Neural Network based Control for Steer-by-Wire Systems Vehicles

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Abstract: - Steer-by-wire (SbW) is the future of steering system. The main problem is to accurately track the driver's hand wheel command so that the error remain within the specified bound, when the disturbance forces are available between the Tire and Road. So in this paper, a cosine function neural network (NN) based control is proposed for tracking the hand-wheel steering command in steer-by-wire (SbW) system vehicles. The NN based controller shows that the error remain within the specified bound when the self-aligning torque act as disturbance for the controller.

Key-Words: - Steer-by-Wire (SbW), Neural Network (NN).

1 Introduction

Steer-by-wire (SbW) system is a next generation steering system. The advantages of using SbW systems in road vehicles are to improve the overall steering performance, lower the power consumption, and enhance the safety and comfort of the passengers.

The modern SbW systems have the following distinct characteristics: 1) The mechanical link in conventional road vehicles used to connect the hand-wheel to the steered front wheels, through the rack and pinion gearbox, is removed; 2) the hand-wheel angle sensor is installed on the steering column to provide the reference signal for the front-wheel steering angle to follow; and 3) the steering motor, coupled to the rack and pinion gearbox, is adopted to steer the front wheels based on the reference information provided by the hand-wheel angle sensor. In addition, a feedback motor is employed on the hand-wheel side to provide drivers with the feeling of the effects of self-aligning torque between the front wheels and the road surface, based on the error information between the reference and the actual steering angle measured indirectly by the pinion angle sensor.

Previously researchers group developed control algorithm for rack actuated and tie-road actuated SbW system [1][2]. Slinging mode based controller and Robust sliding mode learning based controller is proposed by[3] [4]. With help of parallel control units the front wheel angle can also be controlled so for that fault tolerant control is proposed by [5], [6]. And also multiple control schemes are available for tracking the hand wheel signal in SbW system [7][8][9].

So far most of the controller need model parameter information for tracking the hand wheel signal. But the proposed Cosine function NN based controller is a model free controller. During different handling tests the controller shows the robust performance. The remaining paper is organized as follows. Section 2, Discusses the Problem formulation by using the Dynamics of Vehicle and SbW. In Section 3, the problem solution is proposed based on cosine function NN controller and Simulation Results. Section 4, discusses the conclusion and feature work.

2 Problem Formulation

In SbW system vehicles the hand wheel is not connected to the front wheels. When the driver rotates the steering wheel, the hand wheel angle sensor provides the desired angle information to the controller. And another front wheels angle sensor provides the feedback signal the controller. So for simulating the controller, the dynamics SbW systems is discussed in the following section.

2.1 Dynamics of Steer-By-Wire System

Fig.1 shows a SbW system and the corresponding system parameters are listed in Table 1. It is seen that the mechanical linkage used to connect the hand-wheel with the steered front-wheels in conventional steering systems has been substituted by two motors, that is, the steering motor and the hand-wheel motor.

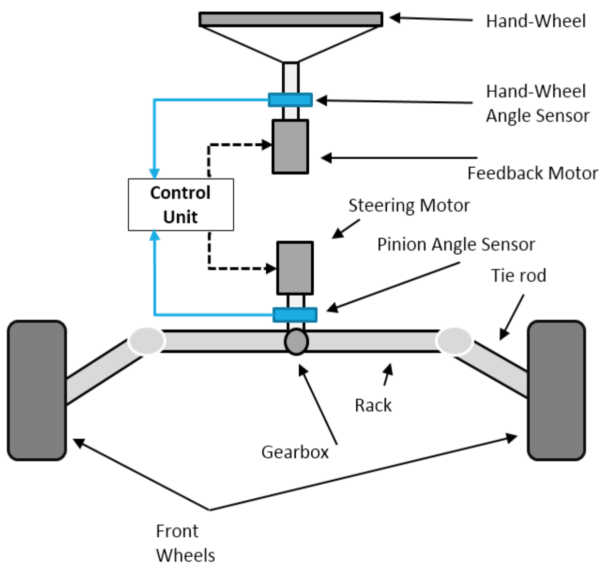

Fig. 1

The hand-wheel motor provides a driver with a reaction torque from the interactions between the vehicle tires and road surface. Thus the following relationship holds that:

$$\frac{\ddot{\delta}_f}{\ddot{\delta}_{sm}} = \frac{\dot{\delta}_f}{\dot{\delta}_{sm}} = \frac{\delta_f}{\delta_{sm}} = \frac{1}{\sigma r} = \frac{\tau_{12}}{\tau_s} \qquad (1)$$

Where σ is the rack and pinion system's gear ratio, and r is a scale factor accounting for the conversion from the linear motion of the rack to the rotation of the front wheels.

The rotation of the steering motor is described by the following dynamical equation:

$$J_{sm}\ddot{\delta}_{sm} + B_{sm}\dot{\delta}_{sm} + \tau_{12} = \tau_{sm} \qquad (2)$$

Also, the rotation of the steered front-wheels about their vertical axes crossing the wheel centers can be described by:

$$J_{sw}\ddot{\delta}_f + B_{sw}\dot{\delta}_f + \tau_F + \tau_e = \tau_s \qquad (3)$$

Where τ_F is the coulomb friction defined as:

Table 1
Parameters of SbW System

Symbols	Description
$\Theta_h, \delta_f, \delta_{sm}$	Rotational angles of hand-wheel, front wheels, and steering motor shaft
$\tau_h, \tau_{hm}, \tau_{sm}$	Torques generated by driver, hand-wheel motor, and steering motor
τ_e	Self-aligning torque
τ_f	Coulomb friction in the SbW system
τ_{eq}	Equivalent drive torque
τ_{12}	Torque exerted on the steering motor shaft by the front-wheels
τ_s	Torque transmitted to steering arms of the front-wheels by the steering motor through the rack and pinion gearbox
B_h, B_{sw} B_{sm}, B_{eq}	Moments of inertia of hand-wheel, front wheels, steering motor, and equivalent system
J_h, J_{sw} J_{sm}, J_{eq}	Viscous frictions of hand-wheel, front wheels, steering motor, and equivalent system

$$\tau_F = F_s sign(\dot{\delta}_f) \qquad (4)$$

Where F_s is the friction constant.

Using (1) and (2), we can express τ_s as

$$\tau_s = k(\tau_{sm} - J_{sm}\ddot{\delta}_{sm} - B_{sm}\dot{\delta}_{sm}) \qquad (5)$$

where $k = \sigma r$ known as steer ratio.

Substituting (5) into (3) leads to

$$\begin{aligned} &J_{sw}\ddot{\delta}_f + B_{sw}\dot{\delta}_f + F_s sign(\dot{\delta}_f) + \tau_e \\ &= k(\tau_{sm} - J_{sm}\ddot{\delta}_{sm} - B_{sm}\dot{\delta}_{sm}) \end{aligned} \qquad (6)$$

By eliminating $\dot{\delta}_{sm}$ and $\ddot{\delta}_{sm}$ in (6) with the help of (1), we obtain

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$$J_{sw}\ddot{\delta}_f + B_{sw}\dot{\delta}_f + F_s sign(\dot{\delta}_f) + \tau_e = k(\tau_{sm} - kJ_{sm}\ddot{\delta}_f - kB_{sm}\dot{\delta}_f) \quad (7)$$

Re-arranging (7), we have

$$J_{eq}\ddot{\delta}_f + B_{eq}\dot{\delta}_f + F_s sign(\dot{\delta}_f) + \tau_e = \tau_{eq} \quad (8)$$

Where

$$J_{eq} = J_{sw} + k^2 J_{sm}$$
$$B_{eq} = B_{sw} + k^2 B_{sm} \quad (9)$$
$$\tau_{eq} = k\tau_{sm}$$

It is seen from (8) that, although the SbW system contains a few components such as the steered front-wheels, the rack and pinion gearbox, and the steering motor, the integrated SbW system can be modelled by a second-order differential equation.

Where, τ_e the linearized self- aligning for linear region is given by:

$$\tau_e = -C_f(t_p + t_m)(\beta + \frac{\gamma l_f}{V_{CG}} - \delta_f) \quad (10)$$

For calculating the self-aligning torque parameters, we are considering vehicle bicycle model. The dynamics of yaw motion of the vehicle is given by:

$$\begin{bmatrix}\dot{\beta}\\ \dot{\gamma}\end{bmatrix} = \begin{bmatrix}\frac{-C_f - C_r}{mV_{CG}} & -1 + \frac{C_r l_r - C_f l_f}{mV_{CG}} \\ \frac{C_r l_r - C_f l_f}{I_Z} & \frac{-C_f l_f^2 - C_r l_r^2}{I_Z V_{CG}}\end{bmatrix}\begin{bmatrix}\beta\\ \gamma\end{bmatrix} + \begin{bmatrix}\frac{C_f}{mV_{CG}} \\ \frac{C_f l_f}{I_Z}\end{bmatrix}\delta_f$$

(11)

where the vehicle body slip angle β at the center of gravity (CG) and the yaw rate γ are the state variables, respectively, the constant longitudinal velocity is V_{CG} in m/s at the CG, the vehicle mass m in kg, the moment of inertia I_Z of the vehicle about the CG in $kg.m^2$, the distances of the front wheel and rear-wheel axles from the CG are l_f and l_r in m respectively, the front and rear cornering stiffness coefficients C_f and C_r respectively, and where t_p and t_m are the pneumatic and mechanical trails, respectively. The values of all the above parameters are given in Table 2.

Table 2

Parameters of vehicle dynamics for simulation

Parameter	**Value**
V_{CG} in (m/s)	10
I_Z $(kg.m^2)$	1300
l_f , l_r (m)	1.2 , 1.05
$C_f = C_r$	12000
t_p, t_m (m)	0.023 , 0.016
J_{sw}, J_{sm} $(kg.m^2)$	3.8 , 0.0035
B_{sw}, B_{sm} (Nms/rad)	10 , 0.018
k	18
F_S (Nm)	30
ΔT (sec)	0.001

3 Cosine Function Based NN Control

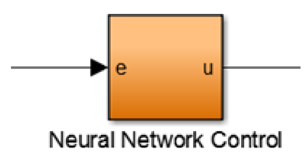

Fig. 2

The cosine function NN based control[10] is used for tracking the hand-wheel angle. The input variables are selected as $x(t) = e(t) = \delta_d(t) - \delta_f(t)$ shown in Fig 2. Here $e(t)$ is the error between the desired out angle and actual out angle. The output of NN controller is expresses by flowing formula.

$$u = \sum_{k=1}^{n} w(t)\phi(t) \quad (12)$$

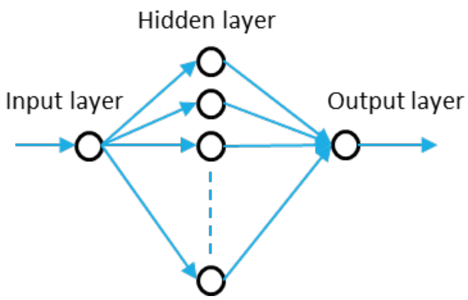

Fig. 3

The single input and single output multi-layer feedforward network structure is used as shown in Fig 3. The function of kth neuron in the hidden layer is composed of the cosine function, which is represented by the following function:

$$\phi_k(t) = \cos(k \cdot \arcsin\varphi)$$
$$= \cos(k.\arcsin(\frac{1}{1+e^{-a \cdot x}})) \qquad (13)$$

$for\ k = 1, 2, ..., n$

Where n indicates n neurons with cosine function in the NN hidden layer and φ is taken as a unipolar sigmoid function (S function):

$$\varphi = \frac{1}{1+e^{-a \cdot x}} \qquad (14)$$

The unipolar S function can transform the input interval $(-\infty, +\infty)$ into the output interval $(0,1)$.

In the unipolar S function, $x(t)$ is the input signal of the NN and the scalar parameter a can be adjusted to change the slant degree of the S function curve and the adaptive learning capability of the NN. The weight value between the output layer and the hidden layer $w(t)$ is obtained from an online learning process.

The learning performance index of NN is to minimize the system tracking errors between the desired output and the actual output of the SbW control system, which is expressed as follows:

$$J(t) = \frac{1}{2}(e(t))^2 \qquad (15)$$

Where $J(t)$ is error cost function. Objective of this cost function is to minimize the error or to minimize the input of controller.

The NN weights values can be adjusted by the following algorithm:

$$\frac{dw_k(t)}{dt} = \eta e(t)\phi_k(t) \ \text{ for } k = 1, 2, ..., n \qquad (16)$$

where $\eta \in (0, \infty)$ is learning rate of the network to determine the convergence velocity. The two side integral of Equation (15) can yield the following formula:

$$w_k(t) = w_k(0) + \int_0^t \eta e(t)\phi_k(t)dt \qquad (17)$$
$$\text{for } k = 1, 2, ..., n$$

The parameter values of cosine function NN based controller is given is Table. 3. The effectiveness of the proposed cosine function NN based controller in demonstrated in the following section.

Table 3

Parameters for NN based controller

Parameter	Values
No. of hidden layer neurons, k	10
Learning rate, η	300
Scalar constant, a	100
Sampling time, Δt	0.001

For the optimum performance we have chosen 10 no. of neurons. By increasing the no. of neurons greater then 10, computational power is increased in other words it requires more power full controller. Or by decreasing the no. of neurons from 10, the tracking performance is decreased and the error may go beyond the bounded value.

4 Simulation Results.

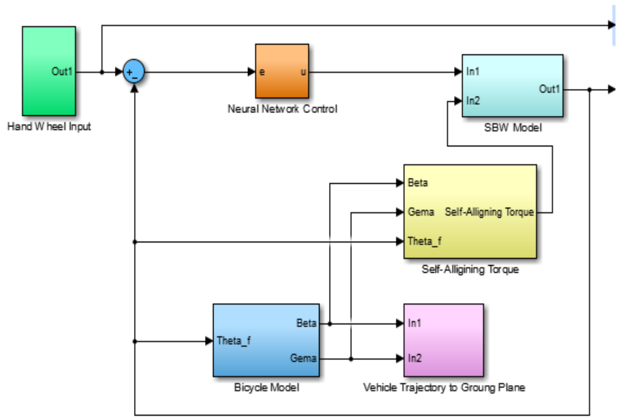

Fig. 4 Simulink Model.

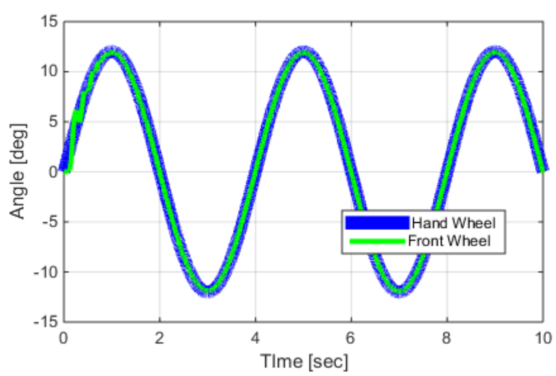

Fig. 5 Hand wheel input angle and output front wheels angle

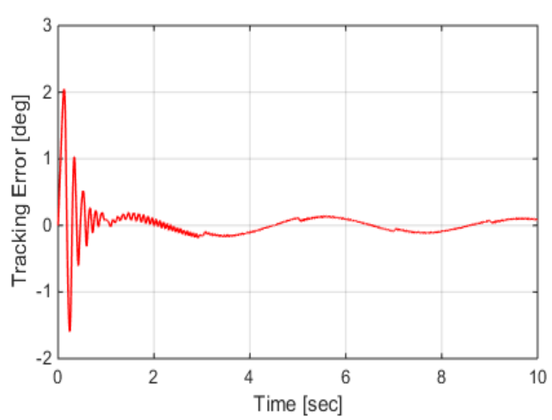

Fig. 6 Tracking error

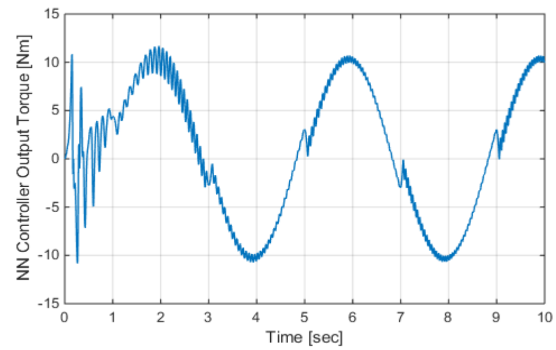

Fig. 7 NN Controller output Torque

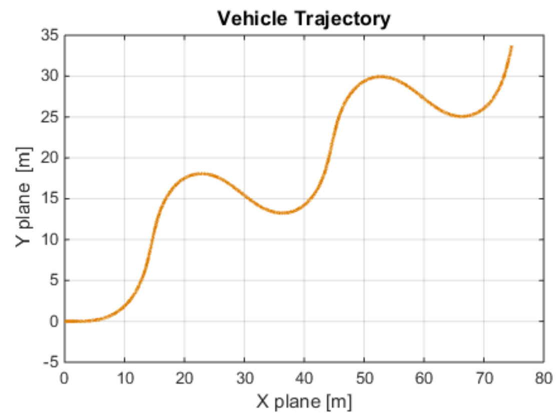

Fig. 8 Vehicle trajectory on XY plane.

$$\delta_d = 12\sin(0.5\pi t) \qquad (18)$$

The NN based controller is simulated in Matlab/Simulink as shown in Fig 4. In the beginning of simulation there are small oscillations in tracking reference angle but after the few seconds the system start learning and oscillations are compensated as shown in Fig 5.

Fig 6 show that there is small tracking error remains in the system which afterwards bounded to ± 0.25 deg . Fig 7 shows NN controller output which represents small amount of chattering during the tracking the desired output but system cannot exceed the bound limits. And Fig 8 shows the vehicle trajectory in XY plane.

5 Conclusion

However this paper represents the effectiveness of the NN based controller for tracking the desired hand-wheel angle in steer by wire system vehicles. The error remains within the specified bound. Further improvement can be made in designing the controller for reducing chattering in output torque and in reducing the tracking error bound.

References:

[1] C.-J. Kim, J.-H. Jang, S.-K. Oh, J.-Y. Lee, C.-S. Han, and J. K. Hedrick, “Development of a control algorithm for a rack-actuating steer-by-wire system using road information feedback,” *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 222, no. 9, pp. 1559–1571, Sep. 2008.

[2] C.-J. Kim, J.-H. Jang, S.-N. Yu, S.-H. Lee, C.-S. Han, and J. K. Hedrick, “Development of a control algorithm for a tie-rod-actuating steer-by-wire system,” *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 222, no. 9, pp. 1543–1557, Sep. 2008.

[3] H. Wang, H. Kong, Z. Man, D. Tuan, Z. Cao, and W. Shen, “Sliding mode control for steer-by-wire systems with AC motors in road vehicles,” *IEEE Trans. Ind. Electron.*, vol. 61, no. 3, pp. 1596–1611, Mar. 2014.

[4] M. Do, Z. Man, and C. Zhang, “Robust sliding mode based learning control for steer-by-wire systems in modern vehicles,” *IEEE Trans. Veh. …*, vol. 63, no. 2, pp. 580–590, Feb. 2014.

[5] S. Anwar and L. Chen, “An Analytical Redundancy-Based Fault Detection and Isolation Algorithm for a Road-Wheel Control Subsystem in a Steer-By-Wire System,” *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2859–2869, Sep. 2007.

[6] C. Altemare and S. Anwar, “Fault tolerant steer-by-wire road wheel control system,” in *Proceedings of the 2005, American Control Conference, 2005.*, 2005, pp. 1619–1624.

[7] M. Bertoluzzo, G. Buja, and R. Menis, “Control schemes for steer-by-wire systems,” *Ind. Electron. Mag. …*, 2007.

[8] P. Yih and J. Gerdes, “Modification of vehicle handling characteristics via steer-by-wire,” *Control Syst. Technol. IEEE …*, vol. 13, no. 6, pp. 965–976, 2005.

[9] N. Daher and M. Ivantysynova, “An Indirect Adaptive Velocity Controller for a Novel Steer-by-Wire System,” *J. Dyn. Syst. Meas. Control*, vol. 136, no. 5, p. 051012, Jun. 2014.

[10] J. Ye, “Tracking control of a nonholonomic mobile robot using compound cosine function neural networks,” *Intell. Serv. Robot.*, vol. 6, pp. 191–198, 2013.