PID Controller for A Bearing Angle Control in Self-Driving Vehicles

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Abstract—**The enhancement of self-driving vehicles has the potential to disrupt traditional transportation systems, Utilizing progress in secure and intelligent mobility. However, control of movement in self-driving vehicles is still difficult to carry out driving duties in a constantly changing road environment. The regulation of bearing angle is an essential component in self-driving vehicles navigation systems, facilitating the secure and efficient operation of vehicles across a range of environments, including urban streets, highways, and off-road terrain. It employs algorithms and sensor fusion to perceive surroundings, compute trajectories, and execute precise steering commands. The bearing angle represents the angle between the vehicle's current and desired directions. By consistently monitoring this angle and implementing appropriate steering inputs, the self-driving vehicle can accurately stay on track and proactively adapt to obstacles or adhere to a designated route. In this context, we explore the advancements in bearing angle control methods for self-driving vehicles. By conducting simulations of a simplified block diagram for a self-guiding vehicle's bearing angle control techniques, the efficacy of the steering system of self-driving cars has been briefly examined. We provide various methods of control, which are considered approaches for controlling the angle of bearings through lag lead compensation and PID auto-tuned controllers. The results show that the auto-tuned PID controller outperforms all other controllers in terms of transient and steady-state responses.**

Keywords—Bearing Angle; Closed-Loop Control; Lag-Lead Compensation; PID Controller; Self-Driving Vehicles; Controller Design; Simulation.

I. INTRODUCTION

Self-driving vehicles are currently a viral subject of research. The development of self-driving technology has been ongoing for several decades and holds significant potential to revolutionize traditional transportation systems. Technological advancements have experienced a significant surge in recent years. As a result, the computational capacity of self-driving vehicles has grown while the time required for sensing and computing has decreased [1]-[4]. Self-driving vehicles must possess comprehension and establish collaboration with critical functionalities, including perception, mapping, trajectory generation, localization, and and the option to regulate autonomous driving [5][6]. Due to the rapid progress in sensing and computational technologies, these developments are amplified, so it is essential to consider their potential influence on societal trends. Based on recent data provided by the World Health Organization [7][8], Every year, approximately 1.35 million individuals lose their lives in road accidents worldwide. Of these, 94% of road crashes are caused by human drivers' negligence, particularly speeding and driving under the influence [9]-[10]. Self-driving technology is regarded as a solution for decreasing road collisions and offering convenient and cost-effective transportation services to passengers [11][12]. The efficiencies stem from the ample possibilities for leisure, practical fuel usage, improved throughput, and optimal motion planning along predetermined routes [13][14].

Many control laws in the literature have assumed the measurability of relative positions or distances between agents to achieve target formations (see [15]-[20]). However, it can be challenging to fulfil this assumption, especially without an external localization system [21]. There has been a recent increase in interest regarding the proposed bearing-only control laws (refer to [22]-[27]). Formations targeted in bearing-only control laws cannot be achieved through relative positions and distances. However, relative bearings obtained from vision sensors [28] or wireless sensor arrays [29] can be utilized. Because relative bearings are easily accessible, control laws that rely solely on bearing information offer possible solutions for achieving formation control using only onboard sensors.

Autonomous vehicle control and navigation systems face a significant challenge in following the reference trajectory. Considering its motion limitations, the trajectory tracking system generates control commands for the autonomous vehicle's predefined path. Various techniques for monitoring trajectories are available in the literature. There are three categories of path tracking methods: geometric approaches like pure pursuit, optimum control-based methods including LQR and optimal preview control, and model-based methods such as PID, MPC, sliding mode control, and fuzzy logic controller. This portion extensively discusses evaluating various path-tracking algorithms currently undergoing comprehensive testing for trajectory tracking in autonomous vehicles. Path tracking in autonomous vehicles is achieved using several geometric and kinematic controllers [30]. At every time step, the pure pursuit algorithm computes the autonomous vehicle's steering angle (δ) by calculating the look-ahead distance along the reference trajectory [31]. The Stanley is an additional geometric steering controller that is highly efficient. This controller does not need a look-ahead distance as it considers the autonomous vehicle's dynamics model and instantaneous velocity [32]. The DARPA Grand Challenge of 2005 was won by the Stanley controller, which was developed by the Stanford University team. Based on lateral errors [33], the front wheel axle of the vehicle calculates the steering command using a non-linear feedback function. The combination of braking and steering is controlled using a non-linear model predictive control (NMPC) technique on two distinct vehicles [34]. In [35], a novel algorithm for real-time trajectory tracking MPC, specifically designed for autonomous vehicles operating at low speeds, is introduced. A new model predictive control (MPC) method was proposed in reference [36] for accurately tracking high-speed vehicle paths. The method incorporates a tire slip angle constraint to control the front steering angle effectively, enabling the vehicle to follow a desired path even on slippery roads.

Most path-tracking controllers encounter issues when the self-driving vehicle encounters a sharp curve in the reference path [37][38]. Not properly adjusting the speed and steering angle for the vehicle can make driving through a sharp curve highly dangerous. When it comes to driving in real life, if a driver wants to navigate a sharp curve without any issues, they need to be able to lower their speed and handle the steering wheel simultaneously. Autonomous vehicles should employ a similar principle when following a reference trajectory. This study investigates the design of various bearing angle control systems using lag lead compensation and auto-tuned PID controllers.

The conventional method for developing and evaluating a controller for bearing angle control in self-driving vehicles causes the completion of several crucial steps: i) Define the problem. ii) Modeling and Simulation. iii) Controller Design. iv) Implementation. v) Evaluation and Verification. vi) Tuning and Optimization. vii) Integration and Deployment.

Compliance with best practices is crucial for achieving reliability, scalability, and safety in the controller for self-driving vehicle bearing angle control. Efficient self-driving vehicle controllers require concert among engineers, researchers, and domain experts.

II. Literature Review and Problem Statement

Control theory and techniques have been extensively studied for path tracking. PID-based control approaches have gained significant traction regarding steering control in autonomous vehicles. The use of PID controllers in self-driving cars is more straightforward and more robust for steering control when compared to the techniques mentioned earlier. Conventional PID controllers do not adequately address parameter optimization, cannot adapt to external environmental disturbances, and are excessively intensive when steering control on dynamic roads. The authors Baskaran et al. [39] have suggested using a PID controller to effectively manage the steering control of self-driving cars. By adjusting the voltage in the brake and throttle modules, this can be achieved. In another academic paper, Zhao and colleagues [40] introduced an adaptive PID controller for intelligent pioneer autonomous vehicles (AVs). The purpose of developing this controller was to address the difficulties of navigating and maintaining stability while following a desired path in unfamiliar surroundings. In order to decrease computational complexity, Yin et al. [41] put forward the idea of utilizing a fuzzy-PID controller for steering control in a rice transplanter. Immediate modification of control parameters is possible with this controller, allowing for optimal steering angle. Chen et al. [42] demonstrated an adaptive fuzzy-PID-based controller for EVs with 4WIS. By examining the four-wheel steering mechanism, the authors obtained a correlation between the s's zero-centroid angle. The findings highlight the need to study the proposed controller for regulating the bearing angle effectively.

The central goal of the study is to assess the practicability and efficiency of diverse control strategies for manipulating the bearing angle in self-driving vehicles. These methods suggest the application of lag lead compensation and auto-tuned PID controllers. The goal is to improve control precision during transient response by reducing settling time, rise time, and enhancing steady-state performance. This will be achieved by systematically optimizing the parameters of the controllers.

III. The Aim and Objectives of the Study

This research aims to provide a lag lead compensation and auto-tuned PID controller for bearing angle control in self-driving vehicles. The comprehending research objectives are met in order to reach this goal.

- Modelling and simulation of the proposed system's simplified block diagram;
- Stability analysis for all controllers;
- Performance evaluation of controllers;
- Investigate the performance of the lag lead compensation and auto-tuned PID controller that creates the bearing angle control signal in self-guiding vehicles.

IV. Materials and Methods of Research

A. *The Study's Goal and Hypothesis*

The article describes a novel self-driving vehicle bearing angle control solution that employs lag lead compensation and an auto-tuned PID controller. The process of root-locus analysis and design involves the in-depth examination and manipulation of positive feedback systems and potentially unstable systems, with the goal of determining the parameters for lag-lead compensation.

A PID auto-tuner block in a closed-loop system is used to evaluate the PID controller settings provided.

The system is conceptualized and the transfer function is derived. The root locus technique is used for studying lag-lead compensation in the second stage. Auto-tuned characteristics are used to refine the PID controller in the third stage, controlling the bearing angle in self-driving vehicles.

B. *Modeling of A Self-Guiding Vehicle's Bearing Angle Control*

Researchers have developed a novel steering control method for autonomous vehicles. This method uses a simulated closed-loop feedback system to ensure stability and optimize performance [43][44]. Within this closed-loop control system, the controller adeptly grows the bearing Angle to achieve the desired results. The simplified block diagram in Fig. 1 depicts the control system for the bearing angle of a self-guiding vehicle [45].

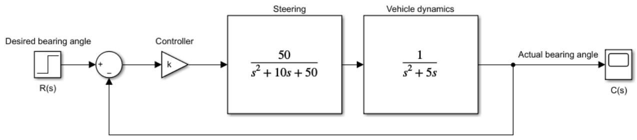

Fig. 1. Bearing angle control system in a self-guiding vehicle

The bearing angle control transfer function (TF) of the self-guiding vehicle is represented by the following equation:

$$TF = C(s)/R(s) \tag{1}$$

Using the following equations, the mathematical equations that characterize the modelling of an autonomous vehicle's angular control are defined as a close loop system:

$$C(s)/R(s) = \frac{50\,k}{s^4 + 15s^3 + 100s^2 + 250s + 50} \tag{2}$$

where $C(s)$ represents the actual bearing angle and $R(s)$ represents the desired bearing angle.

C. Proposed Lag Lead Compensation

Lead compensation essentially enhances the system's reaction time and stability. The addition of lag correction improves the system's accuracy when it reaches a stable state, but it does come with the drawback of a slower response time. By using both a lead compensator and a lag compensator at the same time, it is possible to improve both the transient and steady-state responses [46].

The advantage of lag-lead compensation is that it combines the strengths of both lag and lead compensations. The system's order will be increased by two if the lag-lead compensator includes two poles and two zeros, unless there is a cancellation of poles and zeros in the compensated system. The transfer function of a lag-lead compensator can be derived using the root-locus technique [47].

$$G_C(s) = K_C\,\left(\frac{s+\frac{1}{T_1}}{s+\frac{\gamma}{T_1}}\right)\left(\frac{s+\frac{1}{T_2}}{s+\frac{1}{\beta T_2}}\right) \tag{3}$$

where $\beta > 1$ and $\gamma > 1$. Also, consider K_C belongs to the compensator's lead part.

If $\beta \neq \gamma$, The design approach is thus a blend of the lead and lag compensator designs. The subsequent steps outline the design procedure for the lag-lead compensator [48][49].

1. Determine the optimal placement for the dominating closed-loop poles based on the performance parameters provided.
2. Calculate the angle deficiency and determine if the main closed-loop poles should be positioned as intended using the unadjusted open-loop transfer function. This angle is influenced by the phase-lead section of the lag-lead compensator.
3. Assuming that we subsequently pick T_2 to be sufficiently high that the amount of the lag component

$$\left|\left(\frac{s+\frac{1}{T_2}}{s+\frac{1}{\beta T_2}}\right)\right| \tag{4}$$

is near to unity, where $s = s_1$ is one of the closed-loop poles, select the values of T_1 and γ from the prerequisite that

$$\left|\left(\frac{s_1+\frac{1}{T_1}}{s_1+\frac{\gamma}{T_1}}\right)\right. \tag{5}$$

The selection of T_1 and γ is not unique, and several sets of T_1 and γ are conceivable. Then, using the magnitude condition, calculate the value of K_C:

$$\left|K_C\,\frac{s_1+\frac{1}{T_1}}{s_1+\frac{\gamma}{T_1}}\,G(s_1)\right| = 1 \tag{6}$$

4. The lag portion settings so that both of the following conditions are fulfilled

$$\left|\left(\frac{s_1+\frac{1}{T_2}}{s_1+\frac{1}{\beta T_2}}\right)\right| \cong 1 \tag{7}$$

and

$$\left|\,-5^o < \left(\frac{s_1+\frac{1}{T_2}}{s_1+\frac{1}{\beta T_2}}\right) < 0^o\right. \tag{8}$$

D. Closed-Loop PID Auto Tuner

Using closed-loop control in PID controllers is a popular method to minimize errors in process variables [50]-[55]. The PID Controller block operates in the feed-forward path of a feedback loop, as depicted in Fig. 2. The process depicted in Fig. 2 demonstrates how a PID controller utilizes a continuous feedback loop to receive an error in the process variable, compare it to the actual bearing angle, and adjust the control output accordingly.

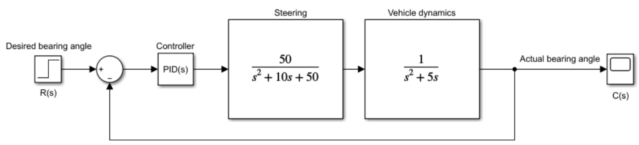

Fig. 2. Simplified block diagram for PID controller in self-guiding vehicle

Start the auto-tuning procedure for the PID controller by sending the start/stop signal and allow it to run for a suitable duration until the automated tuning approach based on the experiment's transfer function estimate is successfully executed. Stop the auto-tuning procedure. When the experiment ends, the auto-tuner calculates and returns the tuned PID parameters. Apply the specific PID settings from the block to your PID controller.

V. Simulations and Results

Execute the bearing angle control algorithm within the simulation environment, following the simplified block diagram illustrated in Fig. 1.

The setup of the simulation for generating and assessing a controller for bearing angle control in self-driving vehicles may differ depending on the level of detail required, the complexity of the control algorithm, and the objectives of the study. The mathematical models that have been selected accurately depict the dynamics of the self-driving vehicle, encompassing its motion dynamics, steering dynamics, and controller. Perform the simulation experiments using the following controllers.

A. Using Gain k Only

The closed-loop transfer function, illustrated in Fig. 1, characterizes the dynamic behaviour of a closed-loop control system. This includes the poles and zeros of the closed-loop system. We employed controller gains of k=8.65 to fulfil the system requirements. The system's step response, as illustrated in Fig. 3, can be adjusted according to the system's needs.

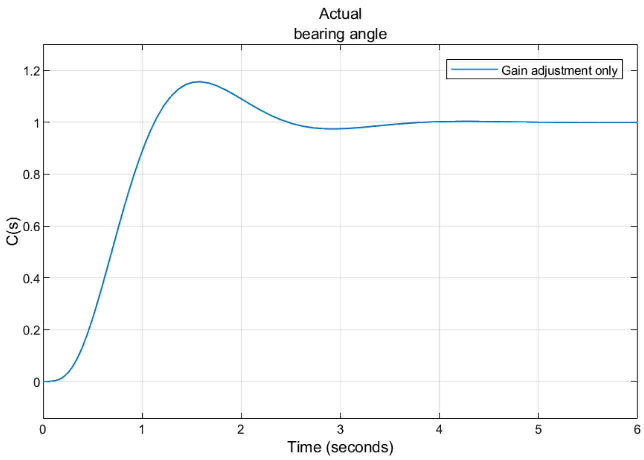

Fig. 3. k controller of self-guiding vehicle's bearing angle control

B. Lag and Zero Lead Compensation

The performance of the lag and zero of lead compensation is illustrated in Fig. 4. Assume the compensating zero of lead compensation is set to -5 in order to terminate the open-loop pole at -5 and $K_C = 2.52$ is the calculated system gain [56][57].

C. Lag and Lead Compensation

The design of a phase lead-lag compensator follows the previously stated approaches for improving transient responsiveness.

Angle summation using the root locus technique, with the compensatory zero set to -5 (to cancel the open-loop pole at -5, is -170.88 degrees). As a result, the compensator pole must provide 180-170.88= -9.12 degrees. Therefore, the lead part should be (s+5)/(s+25.34), and the intended system gain should be $K_C = 50.08$. The lag portion parameters for checking and achieving both conditions must be (s+0.1)/(s+0.01). Fig. 5 shows the system performance after the lag-lead correction was applied.

Implementing lag and lead compensation in the design of control systems for self-driving vehicles enhances vehicle dynamics, stability, and performance.

By employing Lag compensation, stability can be improved by boosting the phase margin and minimizing the chances of oscillations or instability. Furthermore, it guarantees robustness in the presence of uncertainties in the vehicle dynamics model, sensor noise, and environmental disturbances. The utilization of Lead compensation offers advantages that can enhance the transient response of autonomous vehicle control systems, leading to quicker settling times and decreased overshoot.

Lag compensation's drawbacks can naturally impose restrictions on the response speed and agility of the autonomous vehicle control system. This limitation may affect the vehicle’s ability to respond quickly to sudden environmental changes and reduce the system’s bandwidth. The drawbacks of Lead compensation include the introduction of additional phase lead and increased sensitivity to variations in system parameters and sensor characteristics

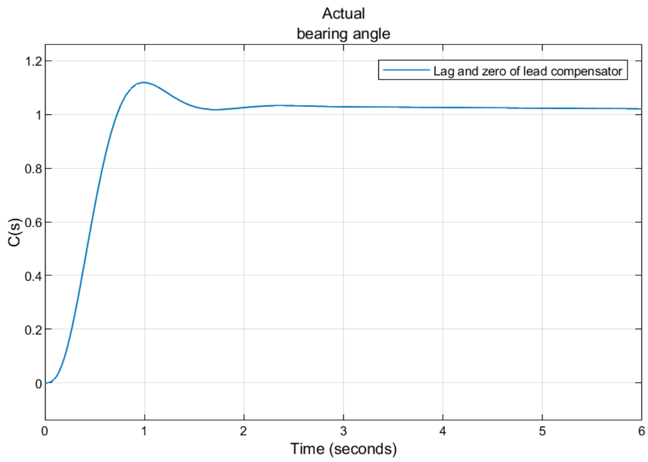

Fig. 4. The bearing angle control performance of a self-guiding vehicle using lag and zero of lead compensating

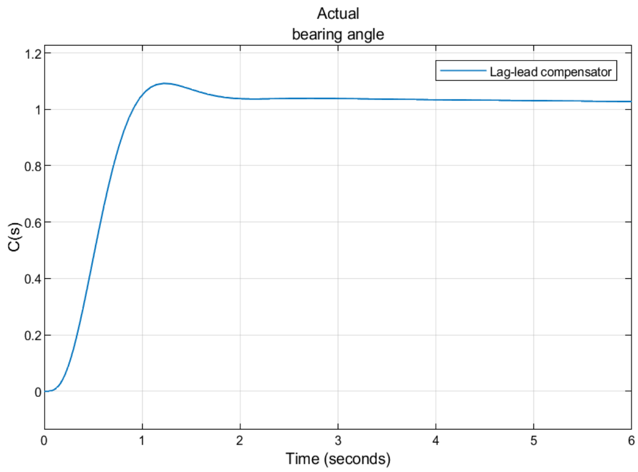

Fig. 5. The performance of lag lead compensation of self-guiding vehicle's bearing angle control

D. PID Auto Tunned

PID Tuner automatically computes PID controller gains to satisfy system requirements once the transfer function has been determined. Fig. 6 depicts the output response of the bearing angle control of a self-guiding vehicle utilizing an auto-tuned PID controller [58]-[60].

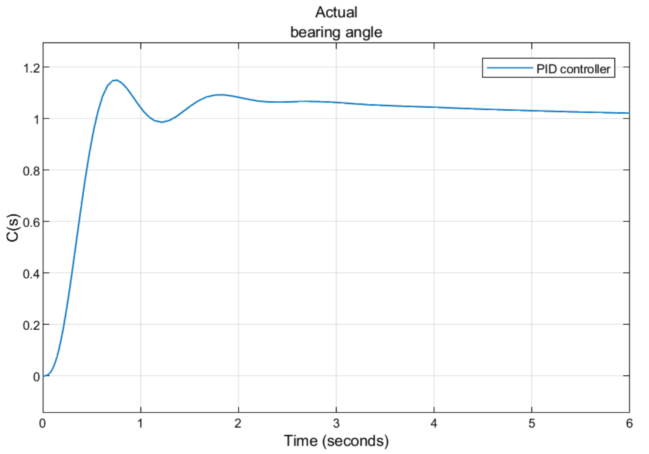

Fig. 6. Bearing angle control performance of a self-guiding vehicle using a PID controller

Several simulations are performed to test the effectiveness of the developed controller using the PID controller settings shown in Table I.

TABLE I. IDENTIFICATION RESULTS OF PID AUTO-TUNER

Controller	Value
Proportional (P)	14.564
Integral (I)	4.172
Derivative (D)	4.709
Filter Coefficient (N)	383

Using a PID controller to control bearing angle offers several advantages, such as its ability to adapt to changes in vehicle dynamics and ambient conditions. PID controllers have the ability to maintain stability and robustness, and when adjusted appropriately, can provide precise and rapid control of the vehicle's bearing angle, thus enhancing overall driving performance.

When using a PID controller, it is important to acknowledge the drawbacks and challenges that arise, including the complexity of adjustment, adaptability to complex scenarios, and potential performance limitations in nonlinear systems.

VI. DISCUSSION OF SIMULATION RESULTS

This section compares the simulation results of the indicated controllers. The proposed controllers' designs are validated using simulation to acquire real performance values.

The suggested controllers' performance is compared to several bearing angle control methods: (1) using gain k. (2) the lag and zero of lead compensation. (3) the lag and lead compensation. (4) The PID controller has auto-tuning.

Fig. 7 displays the step response of the controllers that have been proposed. The goal is to see how bearing angle control improves when the PID controller considers the unit step input response.

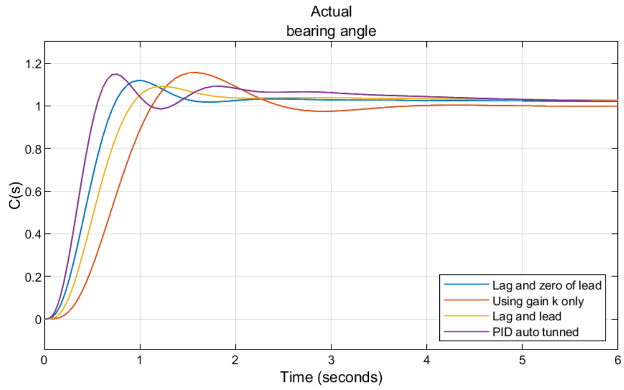

Fig. 7. Bearing angle controllers for self-guiding vehicles

Table II highlights the system's transient response characteristics and displays the following:

- Using gain k results in an overshoot of 15.7102%, higher than other controllers, and settling and rising times of 3.1986 and 0.6518 seconds, respectively.

A larger overshoot in bearing angle control can result in diminished accuracy, delayed response times, heightened collision risk, compromised passenger comfort, energy inefficiency, and degraded control performance. The act of reducing overshoot is crucial in guaranteeing accurate and secure driving situations. This objective can be reached by precise calibration of control algorithms, meticulous modeling of vehicle dynamics, and robust integration of sensors.

- Lag and zero lead compensation result in an overshoot of 10.9834%, better than utilizing gain k only.
- Lag and lead compensation provides an overshoot of 9.2503%, which is better than other controllers, but a settling time of 9.0821 seconds is not favoured when compared to other controllers.
- The PID controller has the shortest settling and rising times of 5.7856 and 0.3351 seconds, respectively, with the least overshoot of 13.3592%.

Fig. 8 shows the proposed controllers' unit ramp response curve.

TABLE II. SPECIFICATION OF THE TRANSIENT RESPONSE

Parameter	Using gain k only	Lag and zero lead compensation	Lag and lead compensation	PID auto-tunned controller
Rise Time (seconds)	0.6518	0.4482	0.5343	0.3351
Transient time (seconds)	3.1986	6.8605	9.0821	5.7856
Settling time (seconds)	3.1986	6.8605	9.0821	5.7856
Overshoot (%)	15.7102	10.9834	9.2503	13.3592
Peak	1.1571	1.1098	1.0925	1.1336
Peak Time (seconds)	1.5731	0.9955	1.2361	0.7459

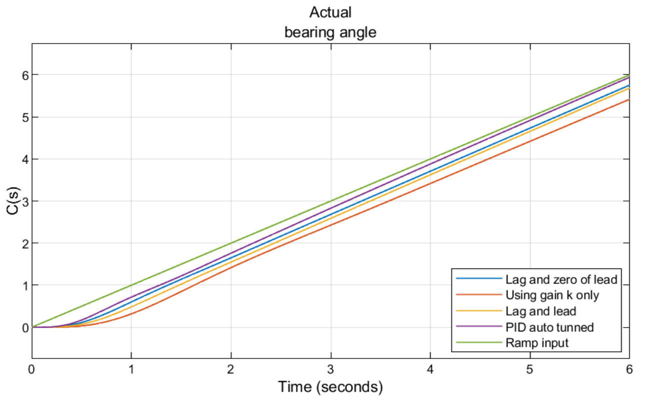

Fig. 8. Unit ramp response curves for self-guiding vehicle's bearing angle control

It can be seen from Fig. 8 that the PID auto-tuned controller has the least lateral steady-state error of all controllers.

The performance of the bearing angle control controller in self-driving vehicles is dependent on its robustness in managing disturbances. Through the implementation of robust design principles, such as adaptive control strategies, parameter optimization techniques, and sensor fusion algorithms, the controller exhibits resilience when confronted with fluctuating environmental conditions, sensor noise, and modeling inaccuracies. In the future, it will be essential to prioritize research and development efforts aimed at strengthening the controller's durability. This is necessary to advance the capabilities and promote the widespread acceptance of autonomous driving technology.

VII. Conclusions

This paper presents a novel control solution for self-driving vehicles, utilizing lag lead compensation and an auto-tuned PID controller.

The results indicate that increasing the gain k leads to a more significant overshoot than the other controllers but also shorter settling and rising times. However, the steady-state error is higher when compared to the other controllers. Lag and zero lead compensation yield better settling time and steady-state error results than lag-lead compensation. The proposed lag lead compensation yields improved overshoot compared to the controllers mentioned. Using an auto-tuned PID controller proves it surpasses all other controllers regarding transient and steady-state responses.

A future work will involve merging the vehicle's control system with a real-time auto-tuned PID controller, thereby enabling adaptability to changes in both vehicle dynamics and ambient circumstances.

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