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RESEARCH ARTICLE

Autonomous Vehicles Control, Part XIV: Satellite Yaw Angle Control using 2DOF-3, PD-PI and PI-PD Controllers Compared with a PID Controller

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Abstract. This is the 14th part in a series of research papers investigating autonomous vehicles control. The paper proposes three controllers from the second generation of PID controllers handled by the author since 2014. The paper proposes the 2DOF-3, PD-PI and PI-PD controllers to control the yaw angle of a satellite. The controllers are tuned using tuning techniques based on zero/pole cancelation, desired characteristics of the closed-loop controller comprising the controller and the satellite yaw angle process and using the MATLAB optimization toolbox. The effectiveness of using the proposed controllers is evaluated through comparison with the use of a conventional PID controller from the first generation of PID controllers and the best controller for the purpose of satellite yaw angle control is assigned.

Keywords: Satellite yaw angle control, 2DOF-3 controller, PD-PI controller, PI-PD controller, PID controller, controller tuning

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1. Introduction

Satellites have too many applications in both civilian and military activities. Some of the civilian applications are: environmental monitoring, meteorology, map making, monitoring earth weather, monitoring power lines and forecasting weather [1]. Some of the military applications are: communication services, gathering data, early warning, nuclear explosion detection, space weapons and directing energy laser weapons [2]. Activities accuracy and high performance requires accurate control of the satellite attitude to follow pre-assigned tracks against disturbances. This research paper proposes three controllers from the second generation of PID controllers to control the the yaw angle of a satellite and compare with a PID controller from the first generation.

Ouhocine and Hamzah (2004) presented some attitude control strategies of a small satellite and their simulation using MATLAB. They derived a linear mathematical model for a gravity-gradient control method and designed control algorithm to damp the satellite oscillation around the roll and yaw axes [3]. Kaplan (2006) in his M. Sc. Thesis studies the application of linear control to control the attitude of a low-earth orbit satellite. He derived the satellite dynamic equations and linearized them for the purpose of controller design and used linear controller and linear quadratic regulator for orbit control. He used MATLAB-Simulink to simulate the satellite dynamic model (nonlinear and linear) [4].

Ar-Ramahi (2009) designed a PID controller for satellite attitude yaw axis control. He derived a mathematical model for the control of the satellite yaw axis control and used MATLAB for the optimal design of the controller for quick settling without excessive overshoot. The transfer function model he derived was a 0/2 + an integrator one with real poles. He tuned the PID controller and presented the unit step time response of the control system having 4.71 % maximum overshoot and 1.81 s settling time [5]. Santana et al. (2012) discussed the development of a 3-axix attitude digital controller for an artificial satellite using a digital signal processor. Their controller design was based on the theory of linear quadratic and Gaussian regulator synthesized from the linearized model of the satellite motion. They used attitude actuators composed of pairs of cold gas jets powered by a pulse width/frequency modulator. They simulated the satellite model using MATLAB/SIMULINK and processed the controller and modulator in the digital signal processor [6].

Yi and Anvar (2013) obtained the attitude kinematic model of a small satellite based on Euler angle and quaternion principles. They investigated the attitude estimation using magnetometers data and fuzzy control method and investigated also the modes of attitude control. They handled the design of a conventional PID and fuzzy logic controllers [7]. Mbaocha, Eza, Ezenugu and Onwumere (2016) designed a PID controller to step the yaw angle of a satellite with optimal response. They derived a mathematical model for the satellite yaw angle control and used MATLAB for the control system analysis for the yaw angle control with minimum settling time (1.09 s) and 4.55 % maximum overshoot [8].

Ajiboye, Popoola, Oniyide and Ayinla (2020) proposed a PID control structure to control a satellite attitude for quality and reliable data acquisition. They used the ITAE robust controller design approach to improve the performance of the PID controller. They reduced the order of the controlled process from 4 to 2 and used it in the controller design. They assigned the design specifications as: overshoot ≤ 5 %, settling time ≤ 2 s and zero steady-state error. They investigated the use of PD and PID controllers with and without a pre-filter [9]. Afifa, Priyamboda and Dharmawan (2021) used a PI controller to control satellite motion around the z-axis as an actuator controller. They achieved control system performance with 10.5 % maximum overshoot and 10.5 s settling time [10].

Sayin, Bitirgen and Bayezit (2023) used a PID controller to control a Hubble space telescope and tuned the PID controller parameters using model-based root locus technique and genetic algorithm based tuning. They claimed that the second method was better in terms of cost function and the root locus based tuning performed better in disturbance rejection[11]. Zhang, Yang, Cheng and Ying (2024) investigated the satellite attitude control system in attitude tracking mode. They constructed a generalized greu number to tackle the uncertainty and inadequacy of flight data due to space environmental and sensor measurement noise. They established the grey-target decision model and the performance evaluation model under tracking mode [12].

2. The Satellite Yaw Angle as a Process

Ar-Ramahi used a 0/2 + integrator transfer function for the satellite yaw angle control using a PID controller [5]. His transfer function $G_p(s)$ is given by [5]:

$$G_p(s) = 1/[s((s+2)(s+5)] \quad (1)$$

The unit step time response of the satellite yaw angle due to a unit step input is generated using the process model in Eq.1 and the step command of MATLAB [13] and shown in Fig.1.

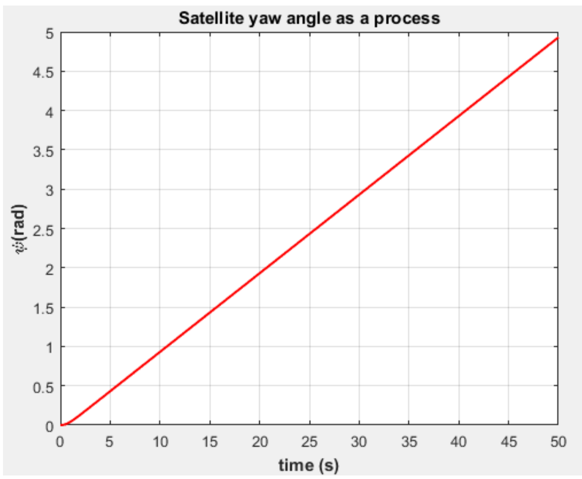

Fig.1 Unit step time response of the satellite yaw angle as a process.

3. Controlling the Satellite Yaw Angle using a 2DOF-3 Controller

The 2DOF-3 is one of the second generation of PID controllers introduced by the author since 2014. The author applied different types of 2DOF controller structures to control a number of processes. One of those structures was used by the author in 2015 to control a second-order-like process [14]. The structure of the 2DOF controller used here is shown in Fig.2 [14]. Later on, the author denoted this structure with PD control mode for both its elements $G_{c1}(s)$ and $G_{c2}(s)$ as 2DOF-3 controller [15].

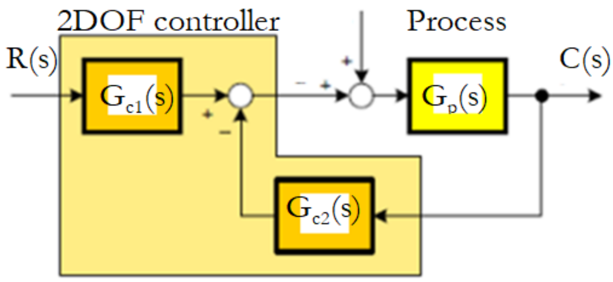

Fig.2 Structure of a 2DOF-3 controlled process [14].

The 2DOF-3 controller has PD control mode elements having transfer functions, $G_{c1}(s)$ and $G_{c2}(s)$ given by [15]:

$$G_{c1}s) = K_{pc1}+K_{d1}s \; , \; G_{c2}(s) = K_{pc2}+K_{d2} \quad (2)$$

Where:

K_{pc1}, K_{d1}: gain parameters of the forward PD control mode.
K_{pc2}, K_{d2}: gain parameters of the feedback PD control mode.

- The 2DOF-3 controller has four gain parameters to be tuned to adjust the performance parameters of the control system for the satellite yaw angle control. They are tuned as follows:
- Using the zero/pole cancellation technique [16] and cancelling the simple zero of the second PD control mode with the process pole (s+2) reveal the following relation between K_{pc2} and K_{d2} of the second

PD control mode using Eqs1 and 2:

$K_{pc2} = 2K_{d2}$ (3)

- The transfer function of the closed-loop control system incorporating the 2DOF-3 controller and the satellite yaw angle process using the block diagram in Fig.2 and Eqs.1, 2, 3, $M_1(s)$ will be:

$$M_1(s) = (K_{d1}s+K_{pc1})/[s^3+7s^2+(10+K_{d2})s+2K_{d2}] \quad (4)$$

- Eq.4 represents a 1/3 transfer function model for the control system under analysis. It has a non-zero steady-state error as expected with control systems incorporating PD control mode elements.
- It is possible to produce step time response with zero steady-state error if the free parameter of the numerator of Eq.4 is set equal to the free term of its denominator. This reveals the following relation between the gain parameters K_{pc1} and K_{d2}. That is:

  $K_{pc1} = 2K_{d2}$ (5)
- Eqs.3 and 5 means that we need to tune only K_{d1} and K_{d2}.
- The ITAE performance index [17] is used to tune the two 2DOF-3 gain parameters using the MATLAB optimization tool box [18]. The result is as follows:

  $K_{d1} = 22.578502$, $K_{d2} = 37.321767$ (6)
- Now, Eqs.3 and 5 gives the other two gain parameters as:

  $K_{pc1} = 74.643534$, $K_{pc2} = K_{pc1}$ (7)

The time response of the control system is obtained for a unit step input and using Eqs.4, 6 and 7 using the step command of MATLAB [13] and shown in Fig.3.

COMMENTS:

- Maximum overshoot: 0.156 % compared with 3.476 % for the PID controller.
- Settling time: 1.545 s compared with 1.8175 s for PID controller application.
- Steady state error: zero.

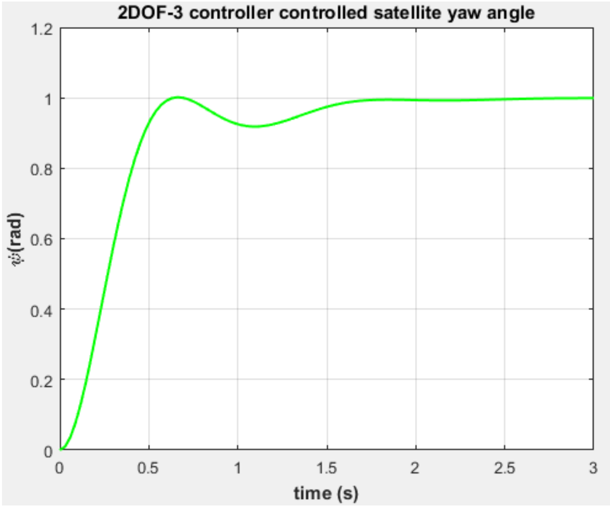

Fig.3 Satellite yaw angle step time response using a 2DOF-3 controller.

4. Controlling the Satellite Yaw Angle using a PD-PI controller

- The PD-PI controller was introduced by the author in 2014 as one of the second generation of PID controllers used to control processes having bad dynamics [19].
- The PD-PI controller is composed of two control modes: PD and PI located in cascade in the forward path of a single-loop control system. The PD-control mode has the transfer function $G_{PD}(s)$ given by:

$G_{PD}(s) = K_{pc1}+K_ds$ (8)

where K_{pc1} and K_d are the proportional and derivative gain parameters of the PD control mode.

- The PI control mode has a transfer function $G_{PI}(s)$ given by:

$G_{PI}(s) = K_{pc2}+(K_i/s)$ (9)

where K_{pc2} and K_i are the proportional and integral gain parameters of the PI control mode.

The four gain parameters of the PD-PI controller are tuned as follows:

- The zero/pole cancellation technique [16] is used to relate two of the PD-PI controller to each other. In the open-loop transfer function $G_{PD}(s)G_{PI}(s)G_p(s)$ the PD zero $(s+K_{pc1}/K_d)$ is set equal to the process pole (s+2). This reveals the relationship:

$$K_{pc1} = 2K_d \quad (10)$$

- The remaining three controller parameters (Kd, Kpc2 and Ki) are tuned by minimizing the ITAE performance index [17] using the MATLAB optimization toolbox [18]. The result is as follows:

$K_{pc1} = 0.3939204$, $K_d = 0.1969602$

$K_{pc2} = 29.585314$, $K_i = -0.059869 \quad (11)$

- The unit step time response of the control system for the satellite yaw angle using the proposed PD-PI controller using its gain parameters in Eq.10 is shown in Fig.4.

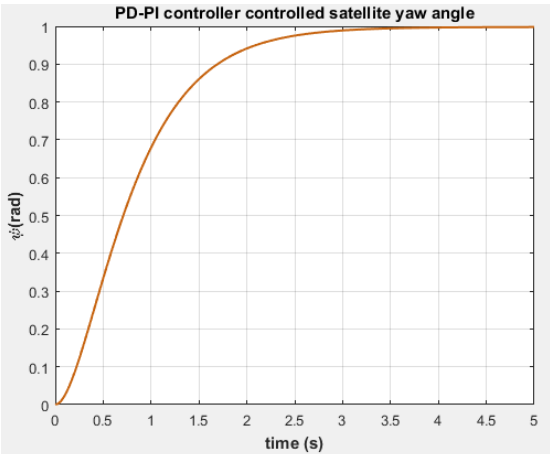

Fig.4 Satellite yaw angle step time response using a PD-PI controller.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 2.627 s compared with 1.8175 s for PID controller application.
- Steady-state error: zero

5. Controlling the Satellite Yaw Angle using a PI-PD Controller

- The PI-PD controller was one of the second generation of PID controllers introduced by the author in 2014. He applied the PI-PD controller to control a highly oscillating second-order process in 2014 [20].

The block diagram of the control system incorporating a PI-PD controller is shown in Fig.5 [20].

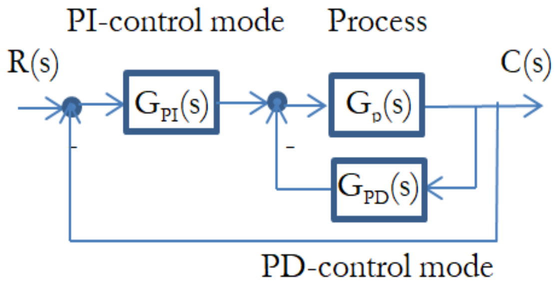

Fig.5 Structure of a PI-PD controlled process [20].

- The PI-PD controller is composed of two elements: PI control mode and PD control mode housed in two-block diagram loops as shown in Fig.5. Its two control modes have the transfer functions $G_{PI}(s)$ and $G_{PD}(s)$ given by:

$$G_{PI}(s) = K_{pc1} + (K_i/s)$$
$$G_{PD}(s) = K_{pc2} + K_d s \quad (12)$$

- The PI-PD controller parameters (K_{pc1}, K_i, K_{pc2}, K_D) are tuned as follows:
- The zero/pole cancellation technique [16] is used to relate two of the PD-PI controller to each other. In the open-loop transfer function of the inner-loop $G_p(s)$ $G_{PD}(s)$, the PD zero $(s+K_{pc2}/K_d)$ is set equal to the process pole (s+2). This reveals the relationship:

$$K_{pc2} = 2K_d \quad (13)$$

- The remaining three controller parameters (K_d, K_{pc1} and K_i) are tuned by minimizing the ITAE performance index [17] using the MATLAB optimization toolbox [18]. The result is as follows:

$K_{pc1} = 0.653554$, $K_i = 1.7026718$

$K_{pc2} = 8.599925$, $K_d = 4.2999627 \quad (14)$

- The unit step time response of the control system for the satellite yaw angle using the proposed PI-PD controller using its gain parameters in Eq.13 is shown in Fig.6.

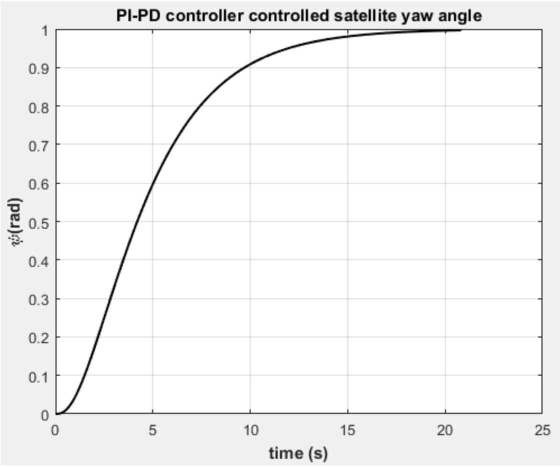

Fig.6 Satellite yaw angle step time response using a PI-PD controller.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 14.885 s compared with 1.8175 s for PID controller application.
- Steady-state error: zero

6. Controlling the Satellite Yaw Angle using a PID Controller

The PID controller is one of the first generation of PID controllers. It was proposed by Ar-Ramahi to control the satellite yaw angle [5]. He used the following transfer function G_{PID} (s) for the PID controller:

$$G_{PID}(s) = K(s+a)^2/s \quad (15)$$

where K and a are the gain parameters of the PID controller.

He tuned the PID controller parameters and provided their values as [5]:

$$K = 21 \ ; \ a = 0.30 \quad (16)$$

The unit step time response of the control system using the PID controller parameters in Eq.15 and the block diagram in Fig.5 incorporating the UAV velocity transfer function in Eq.1 is drawn using the 'step' and 'plot' commands of MATLAB [13] and shown in Fig.7.

COMMENTS:

- Maximum overshoot: 3.976 %
- Settling time: 1.8175 s.
- Steady state error: zero.

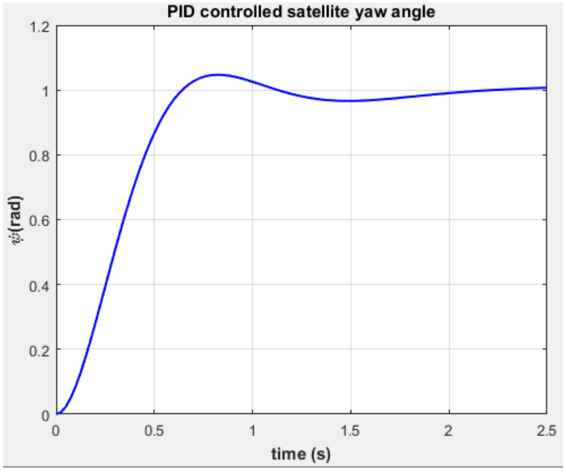

Fig.7 Satellite yaw angle step time response using a PID controller.

7. Comparison of the Time-based Characteristics

The time-based characteristics of the control systems used to control the satellite yaw angle are compared as follows:

7.1. Graphical Comparison

The unit step time response of the control systems proposed to control the satellite yaw angle with graphical comparison with the PID controller is shown in Fig.8.

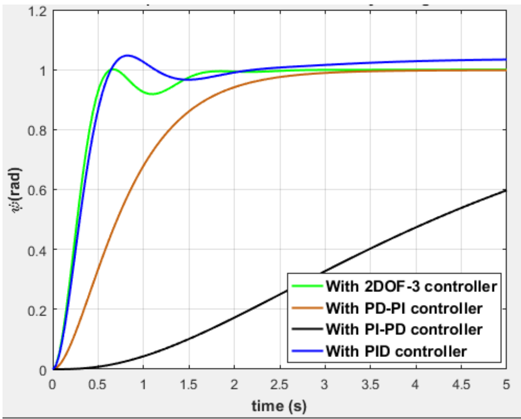

Fig.8 Satellite yaw angle step time response comparison.

7.2. Numerical Comparison

The time-based characteristics of the control systems proposed to control the satellite yaw angle as extracted from Fig.7 are tabulated in Table 1 compared with those PID controlled satellite yaw angle.

Table 1. Comparison of the time-based characteristics of the satellite yaw angle.

Controller	OS_{max} (%)	T_s(s)	e_{ss}(rad)
2DOF-3	0.156	1.545	0
PD-PI	0	2.627	0
PI-PD	0	14.885	0
PID	3.976	1.8175	0

OS_{max}: maximum overshoot
T_s: Settling time
e_{ss}: Steady-state error

8. Conclusions

The control of the satellite yaw angle was investigated in this research paper using three controllers from the second generation of PID controllers: 2DOF-3, PD-PI and PI-PD. The use of the three controllers was compared with the use of a PID controller from the first generation of PID controllers.

1. The controllers were tuned using a combination of two or three techniques: zero/pole cancellation, special requirement for some characteristics of the closed-loop control system and using the MATLAB optimization toolbox.
2. The unit step time response of the closed-loop control system was presented and the main time-based characteristics were extracted from the plot.
3. The controllers performance in controlling the satellite yaw angle was compared with the PID controller graphically and quantitatively.
4. The 2DOF-3 controller could provide a maximum overshoot of 0.156 % (compared with 3.976 % for the PID controller) and achieved a settling time of 1.545 s (compared with 1.8175 s for the PID controller).
5. The PD-PI controller could eliminate completely the maximum overshoot (compared with 3.976 % for the PID controller) and achieved a settling time of 2.627 s (compared with 1.8175 s for the PID controller).
6. The PI-PD controller could eliminate completely the maximum overshoot (compared with 3.976 % for the PID controller) and achieved a settling time of 14.885 s (compared with 1.8175 s for the PID controller).
7. The 2DOF-3 controller was selected as the best controller for the satellite yaw angle control for its very low maximum overshoot and minimum settling time among the other controllers as depicted in Fig.7 and Table 1.

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