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Autonomous Vehicles Control, Part II: Car Steering Angle Control using PD-PI, PI-PD and 2DOF-3 Controllers Compared with a PID Controller

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Abstract:

This paper investigates the tuning of PD-PI, PI-PD and 2DOF-3 controllers from the second generation of PID controllers when used to control the steering angle of an automotive car. The controllers are tuned using MATLAB optimization toolbox and the ITAE performance indices. The tuning results are presented and applied to generate the unit step time response for both reference and disturbance inputs. The disturbance rejection associated with the proposed controllers is improved through a special technique used by the author. The characteristics of the step time responses are compared with those of a PID conventional controller from the first generation of PID controllers. The best controller for both reference and disturbance inputs is assigned.

Keywords — **Automotive cars, steering angle control, PD-PI controller, PI-PD controller, 2DOF-3 controller, PID controller, controller tuning.**

I. INTRODUCTION

The world in now transferring to autonomous cars for better safety in all driving circumferences and avoiding human errors during driving. This is the second research paper in the series of research papers aiming at investigating the introduction of the second generation of PID controllers and control compensators to replace old controllers from the first generation of PID controllers. The series started with the investigation of the control of the longitudinal velocity of an autonomous car using four compensators from the second generation of control compensators. In the present work the author presents the control of the steering angle of an autonomous car using three controllers from the second generation of PID controllers to strengthen the need to change to this new generation by researchers and designers of control systems.

Here are some of the research efforts regarding modeling and control of the autonomous car steering angle:

Lakkad (2004), focused in his M. Sc. Thesis on steering system modeling and simulation and reviewed steering systems used for robotic vehicles and battlefield robot vehicles. He modeled and simulated skid and four wheels steering where a dynamic model was developed for skid steered robot and battlefield robot vehicles [1]. Naghizadeh, Marino, Scalzi, Orlando and Netto (2009) designed a nested PID steering control for lane keeping in vision based autonomous vehicles for path following in case of roads with uncertain curvature. They used a PI active front steering control on yaw rate tracking error to reject constant disturbances and the effect of parameter variations. They used PID control on the lateral offset to reject disturbances on the curvature. They investigated the robustness with respect to speed variation and uncertain vehicle parameters [2]. Rastelli, Milanes and Onieva (2011) stated that good speed and position control of vehicle steering is essential to avoid accidents due to sudden turn of the steering wheel. They presented a cascade control architecture based on fuzzy logic controller emulating the human driver behavior. They tested the proposed control architecture at different vehicle speeds where the results gave good performance [3].

Emirler, Uygan, Guvence and Guvence (2014) designed a parameter space based robust PID steering controller for automated steering in automated path. They presented linear and nonlinear models and used experiments to validate models of the vehicle. They used the linear model to design a PID steering controller and presented simulation results for circular and non-circular trajectories [4]. Zakaria, Zamzuri and Mazlan (2016) discussed the design of dynamic curvature steering control for an autonomous vehicle. They designed the controller based on the dynamic curvature calculation to estimate the path condition and modify the velocity and wheel angle according to the estimated path condition. They presented simulation results showing the capability of the controller to track the reference path [5]. Pereira, Sevensson, Luna and Martensson (2017) proposed a lateral controller for an over-actuated vehicle as a linear time varying model predictive controller. The purpose of the controller was to track a desired path smoothly by the vehicle sideway movement (crabbing capability). They used Ackermann steering geometry to transform the control action, curvature and crabbing angle to wheel angle. They evaluated the performance of the controller experimentally and by simulation [6].

Johannesson and Lillberg (2018) presented transfer functions of traditional steering systems. They used an electric motor to control the vehicle steering using three different control strategies and evaluated the three strategies in terms of reference tracking , stability, robustness and sensitivity [7]. Xu and Peng (2020) presented a preview steering control algorithm for accurate, smooth and inexpensive path tracking of automated vehicles. They designed a digital preview controller in which the disturbance was augmented as part of the state vector. They presented simulation and experimental results for the improved performance in tracking accuracy and steering smoothness compared with model predictive control and full-state feedback control [8]. Wang et al. (2021) studied the uncertainty and changing longitudinal velocity for autonomous vehicles at high speed steering conditions. They considered the lateral location deviation as the lateral control objective and designed a robust active disturbance rejection control path tracking controller. They adapted a feedforward-feedback control method to control the total tire torque and evaluated the robustness of the proposed controller under velocity varying condition and sudden lateral disturbance [9].

Hossain, Habibullah and Islam (2022) presented a longitudinal and lateral control system of an autonomous vehicle. They modified the desired speed according to the estimated size of the reference trajectory and used a PID controller to maintain an optimal speed following the path. They designed the lateral control system using feedforward and feedback controllers to reduce lateral errors. They used simulation and experimental results to evaluate the effectiveness of the proposed controllers [10]. Bachachi, Abdul-Sadah and Khalf (2023) stated that ‘the time delay of the steering actuator is one of the main features affecting the performance of the controller’. They presented a more reliable system that worked during the fusion of multi-sensor information, designed a steering system and found its parameters for high-level control algorithm to compensate for time delay and ensure vehicle stability. They derived, using experimental data, a delayed first-order model for the steering angle at speeds from 20 to 80 km/h [11]. Zhang et al. (2024) proposed a data driven MPC control method autonomous vehicle steering avoiding complex modeling and achieving trajectory tracking with small errors. They checked the validity of their control algorithm through simulation based on CarSim software and comparison with PID and vehicle kinematics MPC [12].

II. THE CONTROLLED STEERING ANGLE AS A PROCESS

Rastelli, Milanes and Onieva (2011) collected data for an autonomous vehicle steering between the steering angle as process output and steering motor input voltage as input. They used the identification toolbox of MATLAB to identify the process using the collected data [3]. They identified a delayed 0/2 transfer function for the steering process, $G_p(s)$ having the form [3]:

$$G_p(s) = 0.8154\, e^{-0.5s}/[(s+3.8913)(s+3.9377)] \quad (1)$$

To simplify the analysis of the control system with time delay, Pade approximation of time delay is used [13]. Using first-degree Pade approximation for the exponential term in Eq.1 and rearranging the equation to be in a standard form of transfer functions of dynamic systems, it becomes:

$$G_p(s) = (-0.4077s+1.6308) / (0.5s^3+5.9145s^2+23.3194s+30.6455) \quad (2)$$

The unit step time response of the steering angle process is evaluated and drawn using the '*step*' command of MATLAB [14]. It is shown in Fig.1.

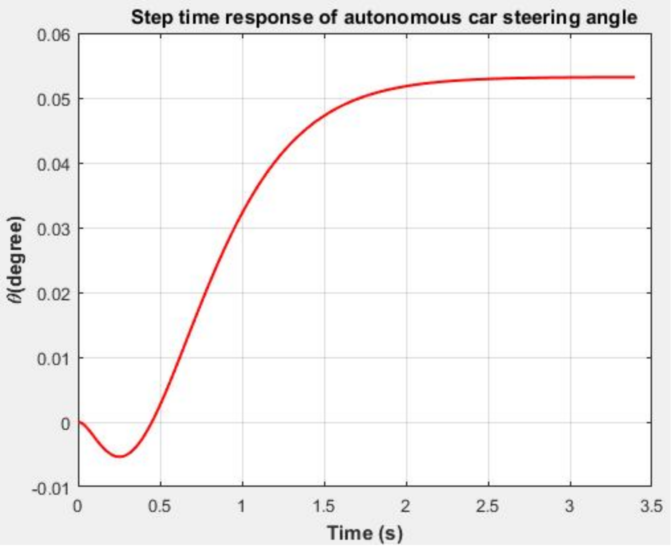

Fig.1 Unit step time response of the steering angle.

Fig.1 reveals the following dynamic characteristics of the controlled autonomous car steering angle:

- Maximum overshoot: zero
- Maximum undershoot: -0.00537 degree
- Settling time: 2.09 s
- Steady-state error: 0.9468

This is another example of processes with bad dynamics where the steady-state error is large which is supposed to be zero under control. Any proposed controller has to overcome this challenge and provide step response with good transient and steady-state characteristics.

III. CAR STEERING ANGLE CONTROL USING A PD-PI CONTROLLER

- The PD-PI controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation of PID controllers. The author used PD-PI control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [15], integrating plus time delay process [16], delayed double integrating process [17], overdamped second-order processes [18], fourth-order blending process [19], coupled dual tanks [20], internal humidity of a greenhouse [21], rocket pitch angle [22], liquefied natural gas tank pressure [23], liquefied natural gas tank level [24], boiler temperature [25], boiler drum water level [26], furnace temperature [27], electro-hydraulic drive [28], rolling strip thickness [29], injection molding mold temperature [23], IMM barrel temperature [31], IMM cavity gate pressure [32], IMM mold packing pressure [33], IMM ram velocity [34], full-electric IMM [35], Al-Jazari turbine [36], Banu Musa axial turbine power [37], Wind turbine speed [38] and steam turbine speed [39].
- The two elements of the PD-PI controller (PD and PI control modes) are set in cascade in the forward path of the block diagram of the barrel temperature control system just after the error detector.
- The transfer function of the PD-PI controller is given by [21]:

$$G_{PDPI}(s)=[K_dK_{pc2}s^2+(K_{pc1}K_{pc2}+K_dK_i)s+K_{pc1}K_i]/s \quad (3)$$

Where:

K_{pc1} = proportional gain of the PD-control mode
K_d = derivative gain of the PD-control mode
K_{pc2} = proportional gain of the PI-control mode
K_i = integral gain of the PI-control mode

- The controller has four gain parameters which have to be tuned for optimum performance for reference track input and good performance for the purpose of disturbance rejection.
- The unit step time response of the control system, c(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance, controller transfer function in Eq.3, process transfer function in Eq.2 and the '*step*' command of MATLAB [14].
- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.

- The ITAE performance index [40] is minimised using the MATLAB optimization toolbox [41].
- Minimizing the error function ITAE reveals the optimal gain parameters of the PD-PI controller as:

$K_{pc1} = 1.450478$; $K_d = 0.0101571$

$K_{pc2} = 0.1030265$; $K_i = 7.2046260$ (4)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PD-PI controller tuned gain parameters in Eq.4 and its transfer functions is shown in Fig.2.

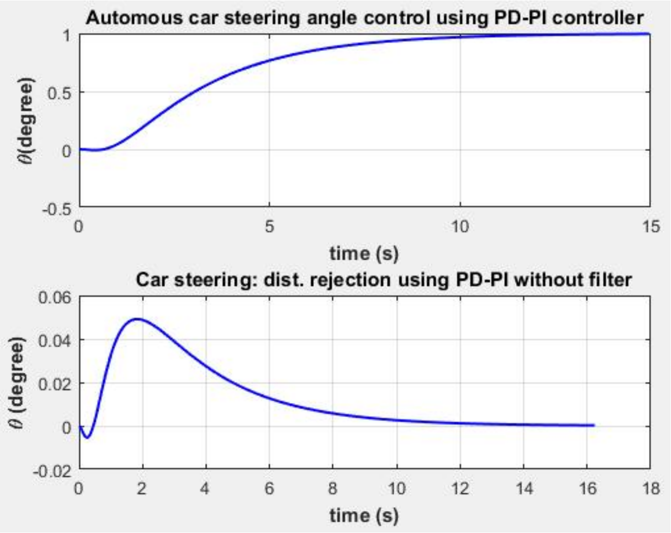

Fig.2 Step time response of the PD-PI controlled car steering angle.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: zero
  - Maximum undershoot: -0.0073
  - Settling time: 11.2 s
- For disturbance rejection using the tuned PD-PI controller (without second order high pass filter):
  - Maximum step time response: 0.0491 degree
  - Minimum step time response: -0.0054 degree
  - Approximate settling time to zero: 14 s

IV. CAR STEERING ANGLE CONTROL USING A PI-PD CONTROLLER

- The PI-PD controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used PI-PD control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [39], third-order process [40], greenhouse humidity [21], fourth-order blending process [19], boost-glide rocket engine [41], BLDC motor [42], boiler drum water level [31], electro-hydraulic drive [28], rolling strip thickness [29], IMM barrel temperature [31], IMM cavity gate pressure [32], IMM packing pressure [33], IMM ram velocity [34], full electric IMM [35], Al-Jazari turbine [36], Bani Musa axial turbine power [37] and wind turbine speed [38].
- The block diagram of a control system incorporating a PI-PD controller controlling the full-electric IMM is shown in Fig.3 [28].
- The PI-PD controller is composed of two elements: PI-control-mode in the forward path receiving its input from the error detector of the control system and a PD-control-mode in the feedback path of an internal loop with the controlled process.

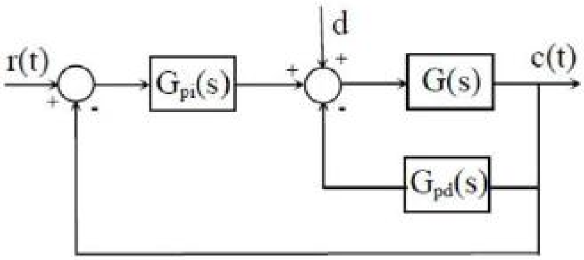

Fig.3 Block diagram of a PI-PD controlled process [28].

- The PI-PD controller elements have the transfer functions:

$G_{PI}(s) = K_{pc1} + (K_i/s)$

And $G_{PD}(s) = K_{pc2} + K_d s$ (5)

- K_{pc1}, K_i, K_{pc2} and K_d are the four controller parameters gains to be tuned to adjust the performance of the closed-loop control system.

- The transfer functions of the closed-loop control system in Fig.3 are derived from the block diagram using Eqs.2 for the process and 5 for the PI-PD controller for both inputs R(s) and D(s).
- The unit step time response of the control system, c (t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [14].
- The parameters of the PI-PD controller are tuned in a way similar to that used with the PD-PI controller where the following optimal parameters are obtained:

$$K_{pc1} = 0.0900 \; ; K_i = 4.9500$$

$$K_{pc2} = 0.100 \quad ; K_d = 0.0090 \qquad (6)$$

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PI-PD controller tuned gain parameters in Eq.6 and shown in Fig.4.

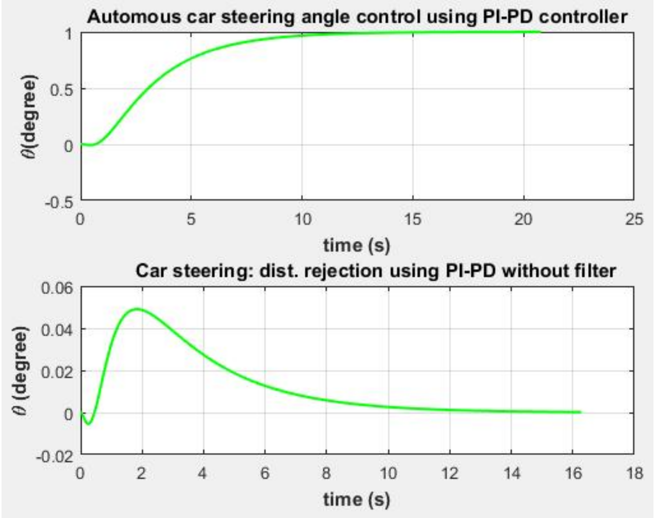

Fig.4 Step time response of the PI-PD controlled car steering angle.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: zero
  - Maximum undershoot: -0.0073 degree
  - Settling time: 11.25 s
- For disturbance rejection using the tuned PI-PD controller without filter:
  - Maximum step time response: 0.0490 degree
  - Minimum step time response: -0.0054 degree
  - Settling time: 16 s

V. CAR STEERING ANGLE CONTROL USING A 2DOF-3 CONTROLLER

- The 2DOF controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used different structures of 2DOF control to control a variety of industrial processes with bad dynamics such as: liquefied natural gas tank pressure control [23], liquefied natural gas level control [24], boost-glide rocket engine [44], BLDC motor control [45], highly oscillating second-order process [46], delayed double integrating processes [47], coupled dual tanks [20], furnace temperature [27], gas turbine speed [48], greenhouse temperature control [49], boiler temperature [25], boiler drum water level [26], electro-hydraulic drive [28], rolling strip thickness [29], IMM mold temperature [30], IMM cavity gate pressure [32], IMM packing pressure [33], IMM ram velocity [34], IMM barrel temperature [31], IMM full-electric machine [35], Al-Jazari turbine [36], Banu Musa axial turbine power [37], wind turbine speed [38] and steam turbine speed [39].
- The block diagram of a control system incorporating a 2DOF-structure 3 controller (denoted as 2DOF-3) proposed to control Banu Musa axial turbine power is shown in Fig.5 [37].

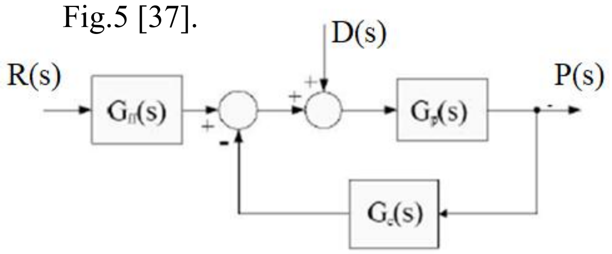

Fig.5 Block diagram of 2DOF-3 controlled process [37].

- The 2DOF-3 controller is composed of two elements: PD-control-mode of $G_{ff}(s)$ transfer function in a forward path receiving the reference input and another PD-control mode of $G_c(s)$ transfer function in the feedback path of the control system loop.
- The 2DOF-3 controller elements have the transfer functions:

$G_{ff}(s) = K_{pc1} + K_{d1}s$

And $G_c(s) = K_{pc2} + K_{d2}s$ (7)

- The 2DOF-3 controller has four gain parameters K_{pc1}, K_{d1}, K_{pc2} and K_{d2} to be tuned to adjust the performance of the closed-loop control system.
- The transfer functions of the closed-loop control system in Fig.5 are derived from the block diagram using Eqs.2 for the car steering angle and 7 for the 2DOF-3 controller for both inputs R(s) and D(s).
- The unit step time response of the control system, c(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [14].
- Investigating the closed loop transfer function of the control system with reference input tracking reveals a condition relating some of the 2DOF-3 controller parameters (K_{pc1} and K_{pc2}) to each other for a zero steady-state error.
- In such a case, an error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ITAE performance index is minimised using the MATLAB optimization toolbox [40].
- Minimizing the error function ITAE using MATLAB optimization toolbox [41] reveals the following optimal gain parameters of the 2DOF-3 controller:

$K_{pc1} = 20.007914$; $K_{d1} = 0.099335$

$K_{pc2} = 1.2161940$; $K_{d2} = 0.050290$ (8)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' using the 2DOF-3 controller tuned gain parameters in Eq.8 and shown in Fig.6.

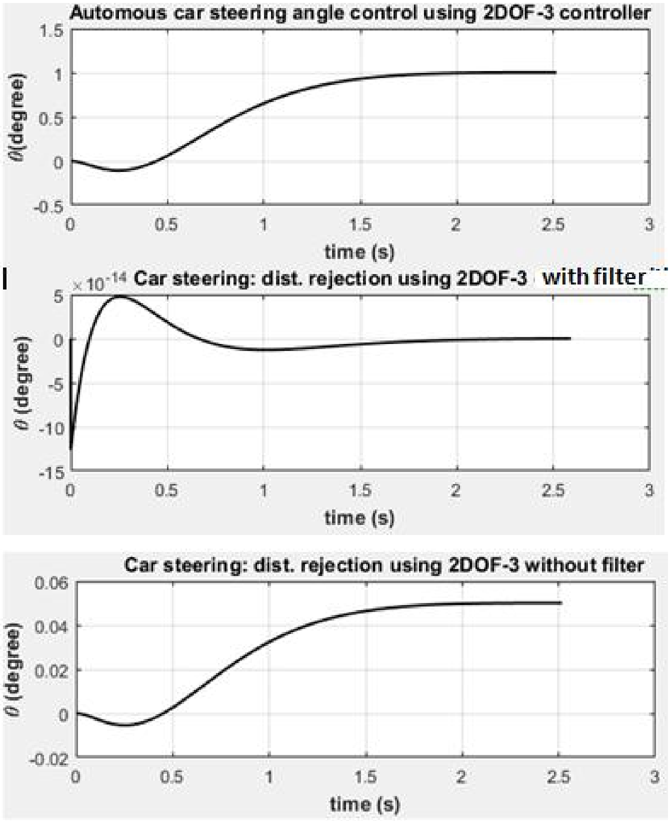

Fig.6 Step time response of the 2DOF-3 controlled car steering angle.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 0.206 %
  - Maximum undershoot: -0.108 degree
  - Settling time: 1.78 s
- For disturbance rejection using the tuned 2DOF-3 controller with second-order high pass filter:
  - Maximum step time response: 4.746×10^{-14} degree
  - Minimum step time response: -1.258×10^{-14} degree
  - Approximate settling time to zero: 2 s

VI. CAR STEERING ANGLE CONTROL USING A PID CONTROLLER

PID controller is one of the controllers of the PID first generation controllers. It still finds place in process control [50] to [53].

- The transfer function of the conventional PID controller, $G_{PID}(s)$ is given by:

$$G_{PID}(s) = K_{pc} + (K_i/s) + K_d s \quad (9)$$

Where:

K_{pc} = proportional gain of the PID controller

K_i = integral gain of the PID controller

K_d = derivative gain of the PID controller

- The controller has three gain parameters which have to be tuned for optimum performance for reference track input and good performance for the purpose of disturbance rejection.
- The unit step time response of the control system, c(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance, controller transfer function in Eq.9, process transfer function in Eq.2 and the '*step*' command of MATLAB [14].
- The PID controller parameters are tuned using the same procedure used to tune the PD-PI, PI-PD and 2DOF-3 controllers. The optimal gain parameters of the PID controller are obtained as:

$$K_{pc} = 0.200502 \;;\; K_i = 10.530248$$
$$K_d = -0.398543 \quad (10)$$

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PID controller tuned gain parameters in Eq.10 and its transfer functions is shown in Fig.7.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 7.295 %
  - Maximum undershoot: -0.036 degree
  - Settling time: 6.10 s
- For disturbance rejection using the tuned PID controller without input filter:
  - Maximum step time response: 4.586×10^{-14} degree
  - Minimum step time response: -1.107×10^{-14} degree
  - Approximate settling time: 4 s

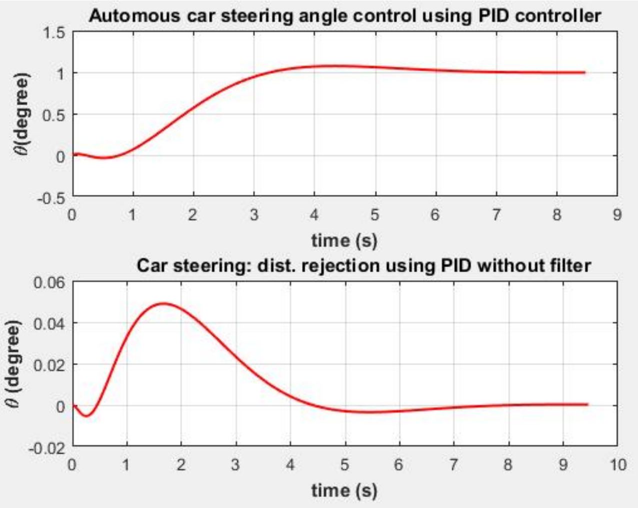

Fig.7 Step time response of the PID controlled car steering angle.

VII. COMPARISON OF TIME BASED CHARACTERISTICS

Numerical comparison for the time-based characteristics of the step time response for reference input and disturbance input of the control system with the three proposed controllers is presented in Tables 1, 2 and 3 with comparison with the application of a conventional PID controller used to control the same process.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF AN AUTONOMOUS CAR STEERING ANGLE CONTROL

Controller	PD-PI	PI-PD	2DOF-3	PID
OS_{max} (%)	0	0	0.206	7.295
US_{max} (degree)	-0.0073	-0.0090	-0.108	-0.036
T_s(s)	11.20	11.25	1.78	6.10

TABLE 2
TIME-BASED CHARACTERISTICS FOR DISTURBANCE REJECTION WITHOUT INPUT FILTER

Controller	PD-PI	PI-PD	2DOF-3	PID
Max. time response (degree)	0.0491	0.0490	0.0500	0.0488
Min. time response (degree)	-0.0054	-0.0054	-0.0054	-0.0053
Settling time to zero (s)	14	16	2	9
Steady-state time response (degree)	0	0	0.05	0

TABLE 3
TIME-BASED CHARACTERISTICS FOR DISTURBANCE REJECTION WITH INPUT FILTER

Controller	PD-PI	PI-PD	2DOF-3	PID
Max. time response (10^{14}degree)	4.712	4.715	4.746	4.586
Min. time response (10^{14}degree)	-12.3	-1.23	-1.258	-1.107
Settling time to zero (s)	2.5	2	2	4
Steady-state time response (degree)	0	0	0	0

VIII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of PD-PI, PI-PD, 2DOF-3 and PID controllers used to control an autonomous car steering angle.
- The paper presented three controllers from the second generation of PID controllers and one controller from the first generation.
- The controlled process was a stable one with bad dynamics of very large steady-state error.
- The four controllers were tuned using the MATLAB optimization toolbox with an ITAE performance index aiming at providing a good dynamic performance for the control system for both reference and disturbance inputs.
- All the proposed controllers succeeded to eliminate completely the steady-state error of the control system.
- The PD-PI controller could generate a step time response for reference input tracking without maximum overshoot (compared with 7.295 % for the PID controller) and 11.2 s settling time (compared with 6.10 s for the PID controller).
- The PI-PD controller could generate a step time response for reference input tracking without maximum overshoot (compared with 7.295 % for the PID controller) and 11.25 s settling time (compared with 6.10 s for the PID controller).
- The 2DOF-3 controller could generate a step time response for reference input tracking of 0.206 % maximum overshoot (compared with 7.295 % for the PID controller) and 1.78 s settling time (compared with 6.10 s for the PID controller).
- The 2DOF-3 controller was selected as the best controller regarding reference input tracking if the selection criterion is the settling time with little maximum undershoot.
- Regarding disturbance rejection associated with the car steering angle, the characteristics of the disturbance input rejection were compared for two cases: without using a filter with the disturbance input and with using a filter.
- Without using a filter, the 2DOF-3 controller provided disturbance rejection with minimum settling time to zero (only 2 seconds) but it exhibited a steady-state response of 0.05 degrees which could be eliminated by using a second-order high-pass filter with the disturbance input.

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DEDICATION
To
AUTOMOTIVE MANUFACTURERS IN EGYPT

The Suzuki 800

- Egyptian automotive industry is the second largest market in Africa [54].
- Annual production: about 20000 vehicles [54].
- The Egyptian automotive companies are focusing on assembly production rather than manufacturing [55].
- Egypt in 2019 had about 83 car manufacturers [56].
- Some of the automotive producers in Egypt are [54]: Al-Fotoah Car Assembly – Arab American Vehicles – Arab Organization for Industrialization – General

Motors Egypt – Gabbour Group – Mercedes Egypt – Suzuki Egypt – Wagih Abaza Company – Speranza Motors – Saudi Group – Egyptian German Automotive Company – Nissan Motor Egypt.

- To all the car manufacturers in Egypt, I dedicate this research work hoping they can get benefit out of it and plan to produce automatic cars in Egypt.

BIOGRAPHY

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- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.
- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 330 research papers in international journals and conferences.
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- Chief Justice of the International Journal of Computer Techniques.
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