Research on the PID control of the ESP system of tractor based on improved AFSA and improved SA

Zhun Cheng, Zhixiong Lu⁎

College of Engineering, Nanjing Agricultural University, Nanjing 210031, China

A R T I C L E   I N F O

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A B S T R A C T

The paper uses the electronic stability program (ESP) on tractors in order to improve their trafficability and steering stability. The paper builds a full-tractor model with an ESP system, as well as a steering-by-wire system based on Matlab and Carsim with the aim to research and improve the ESP system’s control performance. The paper investigated the optimization and the setting method of the PID control parameters. The paper applied the speed and the position update mode of the particle swarm optimization (PSO), the probability judgment Metropolis rule of simulated annealing algorithm (SA), the non-uniform mutation idea of genetic algorithm (GA), and the custom initial swarm implantation method into the artificial fish swarm algorithm (AFSA) in order to improve the AFSA. This paper proposes a new method based on the improved AFSA and the improved SA that would simulate the artificial setting of the PID parameters. This method alters the concurrent optimization process of the PID parameters into a process that is initially serial and then becomes concurrent. The new method is then compared with the parameter setting methods based standard AFSA and the improved AFSA. The comparison results showed that the improved AFSA had a faster rate of convergence and a better precision of optimization. The new setting method for the PID parameters improved the PID’s control result more effectively and enabled a tractor with an ESP system to change directions at the expected yaw velocity.

1. Introduction

The ESP (electronic stability program) is an active safety system developed on the basis of ABS (anti-skid brake system) and ASR (acceleration slip regulation), where it has been widely applied in vehicles (Kim and Kim, 2006; Chu et al., 2012). The coupling dynamics relationship between EPS (electric power steering) and ESP of vehicles were used by Cheng et al. (2015) to propose the coordination control strategy based on the function allocation. Their results show that the strategy effectively improves the driving safety and the stability of vehicles. Zhang and Li (2015) identified the unknown characteristic parameters of the ESP hydraulic system model via the genetic algorithm, with reference test data that was recorded in a real vehicle test environment. Fu et al. (2014) explored and researched the ABS, ASR, and ESP systems of vehicles, based on the 9-DOF dynamical model of car, where an integrated control strategy was proposed. The majority of research on the ESP fails to focus on engineering vehicles, such as tractors.

When a car is being steered towards a specific direction on hard pavement with good road conditions there generally will not be dangerous instances, such as off tracking, drift, rollover or sideslip when the vehicle’s speed is slow. The ESP system would stabilize the car body when the car makes a high-speed turn. A tractor’s speed in field operation is normally slower than 30 km/h. There is little research on the ESP system of tractors, even though non-road vehicles, like tractors, often serve in the field or are operated on the road. Pavement conditions are complicated, so a tractor often suffers from slipping of the steering wheel during speeding up or has bigger or smaller yaw velocities during direction changes. The tractor cannot run along the path dictated by the driver. In addition, the tractors’ maximum running speed during transportation operation on the road has steadily increased, where some tractor speeds have exceeded 60 km/h.

During field farming, tractors are steered to another direction on the edge of field. The tractors enter the next operation line through field edge steering, so the step is integral for tractors and other agricultural machinery within field operations. Soft-soil roads have complicated pavement conditions, and tractors suffer a large steering resistance during direction changes. These two factors affect the steering performance, reduce the operation accuracy, and increase the time needed for the field edge steering. Research regarding reducing the minimum turning radius, increase the trafficability, and improving the steering stability of tractors remains significant.

⁎ Corresponding author at: College of Engineering, Nanjing Agricultural University, 40 Dianjiangtai Road, Nanjing 210031, China.
E-mail address: 1003765165@qq.com (Z. Lu).

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Zhang et al. (2015) designed a fuzzy controller of a full-hydraulic steering system in tractors using the variable universe, where the steering performance was improved to some extent. Fang et al. (2017) designed a drive-by-wire steering system and successfully installed it on a tractor to make a real vehicle test. The test results showed a good steering performance. Cao et al. (2016) analyzed the steering performance of a half-suspension combined cultivating unit and obtained the minimum turn radius of the unit. The research failed to explore and analyze the steering performance of tractors on a road that has a poor adhesion coefficient, in so failing to improve the steering performance of tractors actively during the running of tractors. This does not enable tractors to turn directions at the yaw velocity expected by the driver and thus does not improve the passage performance of tractors.

The working principles of ESP system states that theoretically, installing an ESP system in a tractor would enhance the passage performance of the tractor and improve the steering stability of tractor. The slip rate $s$ is associated with the lateral & longitudinal road adhesion coefficient $\mu$, and the different pavements correspond to different $\mu-s$ curves. When a vehicle is running on pavement, the ESP controls the right and the left driving wheels to maintain the slip rate within the ideal range, which ensures that the vehicle runs along the ideal track when changing directions (Yim et al., 2010, 2012; Yan and Xie, 2014; Wang et al., 2011; Wang and Song, 2007). The proper use of the ESP system within the transportation operation of tractors could improve the steering stability and running safety. The proper use of the ESP system within the tractor farming could effectively reduce the minimum turning radius. The proper use of the ESP system helps to properly determine the field operation path of the tractor and also offers a high line operation accuracy to the tractor during field edge steering, which saves farming time. The ESP system is important for improving the passage performance, the steering stability, and the work efficiency of the tractor.

The most common dynamical models are generally based on many hypotheses and simplifications. There has been little research regarding the multi-body dynamics of the tractor. The tractor running simulation experiment based on the ESP system it met with complicated operational conditions.

The PID control is a common control method used in engineering (Summu et al., 2017; Alkamachi and Ercelebi, 2017). Most researchers use the empirical method or the heuristic-based intelligent optimization algorithm to improve the control performance of the PID and optimize the PID parameters (Wang et al., 2017; Odili et al., 2017). Although the PID control result significantly improves after parameter optimization, it cannot ensure the parameters remain within their optimal values.

The following paper aims to solve the problems outlined above. The paper builds a full-tractor motion simulation model with a steer-by-wire system based on Carsim and Matlab/Simulink. The tractor model with an ESP system and a steer-by-wire system was simulated in poor pavement conditions in order to compressively explore the full-tractor information and improve the freedom degree and the simulation precision. The AFSA has a strong capability for global optimization and the characteristics of distributed processing, as well as a good robustness of parameters & initial values (Duan et al., 2013, 2016; Wu, 2015). The paper improves the AFSA and highlighted the advantages of the improved AFSA by obtaining the maximum of a function. The design of the PID controller was combined with the improved AFSA and the improved SA in order to propose a new method that simulates the artificial setting of the PID control parameters and compares the parameter setting result of the new method with the results from the conventional AFSA and the improved AFSA. The comparison results showed that the tractor with an ESP system changed directions at the expected yaw velocity on poor pavements. The improved AFSA proposed in the paper improved the rate of convergence and precision effectively. The new PID parameter setting method proposed could improve the control performance of ESP system more effectively.

### 2. Full-tractor simulation model

The Carsim is the mature commercial software that offers stable operational performance, high simulation precision, and high freedom degrees. The software has models of various types of vehicles including tractors and has the complete driver model. This software is suitable for simulation experiments on the user-customized closed-loop system (Xiong et al., 2014). Most OEM users believe that the simulation results of the software are consistent with the experimental results of real vehicles. Some tractor parameters that used in the simulation experiment are based on the JS-754 tractor (Cheng et al., 2016). The tractor parameters are shown in Table 1.

We chose the magic formula model for the tire model (Vijay Alagappan et al., 2015). The universal formula of lateral & longitudinal force of driving wheel $Y(x)$ is as follows:

$$Y(x) = D \sin[\arctan(\mu - \arctan(\mu))]$$

$$y(x) = Y(x) + S_y$$

$$x = X + S_t$$

where $Y$ represents the theoretical lateral or the longitudinal force of the tire, $y$ represents the real lateral or the longitudinal force of the tire. $x$ represents the real slip rate. $X$ represents the theoretical slip rate. The parameters $B, C, D, E, S_y, S_t$ represent the rigidity factor, the shape factor, the peak factor, the curvature factor, the horizontal displacement, and the vertical displacement.

The parameters of the magic formula model that were used in the paper come from a reference document (Cheng and Lu, 2017).

The paper built a tractor steering-by-wire system based on Matlab/Simulink. We only selected the parts that played important roles in order to improve the precision of the model (Shi et al., 2007). The mathematical models and the main parameters used in the paper were taken from a reference document (Tang, 2011). The steering wheel model was primarily composed of the end of the steering column and the road-feeling motor through reduction gear engagement. The steering actuator is simplified to be the gear & rack component and the steering front wheel component. The road-feeling motor and the steering motor are found all DC motors.

The yaw velocity was a control variable, where the ESP system built a PID controller and adjusted the yawing moment by controlling the sliding rates of the left and right driving wheels. The tractor’s steering-by-wire model, the pavement model, and the PID controller were built in Matlab/Simulink, but the full-tractor dynamic model was built in Carsim. The steering-by-wire model was used to output the angle of steering wheel. The pavement model offered the lateral and the longitudinal adhesion coefficients of the left and right driving wheels. The PID controller adjusted the driving force of the left and right driving wheels. The seven variables output by Matlab/Simulink included the angle of steering wheel, the longitudinal adhesion coefficients of the left and right driving wheels, and the lateral adhesion coefficients of the left and right driving wheels. The driving force of left and right driving wheels was input into the Carsim module during the simulation experiment.

<table>
<thead>
<tr>
<th>Full-tractor parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-tractor mass (kg)</td>
<td>2935</td>
</tr>
<tr>
<td>Mass of people-seat system (kg)</td>
<td>65</td>
</tr>
<tr>
<td>Full-tractor rotational inertia around center of mass (kg·m²)</td>
<td>3547.2</td>
</tr>
<tr>
<td>Distance from center of mass to front axle (m)</td>
<td>1.315</td>
</tr>
<tr>
<td>Distance from center of mass to rear axle (m)</td>
<td>0.8</td>
</tr>
<tr>
<td>Height of front wheel (m)</td>
<td>0.545</td>
</tr>
<tr>
<td>Height of rear wheel (m)</td>
<td>0.745</td>
</tr>
<tr>
<td>Driving wheel rotational inertia around center of mass (kg·m²)</td>
<td>855.6</td>
</tr>
</tbody>
</table>
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