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Controller Design for Steer-by-Wire System

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Abstract: This study would address the suitability, adaptability and the efficiency of the electronically - controlled Steer-by-Wire (SbW) technology. Future steering technology heading for a fault tolerant and fail-safe steering system with enviable recoverability; electronically - controlled SbW with a back-up would be the best option to meet these demands. With mechanical connections between the hand wheel and front axle gradually phasing out, Moreover, ILC and PID controllers designed for control steering angle and enhance the vehicle performance. PID parameters obtained using Particle Swab Optimization (PSO). Matlab/Simulink used for simulation and controller design tuning. There was moderate correlation of the Matlab/Simulink and theoretical results.

Keywords: Steer - by - Wire System, Steering Angle, PID Controller, ILC Controller

Introduction

Vehicle technology has rapidly developed and its merit and performance have been fast improved over the era. The steering mechanics that communicate the drivers' steering directions to the vehicle have gone through numerous stages of innovation, with a trend toward a pure electronic system (Mortazavizadeh *et al*., 2020). The control system for vehicles is an important part for being substituted by electrical sensors and actuators with the aim of improved the system performance (Mortazavizadeh, 2020). There have been many proposals with the intent of advancing steering systems. Vehicles produced by well-known vehicles companies, majority of front-wheel driving vehicles with heavy front-wheel load employing hydraulic power steering system are behind the use of intelligent electronic controls (Huang *et al*., 2020). In hydraulic power steering systems, the assist force to the steering angle which is a basic characteristic is generally determined by the mechanical position of the hole of the rotary valve shaft relative to the position of the groove located on the inner surface of the housing, making it difficult to obtain desired characteristics. Even when electronic control is used, only the degree of steering feel is improved by changing hydraulic characteristics according to vehicle speed. In either case, it is very difficult to change steering angle to the input of steering wheel angle. Changing steering angle according to steering wheel input in addition to assist steering force would result in lateral movement to its driving direction, so that the vehicle will need to identify its surrounded driving environment. This explains why it has taken such a long time to achieve the use of intelligent functions higher than that of the power steering system (Abe, 2015). Emhemed (2013) explained that GUI and simulation results using fuzzy controller controlled the wheels angle velocity and ultrasonic sensor used to detect the obstacles and distances so that shows the similarity of the behavior in the motion in the desired input and the measured output are achieved with limited error errors during the time. Furthermore, fuzzy controller controlled the industrial motor. The Industrial Motor model developed using its physical parameters and controlled with an AI controller give better response, it means it can used as a controller to the real time Motor (Emhemed and Mamat, 2012). Vehicles require tracking control to achieve the proper steering angle. In autonomous vehicles using Electric Power Steering (EPS) or (SbW) systems, the steering angle control via the steering actuator is researched. Active Disturbance Rejection Control (ADRC) is used to estimate the tyre self-aligning moment and calculate the steering torque based on the study of the nominal model. The proposed steering angle controller is then tested using numerical simulations (Xiong *et al*., 2018). The steering robustness of SbW systems against parameter changes, external disturbances and changes in road conditions is one of the primary issues. Because even a slight movement of the wheels causes a significant change in the vehicle's motion, steering angle control performance necessitates excellent accuracy (Hwang *et al*., 2019). ILC has been successfully applied to many in-industrial areas, such as robot manipulators (Kuc *et al*., 1991). However, the application of ILC controller to SbW systems is still rare, which accordingly support us to investigate the ILC technique for a SbW system to achieve good performance and steering tracking accuracy. PID control has been used in many automation systems such as in Mobile Robots (Emhemed *et al*., 2013); control of SbW system (Xu *et al*., 2019) and hydraulic quadruped robot (Chang *et al*., 2014). Some of these explanations are used in designing PID controller for SbW System. There is no need to make complex mathematical formulas for PID controller because of its simple formula that has complete features and automatically calculates the control signal output based on the parameters entered. Also, PID control is gives effective and improved results, especially if tuned by PSO. For that PSO-PID integrated controller is used in this study with comparison to Iterative Learning Control (ILC) control. The goal of this study is to create a simulation for controlling the steering angle of a SbW system. The following are the main points: Following that, the SbW challenges that have been noticed thus far are explained and the SbW control challenges are presented in the first section. The model of the SbW system is explained and the identification is described in the second section. In the third section, various control algorithms appropriate for SbW implementation are detailed. Based on the simulation findings, the results, comments and potential applications for each controller method are studied and discussed. Finally, the designed controllers-based steering plant with tracking trajectory conclusions are provided.

Modeling and Identification of Steering System

In many previous studies of vehicle handling behaviour, the steering handling dynamics were not considered instead, the front wheel steer angle has been considered as an external input to the vehicle (Doumiati, *et al*., 2013). While such a representation may be of use in examining basic stability issues, in the study of more general handling matters, the simple model is of little value as it can provide only limited information with respect to the driver's reference; i,e the hand wheel input. This is because the simple model is misrepresentative in that it ignores the effect of potentially substantial compliance which typically exists in a steering system. The SbW dynamic model establishes the relationship between the steering mechanism, the electrodynamics of the motor and the rack-and-pinion interaction torque. Figure 1 presents a model of a steering mechanism with a DC motor actuator.

A more useful model system for directing compliance with the steering column and the steering linkages. But, compliance Torsion bar is much more important than any other system in compliance with the steering system and that can be dealt with as a major factor in the modelling. Inputs to the steering wheel hence steering angle road wheels and become another degree of freedom (Sun *et al*., 2017; Pfeffer *et al*., 2008).

The plant model of the SbW system is (Sun, 2017):

$$J\ddot{x} + C\dot{x} + \rho sign(\dot{x}) + \xi \tanh(x) = bu \qquad (1)$$

where, $c = c_o + \varDelta_c$ and $J = J_o + \Delta J°$ Thus, we can rewrite it into following form:

$$J_\circ \ddot{x} + C_\circ \dot{x} + \rho\left[\Delta_\mathrm{I}\ddot{x} + \Delta_c\dot{x} + \rho\sin(\dot{x}) + \xi\tanh(x)\right] = bu \qquad (2)$$

where, J is the equivalent moment of inertia and c is the equivalent viscous friction of the steering system; ρ is the Coulomb friction constant; and sign() is the standard signum function. $\tau = \xi\tanh(x)$ Denotes that τ is the self-aligning torque exerted on the front wheels, in which ξ is the coefficient of the self-aligning torque with respect to road conditions and tanh() is hyperbolic tangent function; b is the scaling factor; u is the steering motor input voltage; J_o and C_o are the nominal parameters in the SbW model.

By treating the impact of the system uncertainties $\Delta_I\ddot{x}+\Delta_c\dot{x}$ the self-aligning torque and the Coulomb friction as external disturbances to the steering system and ignoring them temporarily, we have a simplified linear second-order differential equation:

$$J_o\ddot{X} + C_o = bu \qquad (3)$$

Thus, the corresponding transfer function for the SbW model is (Sun *et al*., 2017):

$$\frac{X(s)}{U(s)} = \frac{b}{J_o^{\,s2} + c_o^{\,s}} \qquad (4)$$

where: $X(s)$ is the steering angle of front wheels which is the Laplace transformation of x, $U(s)$ is the steering motor input voltage which is the Laplace transformation of u.Then, using the values of the parameters of b = 237.5, J_o + = 85.5c_o and = 218.8 (Sun *et al*., 2017).

Many of the detailed mathematical models developed for the steering system. The dynamics of a test based on a particular SbW system are often represented by a simple quadratic model. Results it also shows the dynamics of the individual components compared to the dynamics of the entire steering system. Usually a set of input steering systems. Keep in mind that these results may not be the true steering system of all operating systems, or torque limits depending on the situation. It's a more complex model, but it may be necessary in such cases. Ignoring the tyre force and then the transfer function describes the steering system dynamics as the previous described second order system. They steering wheel angle versus lateral acceleration characteristics; steering wheel torque versus angle characteristics wheel steering system; and work gradient versus lateral acceleration characteristics. Because the restorative torque depends on the slip angle of the front tyres, the weighing function is approximated as a function of the slip angle. Figure 2 shows the mesh shape of the Torque for steering motor control related with angle and vehicle speed.

Controller Design

Controllers have survived many changes in technology, from mechanics and pneumatics to microprocessors via electronic tubes. Control performance steering system, in the sense of self that could arise as a result of driver it is normal steering inputs tend to be smooth and continuous, but can vary greatly in the rate, so an important criterion for a steering Control is that it must be followed rapidly with a minimum of input delay. The system front wheels raised from the ground Temporarily to remove the impact of the wheel forces, With any forces tyres. To lead and steer the angle based the input reference to the closed loop system with stability behaviour is needed.

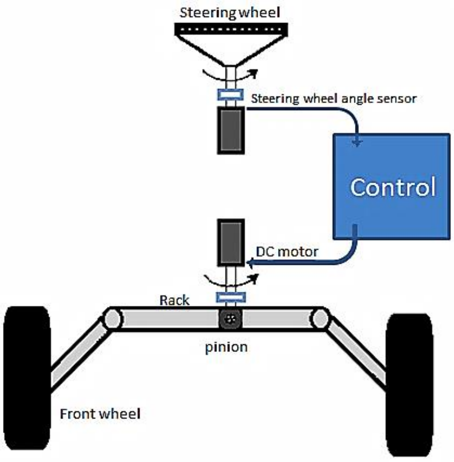
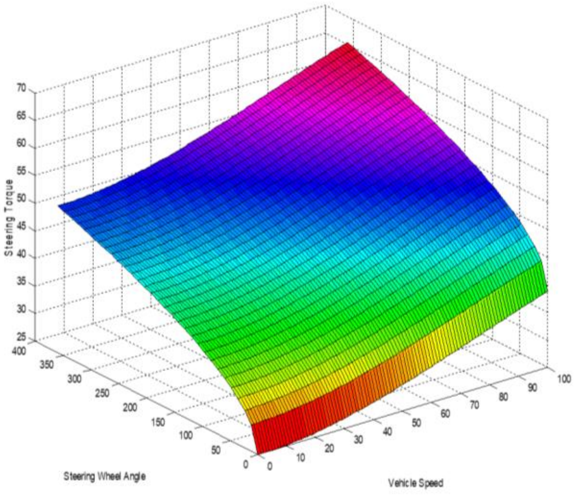
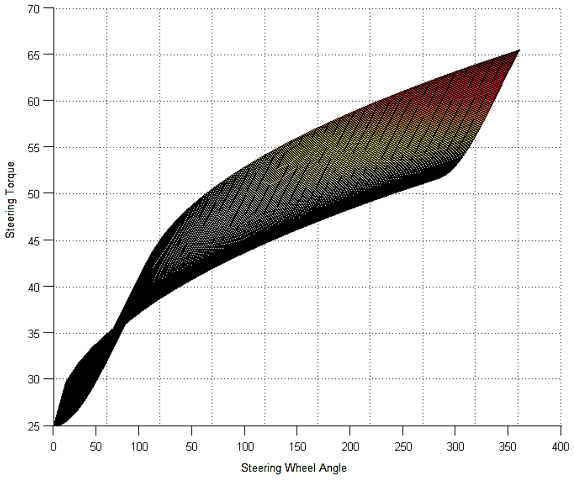


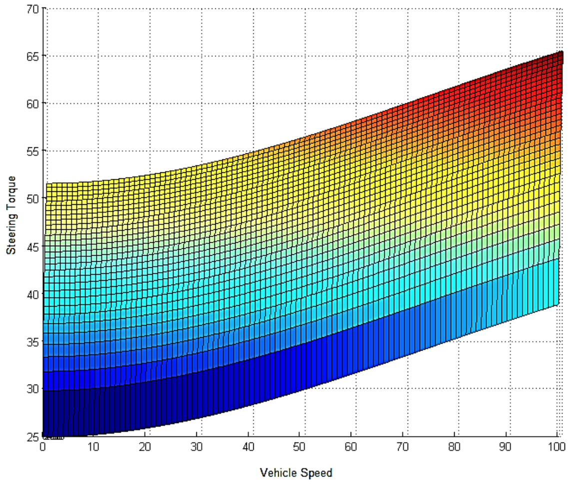
Fig. 1: Structure of Steer-by-Wire system (Mohamed and Albatlan, 2014)



(a)



(b)



(c)

Fig. 2: Torque for steering motor control related with angle and vehicle speed

Iterative Learning Control (ILC)

Iterative Learning Control (ILC) was originally introduced by Arimoto (1984). The objective of ILC is to utilize the repetitive nature of the process and the past control information to alter the shape of demand profile such that the high-precision motion tracking can be achieved.

ILC algorithm can be written as (Xu *et al*., 2012):

$$K(s)=Q(s)+\mu L(s)Q(s)e(s) \tag{5}$$

where, $Q(s)$ is a low-pass filter and $L(s)$ is learning filter; μ is the learning gain; The low-pass filter $Q(s)$ can be selected as follow:

$$Q(s)=\frac{1}{0.016s+1} \tag{6}$$

The learning filter $L(s)$ can be selected as follow:

$$L(s) = \frac{4s^2 + 3912s + 710600}{s^2 + 1565s + 710900} \tag{7}$$

The learning gain $\mu = 0.65$

Proportional Integral Derivative (PID) Control

PSO is one of the optimization techniques that used to optimally tuned parameters of the controllers such as PID control, MPC and so on.

This technique is considered to be most promising optimization technique due to its simplicity, robustness and ease of implementation (Kennedy and Eberhart, 1995).

In this section, the PSO algorithm was applied to optimize unknown main parameters of PID controller (P-I&D). Roughly, Proportional (P) action is related to the present error, Integral (I) action is based on the past history of error and Derivative (D) action is related to the future behaviour of the error.

PID controllers are widely used robotics, automation systems and industrial processes. Theses controllers are simple to design and have been proven to be robust. Also, simple and stable for many real world applications. The equation of PID controller is given by the following form:

$$K(s) = P + I\frac{1}{s} + D\frac{N}{1 + N\frac{1}{s}} \tag{8}$$

Proportional control P will have the effect of reducing the rise time and will reduce but never eliminate the steady-state error. An integral control I will have the effect of eliminating the steady-state error. Derivative control D action is reduced the overshoot and settling time. N is the filter coefficient.

$$p = 34 I = 26.5 D = 0.2 N = 10120$$

Results and Discussion

The models used in this study can be helpful to predict the vehicle responses and steering feel before the production of the prototype car. It was then proceeded by studying the current literature available in this area of work and highlighting the important ones to understand what advancements have been made in this particular field and methods adopted to the SbW system.

In this section, we introduce the simulation effect based SbW system to validate the performance of the controllers schemes, results were performed on the overall output and tracking error signals as shown in the following figures. SbW system requires model uncertainty and robustness against external chaos. Sine-wave signal and multistep signal were chosen as test signals to validate the transient tracking ability of the controllers. The tracking performance indicates that PSO-PID controller is more capable than ILC controller of tracking transient signal. Sine-wave signal used as reference steering angle and it confirms that the designed controllers are an effective ways to track the reference steering angle with different results and observations. PSO-PID controller compensates the delay part of the time-delay that happened by ILC controller as shown in Fig. 3. ILC controller demands that must have more accuracy for the output behaviour. May more tuning is needed for control design where observed that can't achieve the ideal control effect by ILC. Therefore, PSO-PID controller is needed and designed to decrease the tracking error and to achieve good control effect as shown in Fig. 4.

For controller plan utilizing optimization strategies, the objective work for that depending on some performance criteria such as Integral of Time multiplied Absolute Error (ITAE), Integral of Absolute Error (IAE), Integral of Squared Error (ISE).

Is specified. We find that the PSO-PID controller is far superior to the ILC controller in terms of steering angle simulation and sinusoidal tracking error performance criteria. The controller for this task provides good steering operation with relatively little control effort and eliminates errors as shown in Table 1.

Multistep signal test for validate the controllers effect and observation of the results. The multistep response shows that PSO-PID controller steering performance can track the desired steering angle at high speeds and with small errors, as shown in Fig. 5 and 6. You can see that the average steady state error is much lower than that of the ILC controller and that is clear in tracking error performance criteria at Table 2. The overshoot and rise time are decreased based on PSO-PID controller as shown in Table 3.

Table 1: Sine-wave tracking error performance criteria

Controller type	Error value ITAE	IAE	ISE
ILC	1.064	0.212	0.005403
PSO-PID	0.236	0.046	0.000263

Table 2: Multi-step tracking error performance criteria

Controller type	Error value ITAE	IAE	ISE
ILC	1.516	0.3033	0.03388
PSO-PID	0.301	0.0601	0.00627

Table 3: Multi-step performance analysis at staring pulse

Controller type	Overshoot %	Settling Time (sec)	Rise time (sec)
ILC	11%	0.52	0.21
PSO-PID	3%	0.19	0.06

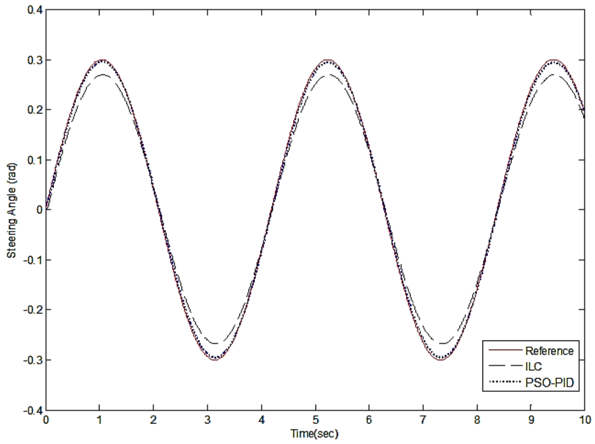


Fig. 3: Sine-wave simulated steering angle output performance based ILC and PSO-PID controller

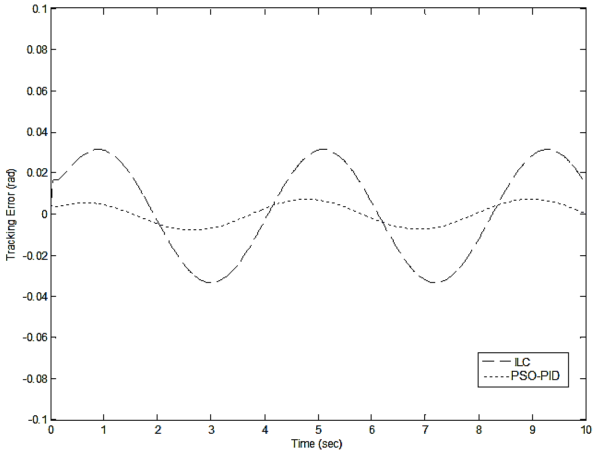


Fig. 4: Sine-wave simulated steering angle tracking output error performance based ILC and PSO-PID controller

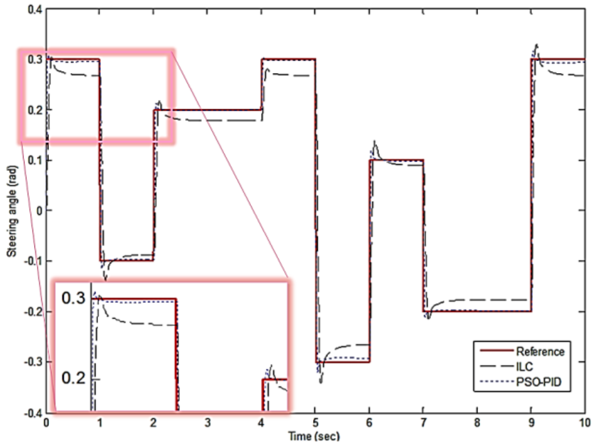


Fig. 5: Multi-step simulated steering angle output performance based ILC and PSO-PID controller

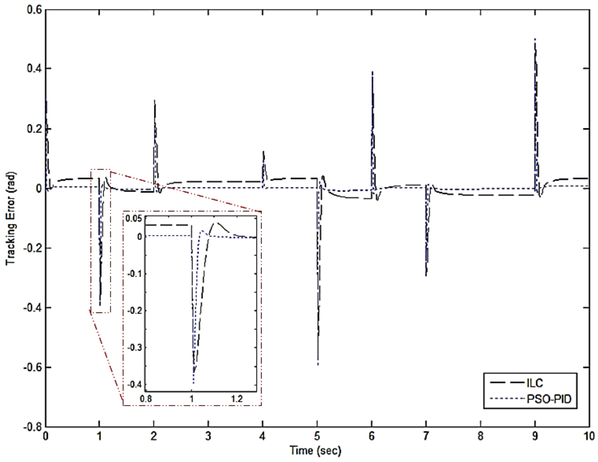


Fig. 6: Multi-step simulated steering angle tracking output error performance based ILC and PSO-PID controller

Conclusion

In this study control design for SbW system is suggested, investigated the advantages and disadvantages of different controllers with different input signals (Sine-wave and Multi-step) for steering angle of SbW system. The controllers are ILC control and tuning method for PID control by PSO is suggested. This algorithm uses PSO-PID control to improve the resistance ability to overcome the time-delay character of controlled object. PID controller parameters are tuned with PSO technology. PSO-PID proves that the best system performance is achieved with a great results based the SbW system. Finally, the desired input tested in two cases sine-wave signal and multi-step signal were applied and the results were found to be quite satisfactory with PSO-PID. It is found that improved system response is obtained with PSO-PID controller better than ILC controller. Simulation results show a superior response performance with PSO-PID algorithm. Moreover, the response behavior and robustness performed on the PSO-PID controller showed more stability and better performance characteristics than the ILC controllers for both tested input signals.

Future Work

As future work it is suggested that the developed the simulation model that can be linked to a virtual environment (real time), where the SbW system could be simulated. The entire vehicle dynamics and controller design and communication lines could be incorporated and the actual behavior of a vehicle as it would be in real world can be simulated.

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Author's Contributions

Salahaddin M. Sahboun: Research methodology, technical writing, organized the study and supervision. Also, he has simulated of mesh shape of the Torque for steering motor control related with angle and vehicle speed.

Abdulrahman A. A. Emhemed: Designed of the controllers: Iterative Learning Control (ILC) and the PSO-PID controller for SBW and programmed using Matlab and analyzed the results.

Ethics

This article is original and contains unpublished material. Authors declare that are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

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