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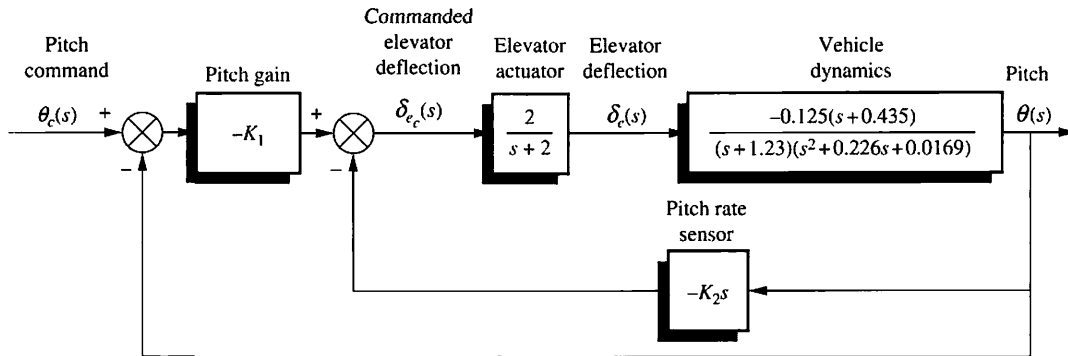
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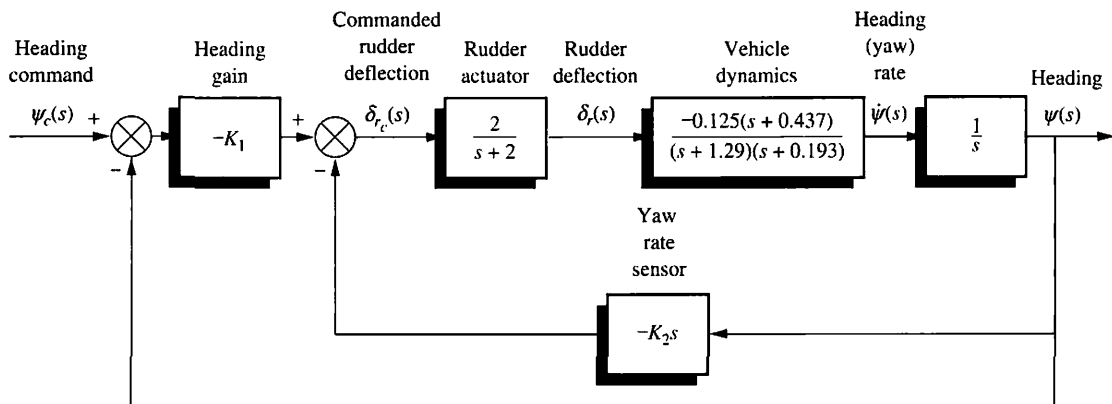
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Unmanned Free-Swimming Submersible Vehicle

Pitch Control System



Heading Control System



Key Equations

Modeling

$$\frac{V_o(s)}{V_i(s)} = -\frac{Z_2(s)}{Z_1(s)} \quad (2.97); \quad \frac{V_o(s)}{V_i(s)} = \frac{Z_1(s) + Z_2(s)}{Z_1(s)} \quad (2.104)$$

$$\frac{\theta_2}{\theta_1} = \frac{r_1}{r_2} = \frac{N_1}{N_2} \quad (2.133); \quad \frac{T_2}{T_1} = \frac{\theta_1}{\theta_2} = \frac{N_2}{N_1} \quad (2.135)$$

$$\left(\frac{\text{Number of teeth of gear on destination shaft}}{\text{Number of teeth of gear on source shaft}} \right)^2 \quad (\text{see after 2.138})$$

$$\frac{\theta_m(s)}{E_a(s)} = \frac{K_t/(R_a J_m)}{s \left[s + \frac{1}{J_m} \left(D_m + \frac{K_t K_b}{R_a} \right) \right]} \quad (2.153)$$

$$\frac{K_t}{R_a} = \frac{T_{\text{stall}}}{e_a} \quad (2.162); \quad K_b = \frac{e_a}{\omega_{\text{no-load}}} \quad (2.163)$$

$$T(s) = \frac{Y(s)}{U(s)} = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D} \quad (3.73)$$

Time Response

$$T_r = \frac{2.2}{a} \quad (4.9); \quad T_s = \frac{4}{a} \quad (4.10)$$

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (4.22)$$

$$\%OS = e^{-(\zeta\pi/\sqrt{1-\zeta^2})} \times 100 \quad (4.38)$$

$$\zeta = \frac{-\ln(\%OS/100)}{\sqrt{\pi^2 + \ln^2(\%OS/100)}} \quad (4.39)$$

$$T_p = \frac{\pi}{\omega_n \sqrt{1-\zeta^2}} \quad (4.34); \quad T_s = \frac{4}{\zeta\omega_n} \quad (4.42)$$

Steady-State Error

$$e(\infty) = e_{\text{step}}(\infty) = \frac{1}{1 + \lim_{s \rightarrow 0} G(s)} \quad (7.30); \quad K_p = \lim_{s \rightarrow 0} G(s) \quad (7.33)$$

$$e(\infty) = e_{\text{ramp}}(\infty) = \frac{1}{\lim_{s \rightarrow 0} sG(s)} \quad (7.31); \quad K_v = \lim_{s \rightarrow 0} sG(s) \quad (7.34)$$

$$e(\infty) = e_{\text{parabola}}(\infty) = \frac{1}{\lim_{s \rightarrow 0} s^2 G(s)} \quad (7.32); \quad K_a = \lim_{s \rightarrow 0} s^2 G(s) \quad (7.35)$$

Root Locus

$$\angle KG(s)H(s) = -1 = 1/(2k+1)180^\circ \quad (8.13)$$

$$\sigma_a = \frac{\sum \text{finite poles} - \sum \text{finite zeros}}{\# \text{finite poles} - \# \text{finite zeros}} \quad (8.27)$$

$$\theta_a = \frac{(2k+1)\pi}{\# \text{finite poles} - \# \text{finite zeros}} \quad (8.28)$$

$$\theta = \sum \text{finite zero angles} - \sum \text{finite pole angles}$$

$$K = \frac{1}{|G(s)H(s)|} = \frac{1}{M} = \frac{\prod \text{finite pole lengths}}{\prod \text{finite zero lengths}} \quad (8.51)$$

Frequency Response

$$M_p = \frac{1}{2\zeta\sqrt{1-\zeta^2}} \quad (10.52); \quad \omega_p = \omega_n \sqrt{1-2\zeta^2} \quad (10.53)$$

$$\omega_{\text{BW}} = \omega_n \sqrt{(1-2\zeta^2) + \sqrt{4\zeta^4 - 4\zeta^2 + 2}} \quad (10.54)$$

$$\Phi_M = \tan^{-1} \frac{2\zeta}{\sqrt{-2\zeta^2 + \sqrt{1+4\zeta^4}}} \quad (10.73)$$

$$\phi_{\text{max}} = \tan^{-1} \frac{1-\beta}{2\sqrt{\beta}} = \sin^{-1} \frac{1-\beta}{1+\beta} \quad (11.11)$$

$$\omega_{\text{max}} = \frac{1}{T\sqrt{\beta}} \quad (11.9); \quad |G_c(j\omega_{\text{max}})| = \frac{1}{\sqrt{\beta}} \quad (11.12)$$

State Space

$$\mathbf{C}_M = [\mathbf{B} \quad \mathbf{A}\mathbf{B} \quad \mathbf{A}^2\mathbf{B} \quad \dots \quad \mathbf{A}^{n-1}\mathbf{B}] \quad (12.26)$$

$$\dot{\mathbf{x}} = (\mathbf{A} - \mathbf{B}\mathbf{K})\mathbf{x} + \mathbf{B}r; \quad y = \mathbf{C}\mathbf{x} \quad (12.3); \quad \mathbf{O}_M = \begin{bmatrix} \mathbf{C} \\ \mathbf{C}\mathbf{A} \\ \vdots \\ \mathbf{C}\mathbf{A}^{n-1} \end{bmatrix} \quad (12.79)$$

$$\dot{\mathbf{e}}_x = (\mathbf{A} - \mathbf{L}\mathbf{C})\mathbf{e}_x; \quad y - \hat{y} = \mathbf{C}\mathbf{e}_x \quad (12.64)$$

Digital Control

$$e^*(\infty) = \lim_{z \rightarrow 1} (1 - z^{-1})E(z) \quad (13.66)$$

$$K_p = \lim_{z \rightarrow 1} G(z) \quad (13.70); \quad K_v = \frac{1}{T} \lim_{z \rightarrow 1} (z-1)G(z) \quad (13.73)$$

$$K_a = \frac{1}{T^2} \lim_{z \rightarrow 1} (z-1)^2 G(z) \quad (13.75)$$

Highly regarded for its accessible writing style and practical case studies, *Control Systems Engineering* is the most widely adopted textbook for this core course in mechanical, electrical, and other engineering programs. This new Sixth Edition has been revised and updated with 20% new problems and greater emphasis on computer-aided design. In addition, the text is now supported by 10 virtual experiments, which enable students to experience the design-simulate-prototype workflow of practicing engineers. Powered by LabVIEW® software and simulations of Quanser's controls laboratory plants, the virtual experiments enrich the homework learning experience by allowing students to implement control solutions and evaluate their results as they prepare to make more effective use of their time in the lab.

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On the cover: CHARLI, a 5-foot tall autonomous humanoid robot built by Dr. Dennis Hong and his students at RoMeLa (Robotics and Mechanisms Laboratory) at the College of Engineering of Virginia Tech.

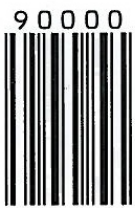


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