Steering System

The steering system of a passenger cars have evolved from the mechanical steering system, to hydraulic and electro-hydraulic power assisted steering system, through to the electric power assisted steering system. In general, a steering system is a group of parts that transmit the movement of the steering wheel to the front, and sometimes the rear, wheels of vehicles. The primary purpose of a steering system is to allow the driver to guide the vehicle. When a vehicle is being driven straight ahead, the steering system must keep it from wandering without requiring the driver to make constant corrections. The steering system must also allow the driver to have some road feel which is the feedback through the steering wheel about road surface conditions. The steering system must help maintain proper tire-to-road contact. For maximum tire life, the steering system should maintain the proper angle between the tires both during turns and straight-ahead driving. The driver should be able to turn the vehicle with little effort, but not so easily that it is hard to control the movement of the vehicle.

There are two main types of steering systems used in modern cars and light trucks. The first one is the parallelogram linkage steering system as shown in Figure 1.1. This is the only type of steering system that is used until the 1970s. The second type of steering system is the rack-and-pinion steering system shown in Figure 1.2. It is a simple system that directly converts the rotation of the steering wheel to straight line movement at the wheels. It consists of the rack, pinion and related housings and support bearings. This system is common in modern vehicle [2].

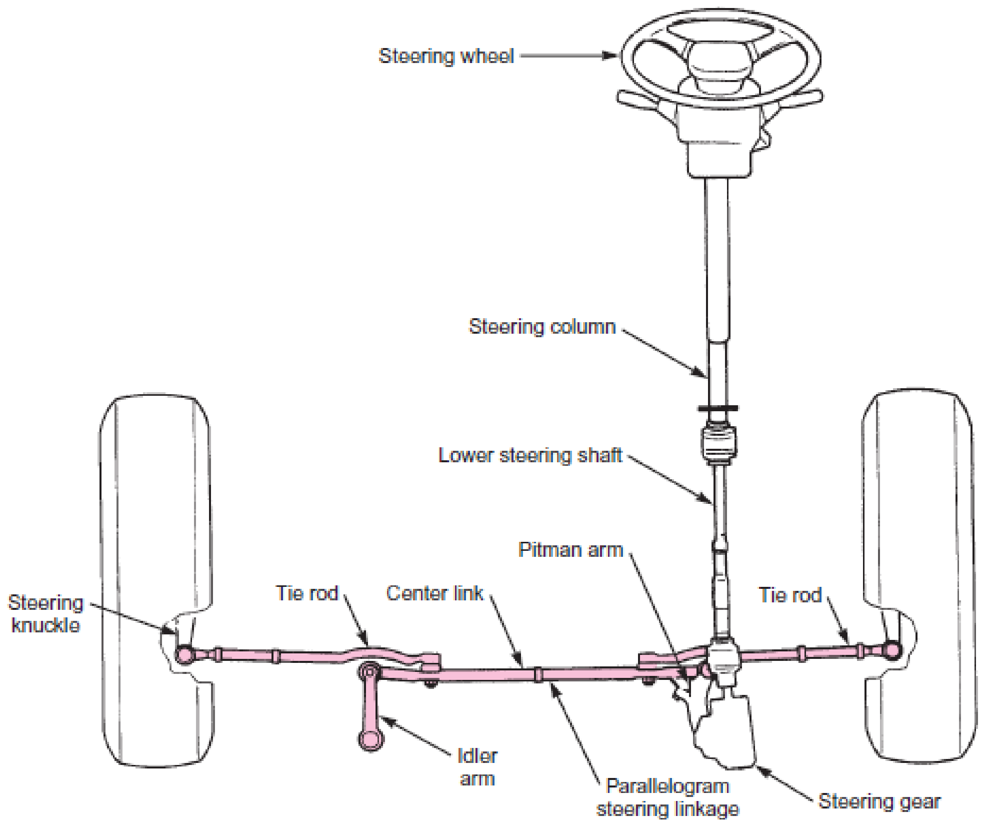

Figure 1.1 Parallelogram Linkage Steering System [2]

Figure 1.2 Rack and Pinion Steering System [2]

1.1.2 Steer-by-Wire (SbW) System

The SbW system is a relatively new technology that is being contemplated by researchers in automotive industry as the alternative to replace the conventional steering systems that are currently being used in the industry. In conventional vehicles, the steering wheel is connected to the front wheels of a vehicle through a link that can be mechanical, hydraulic or a combination of both system [3]. The SbW system eliminates such a link thus, the steering command is transmitted by a communication network to the front wheel. The orientation of the front wheel is controlled by electronic actuators based on electrical signal from the controllers, as shown in Figure 1.3[1].

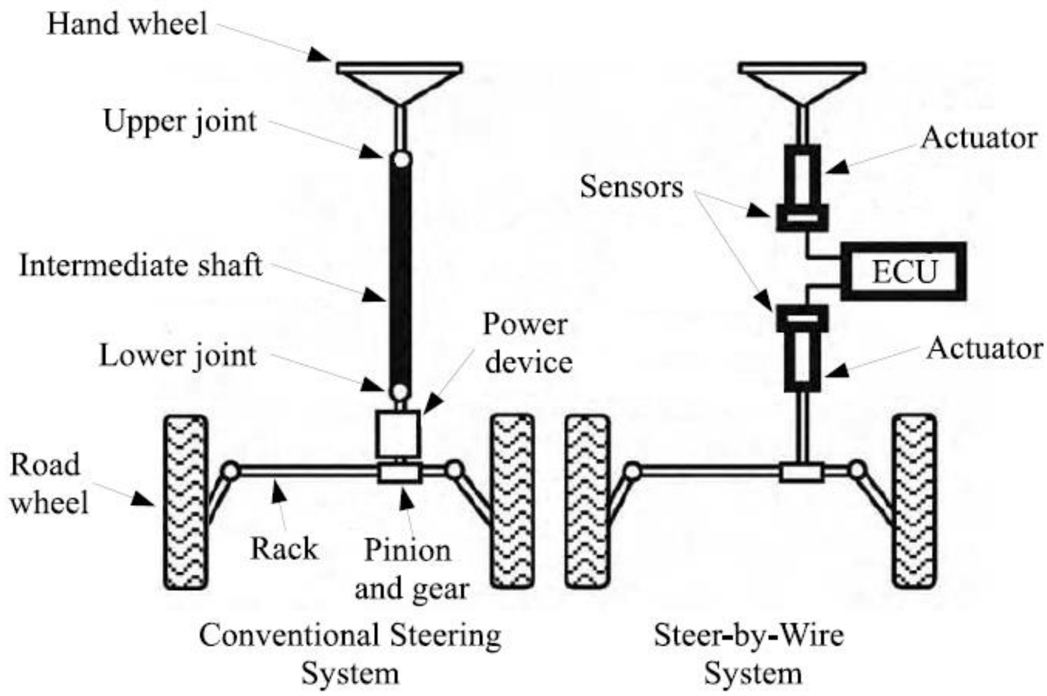

Figure 1.3 Comparison of Conventional Steering System and SbW System [1]

SbW offers many advantages compare to conventional system, in example, reducing vehicle weight as the effect of eliminating the cumbersome mechanical linkages, better space and fuel efficiency due to less weight. Furthermore, it improves the vehicle maneuverability and stability with no oil leakage problem. Moreover, the SbW system brings less injury in front-end collision accident, reduce driver fatigue due to vibration of the vehicle on the front wheel via mechanical linkage and enable self-driving technology. Even though SbW has a few disadvantages such as lacking of realistic driving feelings, challenging control algorithm design and susceptible to hardware/software fault, the advantages offered outweigh those disadvantages which make SbW research work remain significant [1].

1.1.2.1 Steer-by-Wire (SbW) System Requirements

There are main several requirements for SbW system [4]:

1. Directional control and wheel synchronization.
   - The front wheel follow the driver input command from the steering wheel.

2. Capability of steering wheel return or free control.
   - The steering wheel should return automatically to the centre if the hands of driver is removed or released from the steering.

3. Variable steering ratio.
   - The steering ratio between steering wheel angle and front wheel angle. For example, steering ratio 10:1. By means steering wheel it to 10 degrees angle, the front tire wheel should turn to 1 degrees angle.

4. Adjustable variable steering feel.
   - The vehicle driver relies on steering feel to sense the force of road condition with tire to ground contact and maintain control of the vehicle.

This project is only focused on the directional control and wheel synchronization of the SbW system.

1.2 Problem Statement

The delay that occurs in the network between sensors, controller and actuators of a Steer-by-Wire (SbW) system leads to performance deterioration and at worst, destabilizing the SbW system. It is harmful to the vehicle because it affects the vehicle performance and stability and directly, the safety of the driver and passengers cannot be guaranteed.

1.3 Objectives of the Project

The objectives of this project are:

1. To adapt the mathematical model for the SbW system from existing work.

2. To adapt the Proportional-Integral-Derivative (PID) control algorithm that can compensate delay for the SbW system under Controller Area Network (CAN) from existing work.

3. To analyse and evaluate the performance of the proposed PID controller algorithm on SbW system connected in the CAN network protocol.

1.4 Project Scopes

This project is solely based on the software simulation development to implement the designed PID that can compensate delay control method on the SbW system.

The scopes of the project are:

1. SbW system model for vehicle with front wheel drive only.

2. CAN protocol as the network system interconnecting the components of the SbW system.

3. PID controller that can compensate delay as the controller of the system.

4. Simulation is done using the Matlab/Simulink with Truetime toolbox.

1.5 Outline of Thesis

The thesis report is organized in 5 chapters. The first chapter gave an overview of the project that provides a brief description about the subject of study, the problem statement, the objective, and the scope of this project.

Chapter 2 covered literature review on SbW system, related works and controller design. It contains the previous research works done in the area of SbW with difference in controller design methods which brought out a few motivation in building the framework of this project works.

The third chapter covers the flow of methodology and description of each procedure. It starts with the modelling of the SbW system derived from existing work. Then, the control strategy and control method of the SbW model is formulated based from the previous works with the aim to compensate delay.

Chapter 4 mainly present and discuss the simulation results of the performance of the SbW system with PID controller in the CAN network protocol.

The conclusion of the project is discussed in chapter 5. It covers the whole perspective of the project and with some recommendations for the research on the SbW system under network control to be considered in the future work.

REFERENCES

1. Nor Shah, M. B., Husain, A. R. and Dahalan, A. S. A. An Analysis of CAN-based Steer-by-Wire System Performance in Vehicle. *IEEE International Conference on Control System, Computing and Engineering*. Penang, Malaysia: IEEE. 2013. 350–355.

2. Johanson, C. and Stockel, M. T. *Auto Suspension and Steering Textbook*. 3rd. ed. Tinley Park, Illanois: Goodheart-Willcox Publisher, 2010.

3. Bertoluzzo, M., Buja, G., Menis, R. and Sulligoi, G. An Approach to Steer-by-Wire System Design. *IEEE International Conference on Industrial Technology*. Hong Kong: IEEE. 2005. 443–447.

4. Tau, Y. Vehicle Steer-by-Wire System Control. *SAE Technical Paper*. 2006-01-1157, 2006

5. Zhang, X., Kong, H. and Wang, H. A Composite Control Scheme for Automotive Steer-by-Wire System. *International Conference on Modelling, Identification and Control*, Melbourne, Australia. 2014. 237– 242.

6. Fahami, S. M. H., Zamzuri, H., Mazlan, S. A. and Zakaria, M. A. Modelling and Simulation of Vehicle Steer by Wire System. *IEEE Symposium on Humanities, Science and Engineering Research*. Kuala Lumpur, Malaysia: IEEE. 2012. 765–770.

7. Oh, S.-W., Chae, F.-C., Yun, S.-C. and Han, C.-S. The Design of a Controller for the Steer-by-Wire System. *JSME International Journal*. 2004. 47(3). 896-907.

8. Im, J., Ozaki, F., Matsunaga, N. and Kawaji, S. Bilateral Control for Steer-by-Wire Vehicle. *SICE-ICASE Internal Joint Conference*, 2006.

9. Amberkar, S., Bolourchi, F., Demerly, J. and Millsap, S. A Control System Methodology for Steer-by-Wire Systems. *SAE Technical Paper Series*. 2004-01-1106. 2004.

10. Do, M. T., Zhihong, M., Cishen, Z., Wang, H. and Tay, F. S. Robust Sliding Mode-Based Learning Control for Steer-by-Wire Systems in Modern Vehicles. *IEEE Transactions on Vehicular Technology*. 63(2). 2014. 580-590.

11. Daher, N. and Ivantysynova, M. An Indirect Adaptive Velocity Controller for a Novel Steer-by-Wire System. *Journal of Dynamic Systems, Measurement, and Control*. 136(5). 2014. 1–9.

12. Hai, W., Zhihong, M., Weixiang, S., Zhenwei, C., Jinchuan, Z., Jiong, J. and Do, M. T. Robust Control for Steer-by-Wire Systems with Partially Known Dynamics. *IEEE Transaction on Industrial Informatics*. 10(4). 2014. 2003–2015.

13. Jianmin, D., Ran, W. and Yongchuan, Y. Research on Control Strategies of Steer-by-Wire System. *International Conference on Intelligent Computation Technology and Automation*. 2010. 1122–1125.

14. Pimentel, J. R. An Architecture for a Safety-Critical Steer-by-Wire System. *Society of Automotive Engineers Technical Papers*, 2004.

15. Chaaban, K. and Leserf, P. Simulation Of a Steer-By-Wire System Using Flex Ray-based ECU Network. *International Conference on Advances in Computational Tools for Engineering Applications*. 2009. 21 – 26

16. Jianmin, D., Hualin, D. and Yongchuan, Y. Co-Simulation of SBW and FlexRay Bus Based on CANoe_MATLAB. *IEEE International Conference on Automation and Logistics*. 2010. 202–206.

17. Veeramachaneni, S. R. and Watkins, J. M. Robust Performance of PID Controllers for Time-Delay System with a Smith Predictor. *American Control Conference*. 2014. 2462–2467.

18. Mirzal, A. Stability Analysis and Compensation of Time Delays in Analog Control Systems. *International Journal of Control and Automation*, 5(4). 2012. 1–17.

19. Maqsood, I., Nasir, H. A. and Muhammad, A. PID Controller Tuning for Networked Delayed Motion Control. *International Conference on Communications, Computing and Control Applications*. 2011.

20. Xiangdong, D. and Qingling, Z. Stability and PID Control of NCS with Time-Varying Delay and Data Packet Dropout. *Proceeding of Chinese Control Conference*. 2010. 4417–4422.

21. Eriksson, L. *PID Controller Design and Tuning in Networked Control System*. Ph.D. Thesis. Helsinki University of Technology; 2008.

22. Pohjola, M. *PID Controller Design in Networked Control System*. M. Sc. Thesis, Helsinki University of Technology; 2006.

23. Nilsson, J. *Real-Time Control Systems with Delays*. M. Sc. Thesis. Lund Institute of Technology; 1998.

24. Nguyen, B.-H. and Ryu, J.-H. Direct Current Measurement Based Steer-by-Wire Systems for Realistic Driving Feeling. *IEEE International Symposium on Industrial Electronics*. 2009. 1023–1028.

25. Anwar, S. and Chen, L. An Analytical Redundancy-Based Fault Detection and Isolation Algorithm for a Road-Wheel Control Subsystem in a Steer-by-Wire System. *IEEE Transaction on Vehicular Technology*. 56(5). 2007. 2859–2869.

26. Isaksson, A. J. and Graebe, S. F. Derivative Filter is an Integral Part of PID Design". *IEE Proceedings: Control Theory and Applications*. 61(149). 2002.

27. Åström, K. J. and Hägglund, T. *PID Controllers: Theory, Design, and Tuning*. 2nd Edition. Instrument Society of America, Research Triangle Park, North Carolina, 1995.

28. Bosch, R. GmbH, *CAN Specification: Version 2.0*. Stuttgart, Germany. 1991.

29. Cervin, A., Henriksson, D. and Ohlin, M. *TrueTime 2.0 Beta – Reference Manual*. Department of Automatic Control. Lund University. Sweden. 2010.

30. Cervin, A., Henriksson, D., Lincoln, B., Eker, J. and Årzén. K. E. How Does Control Timing Affect Performance? Analysis and Simulation of Timing Using Jitterbug and TrueTime. *IEEE Control System Magazine*. 23(3). 2003. 16-30.

31. Jie, T., Jin, W. and Ning, C. Fractional $PI^{\lambda}D^{\mu}$ Control for Steer-by-Wire System. *Advanced Material Research*. 279. 2011. 423–428.

32. Xuyun, Q., Mingjin, Y., Zhulin, Z. and Jiuhong, R. Research on Steering Control and Simulation of Vehicle Steer-by-Wire System. *Advanced Material Research*. 403–408. 2012. 5076–5081.

33. Hayama, R., Kawahara, S., Nakano, S. and Kumamoto, H. Resistance torque Control for Steer-by-Wire System to Improve Human-Machine Interface. *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*. 48(9). 2010. 1065–1075.

34. Yun, Y. J., Feng, K. and Yuan, W. F. Control Strategy for Front Wheel Angle of Steer-by-Wire based on Variable Steering Ratio. *International Conference on Computer Science and Network Technology*. 2011. 852–856.

35. Bertoluzzo, M., Buja, G. and Menis, R. Control Schemes for Steer-by-Wire Systems: Design and Experimentation Issues for Improved Control of Steering Maneuvers," *IEEE Industrial Electronic Magazine*. 1(1). 2007. 20–27. 2007.

36. Tavoosi, V., Kazemi, R. and Hosseini, S. M. Vehicle Handling Improvement with Steer-by-Wire System Using Hardware in the Loop Method. *Journal of Applied Research and Technology*. 12. 2014. 769–781.

37. Yixin, Y. Vehicle Steer-by-Wire System Control. *SAE Technical Paper Series*. 2006-01-1175. 2006.

38. Saruchi, S. A., Zamzuri, H., Mazlan, S. A., Fahami, S. M. H. and Zulkarnain, N. Wheel Synchronization Control in Steer-By-Wire Using Composite Nonlinear Feedback. *Applied Mechanics and Materials*. 575. 2014. 762–765.

39. O'Dwyer, A. PID Compensation of Time Delayed Process: A Survey. *Proceedings of the Irish Signals and Systems Conference*. 2000. 5–12.

40. Ait-Oufroukh, N., Messaoudene, K. and Mammar, S. Dynamic Model of Steer-by-Wire System for Driver Handwheel Feedback. *IEEE International Conference on Networking, Sensing and Control (ICNSC)*. 2013. 780–785.

41. Fangyuan, W., Feng, K. and Jiangyun, Y. Intelligent Fault Diagnosis of Steer-by-Wire Automobile. *Journal of Computers*. 7(5). 2012. 1204 – 1211.

42. Balachandran, A. and Gerdes, J. C. Designing Steering Feel for Steer-by-Wire Vehicles Using Objectives Measures *IEEE/ASME Transaction on Mechatronics*. vol. 20(1). 2015. 373–383.

43. Xiaoran, S., Fang, L. and Chenglin, L. Network Level Fault Diagnosis of Steer-by-Wire System based on ANFIS. *IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*. 2014. 1–5.

44. Mane, S. P. S., Sonavane, S. and Shingare, P. P. A Review on Steer-By-Wire System Using Flexray. *International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace and Electronics Systems Technology (Wireless VITAE)*. 2011. 1–4.

45. Kleine, S. and van Niekerk, J. L. Modelling and Control of a Steer-by-Wire Vehicle. *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*. 29(1). 1998. 114–142.

46. Bajçinca, N., Cortesão, R. and Hauschild, M. Robust Control for Steer-by-Wire Vehicle. *Journal of Autonomous Robot*. 19(2). 2005. 193–214.

47. Hibi, M., Kobune, T., Miki, D., Kano, Y. and Abe, M. A Study on Steering Reactive Torque for Steer-by-Wire Vehicle Using Driving Simulator. *Proceedings of the FISITA 2012 World Automotive Congress: Lecture Notes in Electrical Engineering*. 10. 2013. 237–246.

48. Sadale, R., Kolhe, R., Wathore, S., Aghav, J., Warade, S. and Udayagiri, S. Steer-by-Wire Implementation Using Kinect. *Proceedings of International Conference on Advances in Computing*. 2012. 163–170.

49. Li, Q., Shi, G., Wei, J. and Lin, Y. Yaw Stability Control of Active Front Steering with Fractional-Order PID Controller. *International Conference on Information Engineering and Computer Science*. 2009. 1–4.

50. Mulder, M., Abbink, D. A., Boer, E. R. and van Paassen, M. M. Human-Centered Steer-by-Wire Design. *IEEE International Conference on Systems, Man, and Cybernetics*. 2012. 3015–3019.

51. Hussain, K., Baharom, M. and Day, A. Analysis of The Properties of A Steering Shaft used as a Back-Up for a Steer-by-Wire System during System Failure. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 223(2).* 2009. *177–189.*

52. Shaheen, S., Heffernaan, D. and Leen, G. A comparison of emerging time-triggered protocols for automotive X-by-wire control networks. *Proceedings of Institute of Mechanical Engineers: Part D: Journal of Automotive Engineering*. 217. 2003. 13–22.