Figure 6.1
Closed-loop poles and response:
a. stable system;
b. unstable system

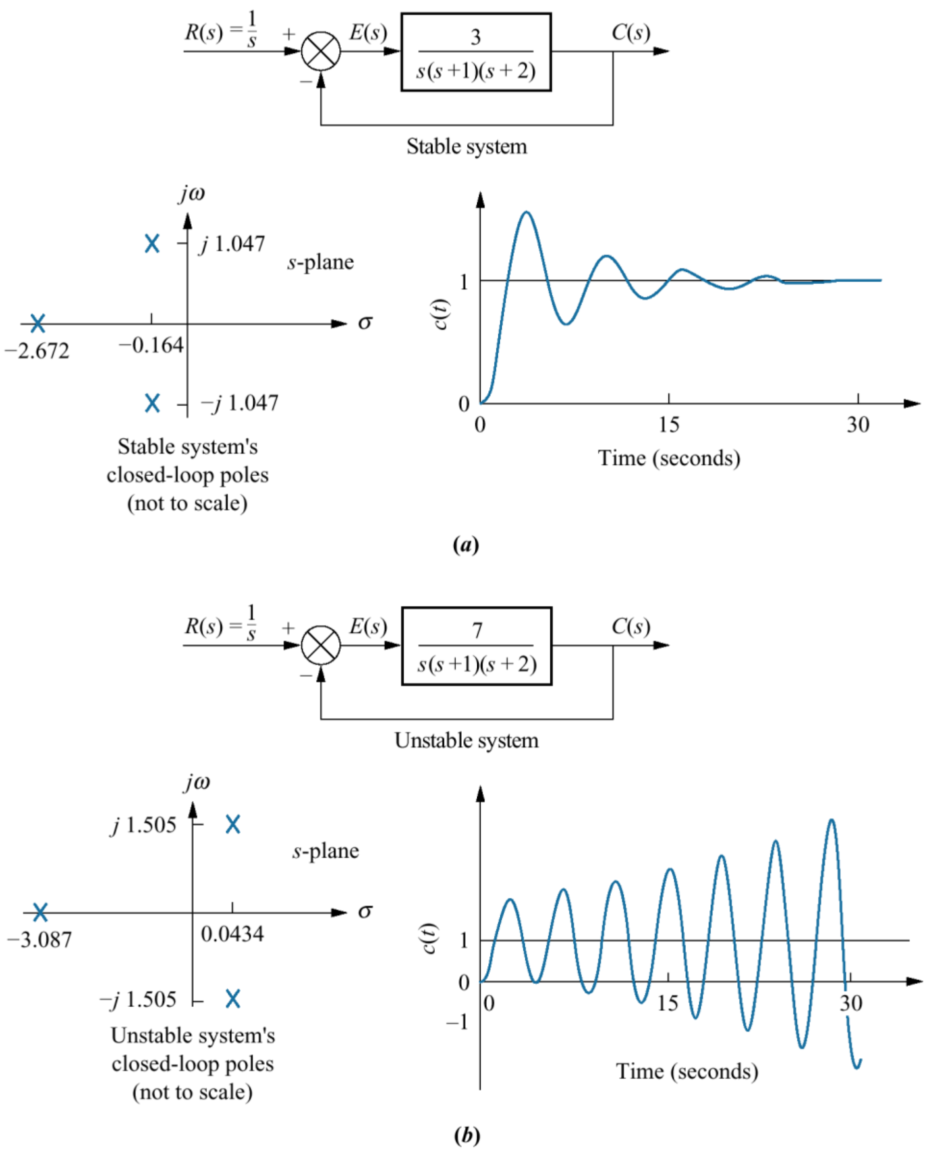


Figure 6.2
Common cause of problems in finding closed-loop poles:
a. original system;
b. equivalent system

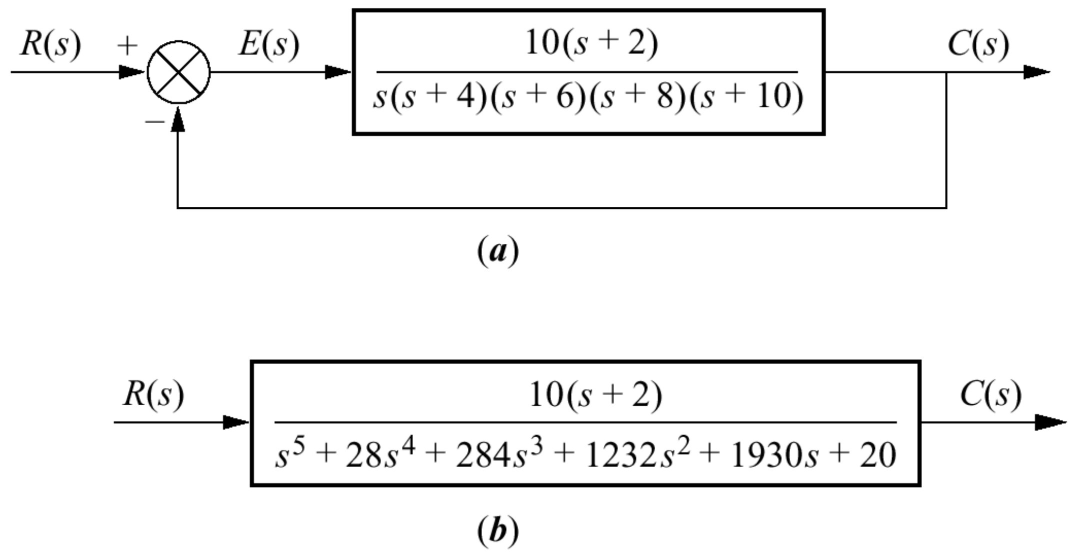
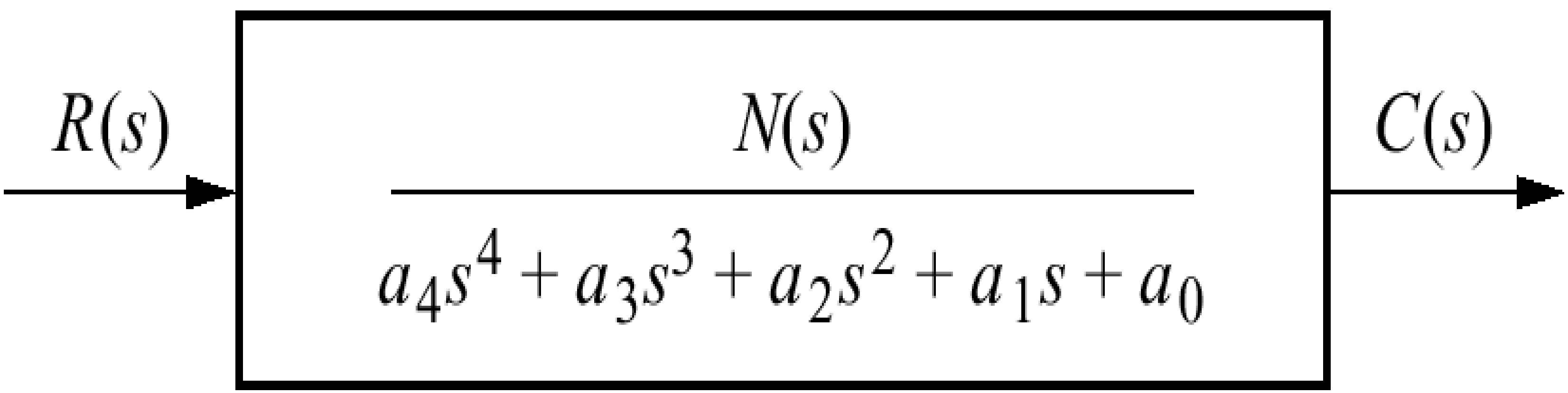


Figure 6.3
Equivalent closed-
loop
transfer function



s^4	a_4	a_2	a_0
s^3	a_3	a_1	0
s^2			
s^1			
s^0			

Table 6.1
Initial layout for Routh table

s^4	a_4	a_2	a_0
s^3	a_3	a_1	0
s^2	$\dfrac{-\begin{vmatrix} a_4 & a_2 \\ a_3 & a_1 \end{vmatrix}}{a_3} = b_1$	$\dfrac{-\begin{vmatrix} a_4 & a_0 \\ a_3 & 0 \end{vmatrix}}{a_3} = b_2$	$\dfrac{-\begin{vmatrix} a_4 & 0 \\ a_3 & 0 \end{vmatrix}}{a_3} = 0$
s^1	$\dfrac{-\begin{vmatrix} a_3 & a_1 \\ b_1 & b_2 \end{vmatrix}}{b_1} = c_1$	$\dfrac{-\begin{vmatrix} a_3 & 0 \\ b_1 & 0 \end{vmatrix}}{b_1} = 0$	$\dfrac{-\begin{vmatrix} a_3 & 0 \\ b_1 & 0 \end{vmatrix}}{b_1} = 0$
s^0	$\dfrac{-\begin{vmatrix} b_1 & b_2 \\ c_1 & 0 \end{vmatrix}}{c_1} = d_1$	$\dfrac{-\begin{vmatrix} b_1 & 0 \\ c_1 & 0 \end{vmatrix}}{c_1} = 0$	$\dfrac{-\begin{vmatrix} b_1 & 0 \\ c_1 & 0 \end{vmatrix}}{c_1} = 0$

Table 6.2
Completed Routh table

Figure 6.4
a. Feedback system for Example 6.1;
b. equivalent closed-loop system

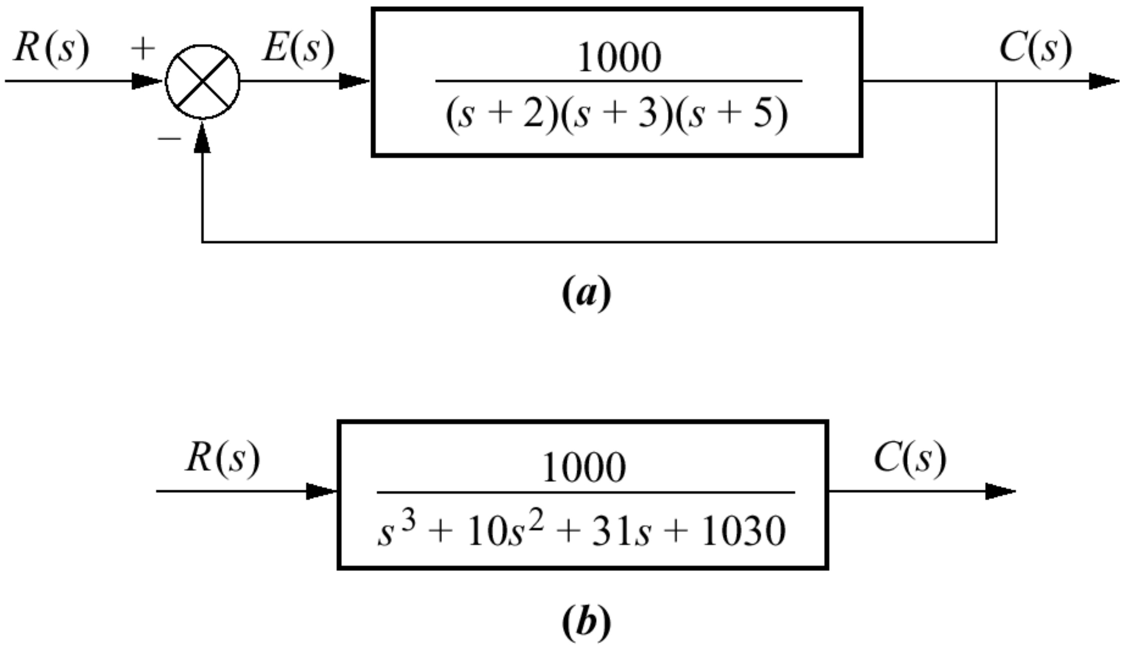


Table 6.3

Completed Routh table for Example 6.1

s^3	1	31	0
s^2	$\cancel{10}\ \ 1$	$\cancel{1030}\ \ 103$	0
s^1	$\dfrac{-\begin{vmatrix} 1 & 31 \\ 1 & 103 \end{vmatrix}}{1} = -72$	$\dfrac{-\begin{vmatrix} 1 & 0 \\ 1 & 0 \end{vmatrix}}{1} = 0$	$\dfrac{-\begin{vmatrix} 1 & 0 \\ 1 & 0 \end{vmatrix}}{1} = 0$
s^0	$\dfrac{-\begin{vmatrix} 1 & 103 \\ -72 & 0 \end{vmatrix}}{-72} = 103$	$\dfrac{-\begin{vmatrix} 1 & 0 \\ -72 & 0 \end{vmatrix}}{-72} = 0$	$\dfrac{-\begin{vmatrix} 1 & 0 \\ -72 & 0 \end{vmatrix}}{-72} = 0$

s^5	1	3	5
s^4	2	6	3
s^3	$\cancel{0}\ \ \epsilon$	$\frac{7}{2}$	0
s^2	$\frac{6\epsilon - 7}{\epsilon}$	3	0
s^1	$\frac{42\epsilon - 49 - 6\epsilon^2}{12\epsilon - 14}$	0	0
s^0	3	0	0

Table 6.4

Completed Routh table for Example 6.2

Label	First Column	$\epsilon = +$	$\epsilon = -$
s^5	1	$+$	$+$
s^4	2	$+$	$+$
s^3	$\cancel{0}\quad \epsilon$	$+$	$-$
s^2	$\dfrac{6\epsilon - 7}{\epsilon}$	$-$	$+$
s^1	$\dfrac{42\epsilon - 49 - 6\epsilon^2}{12\epsilon - 14}$	$+$	$+$
s^0	3	$+$	$+$

Table 6.5

Determining signs in first column of a Routh table with zero as first element in a row

s^5	3	6	2
s^4	5	3	1
s^3	4.2	1.4	
s^2	1.33	1	
s^1	−1.75		
s^0	1		

Table 6.6

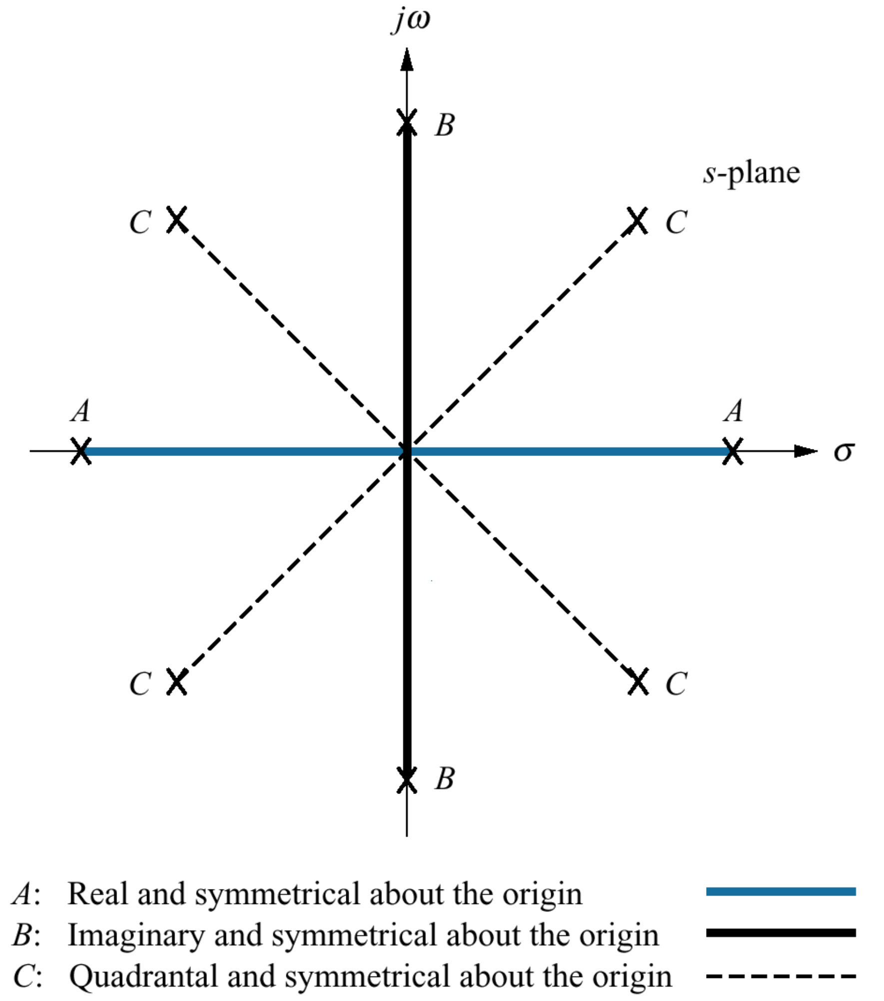
Routh table for Example 6.3

Table 6.7

Routh table for Example 6.4

s^5	1	6	8
s^4	$\cancel{7}$ 1	$\cancel{42}$ 6	$\cancel{56}$ 8
s^3	$\cancel{0}$ $\cancel{4}$ 1	$\cancel{0}$ $\cancel{12}$ 3	$\cancel{0}$ $\cancel{0}$ 0
s^2	3	8	0
s^1	$\frac{1}{3}$	0	0
s^0	8	0	0

Figure 6.5
Root positions
to generate even
polynomials:
A , *B*, *C*,
or any combination



s^8	1	12	39	48	20
s^7	1	22	59	38	0
s^6	$-\cancel{10}\ -1$	$-\cancel{20}\ -2$	$\cancel{10}\ 1$	$\cancel{20}\ 2$	0
s^5	$\cancel{20}\ 1$	$\cancel{60}\ 3$	$\cancel{40}\ 2$	0	0
s^4	1	3	2	0	0
s^3	$\cancel{0}\ \cancel{4}\ 2$	$\cancel{0}\ \cancel{6}\ 3$	$\cancel{0}\ \cancel{0}\ 0$	0	0
s^2	$\cancel{\frac{3}{2}}\ 3$	$\cancel{2}\ 4$	0	0	0
s^1	$\frac{1}{3}$	0	0	0	0
s^0	4	0	0	0	0

Table 6.8

Routh table for Example 6.5

Table 6.9 Summary of pole locations for Example 6.5

	Polynomial		
Location	**Even (fourth-order)**	**Other (fourth-order)**	**Total (eighth-order)**
Right half-plane	0	2	2
Left half-plane	0	2	2
$j\omega$	4	0	4

Table 6.9

Summary of pole locations for Example 6.5

Figure 6.6
Feedback control system for Example 6.6

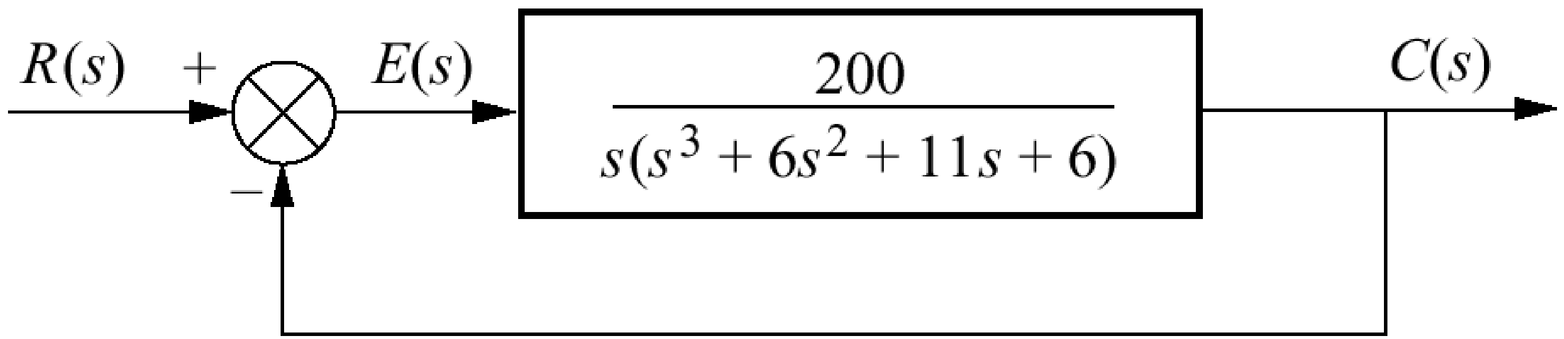
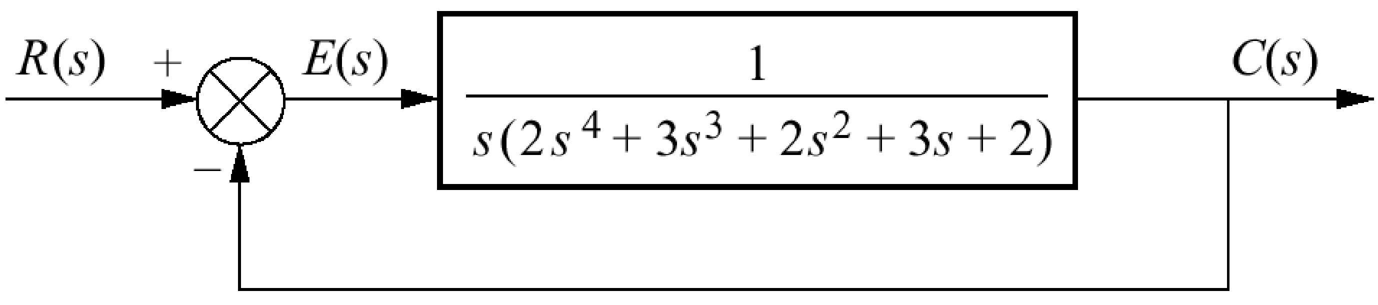


Table 6.10

Routh table for Example 6.6

s^4	1	11	200
s^3	$\cancel{6}$ 1	$\cancel{6}$ 1	
s^2	$\cancel{10}$ 1	$\cancel{200}$ 20	
s^1	-19		
s^0	20		

Figure 6.7
Feedback control system for Example 6.7



s^5	2	2	2
s^4	3	3	1
s^3	$\cancel{0}\ \epsilon$	$\frac{4}{3}$	
s^2	$\frac{3\epsilon - 4}{\epsilon}$	1	
s^1	$\frac{12\epsilon - 16 - 3\epsilon^2}{9\epsilon - 12}$		
s^0	1		

Table 6.11 Routh table for Example 6.7

s^5	1	3	3
s^4	2	2	2
s^3	2	2	
s^2	$\cancel{0}\ \epsilon$	2	
s^1	$\dfrac{2\epsilon - 4}{\epsilon}$		
s^0	2		

Table 6.12

Alternative Routh table for Example 6.7

Figure 6.8
Feedback
control system
for Example 6.8

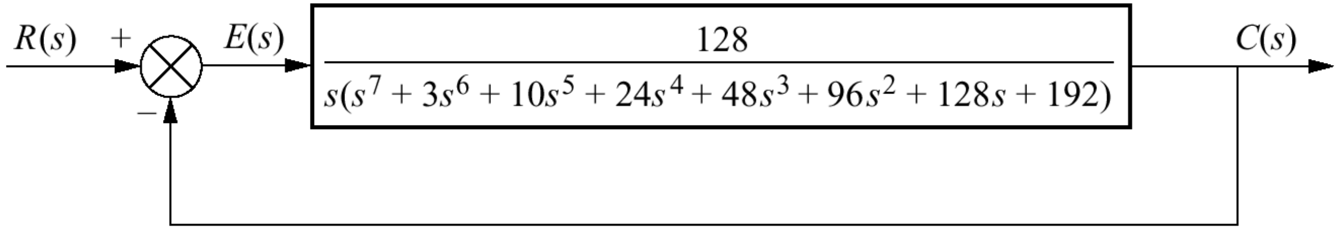


Table 6.13

Routh table for Example 6.8

s^8	1	10	48	128	128
s^7	$\cancel{3}\ 1$	$\cancel{24}\ 8$	$\cancel{96}\ 32$	$\cancel{192}\ 64$	
s^6	$\cancel{2}\ 1$	$\cancel{16}\ 8$	$\cancel{64}\ 32$	$\cancel{128}\ 64$	
s^5	$\cancel{0}\ \cancel{6}\ 3$	$\cancel{0}\ \cancel{32}\ 16$	$\cancel{0}\ \cancel{64}\ 32$	$\cancel{0}\ \cancel{0}\ 0$	
s^4	$\cancel{\frac{8}{3}}\ 1$	$\cancel{\frac{64}{3}}\ 8$	$\cancel{64}\ 24$		
s^3	$\cancel{-8}\ -1$	$\cancel{-40}\ -5$			
s^2	$\cancel{3}\ 1$	$\cancel{24}\ 8$			
s^1	3				
s^0	8				

Table 6.14 Summary of pole locations for Example 6.8

	Polynomial		
Location	**Even (sixth-order)**	**Other (second-order)**	**Total (eighth-order)**
Right half-plane	2	0	2
Left half-plane	2	2	4
$j\omega$	2	0	2

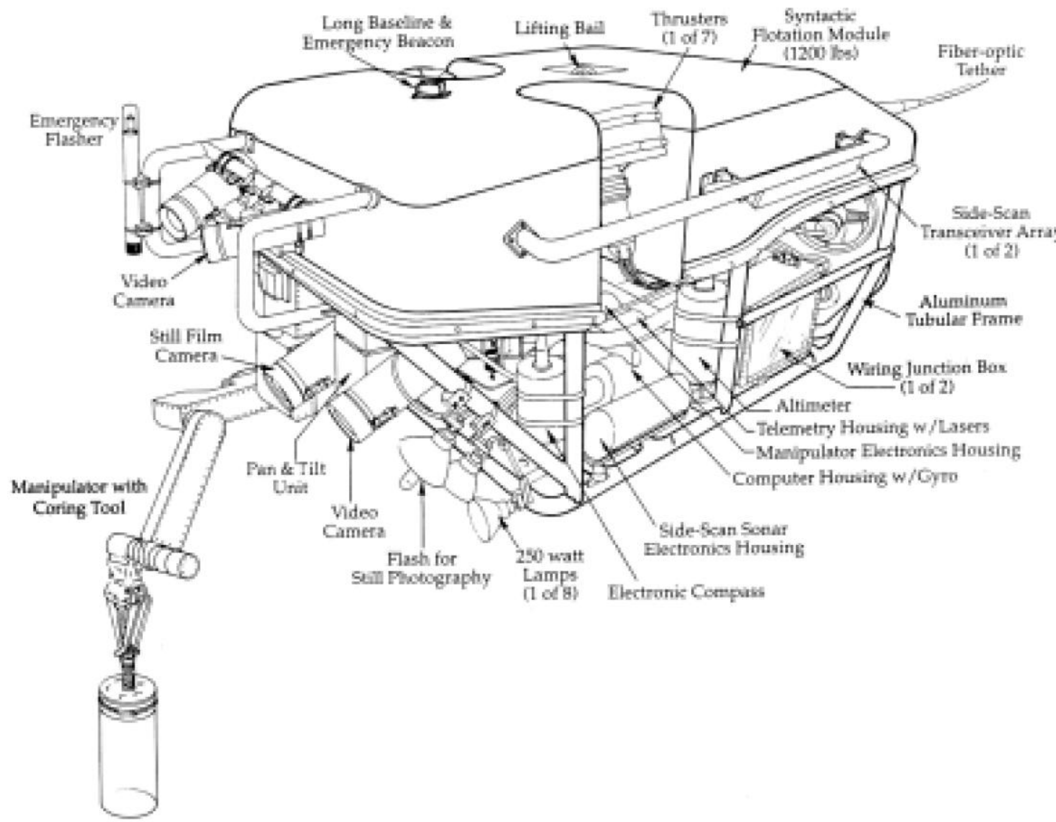
Note: rhp = right half-plane, lhp = left half-plane.

Table 6.14

Summary of pole locations for Example 6.5

Figure 6.9

Jason is an underwater, remote-controlled vehicle that has been used to explore the wreckage of the *Lusitania*. The manipulator and camera comprise some of the vehicle's control systems.



Courtesy of Woods Hole Oceanographic Institution.

Figure 6.10
Feedback control
system for Example 6.9

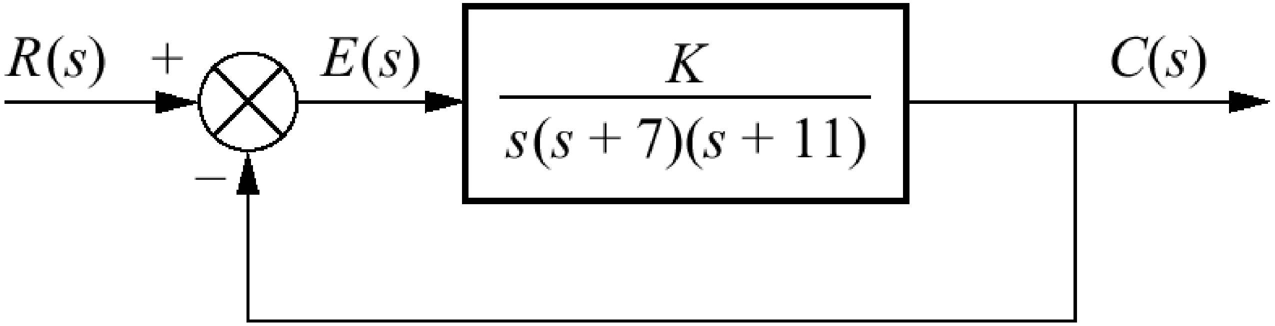


Figure 6.11
The FANUC Robot M- 400 can be configured for 4- or 5-axis of motion. It is seen here moving and stacking boxes.

Courtesy of Fanuc Robotics.

s^3	1	77
s^2	18	K
s^1	$\frac{1386-K}{18}$	
s^0	K	

Table 6.15

Routh table for Example 6.9

s^3	1	77
s^2	18	1386
s^1	$\cancel{0}$ 36	
s^0	1386	

Table 6.16
Routh table for
Example 6.9 with K = 1386

Table 6.17

Routh table for Example 6.10

s^4	1	30	200
s^3	$\cancel{3}$ 1	$\cancel{30}$ 10	
s^2	$\cancel{20}$ 1	$\cancel{200}$ 10	
s^1	$\cancel{0}$ 2	$\cancel{0}$ 0	
s^0	10		

Table 6.18

Routh table for Example 6.11

s^3	1	-7
s^2	$-\cancel{6}\ -3$	$-\cancel{52}\ -26$
s^1	$-\dfrac{47}{\cancel{3}}\ -1$	$\cancel{0}\ \ 0$
s^0	-26	

Table 6.19
Routh table for antenna control case study

s^3	1	171
s^2	101.71	$6.63K$
s^1	$17392.41 - 6.63K$	0
s^0	$6.63K$	

Table 6.20

Routh table for UFSS case study

s^4	1	3.457	$0.0416 + 0.109K_1$
s^3	3.456	$0.719 + 0.25K_1$	
s^2	$11.228 - 0.25K_1$	$0.144 + 0.377K_1$	
s^1	$\dfrac{-0.0625K_1^2 + 1.324K_1 + 7.575}{11.228 - 0.25K_1}$		
s^0	$0.144 + 0.377K_1$		

Note: Some rows have been multiplied by a positive constant for convenience.

Figure P6.1

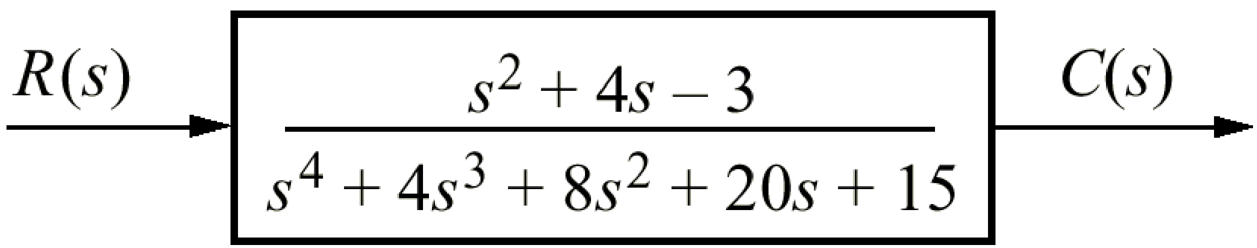
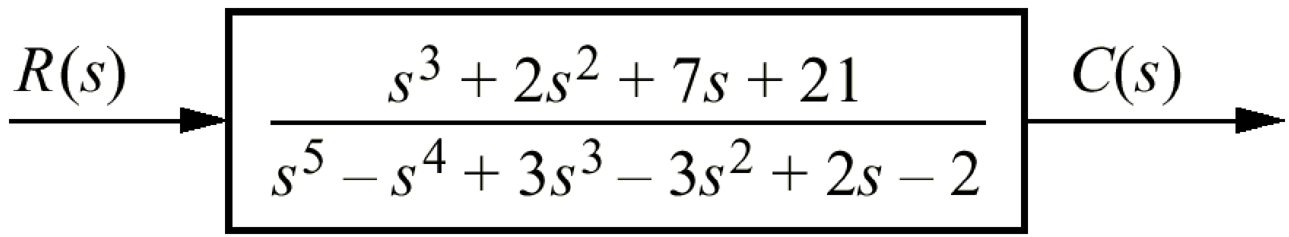


Figure P6.2



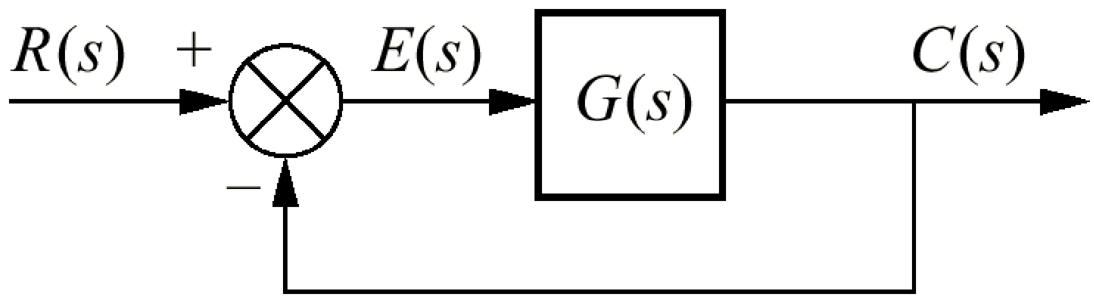


Figure P6.3

Figure P6.4

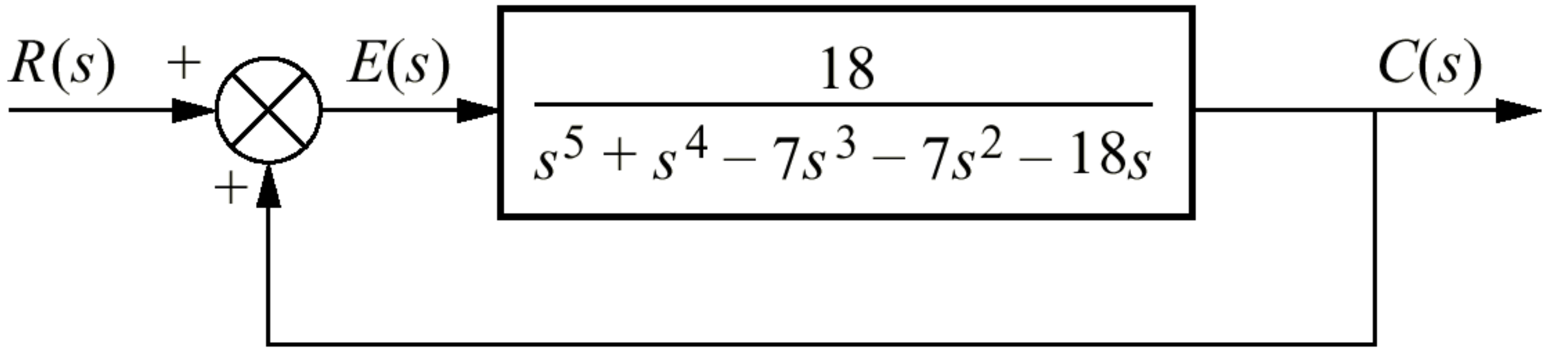


Figure P6.5

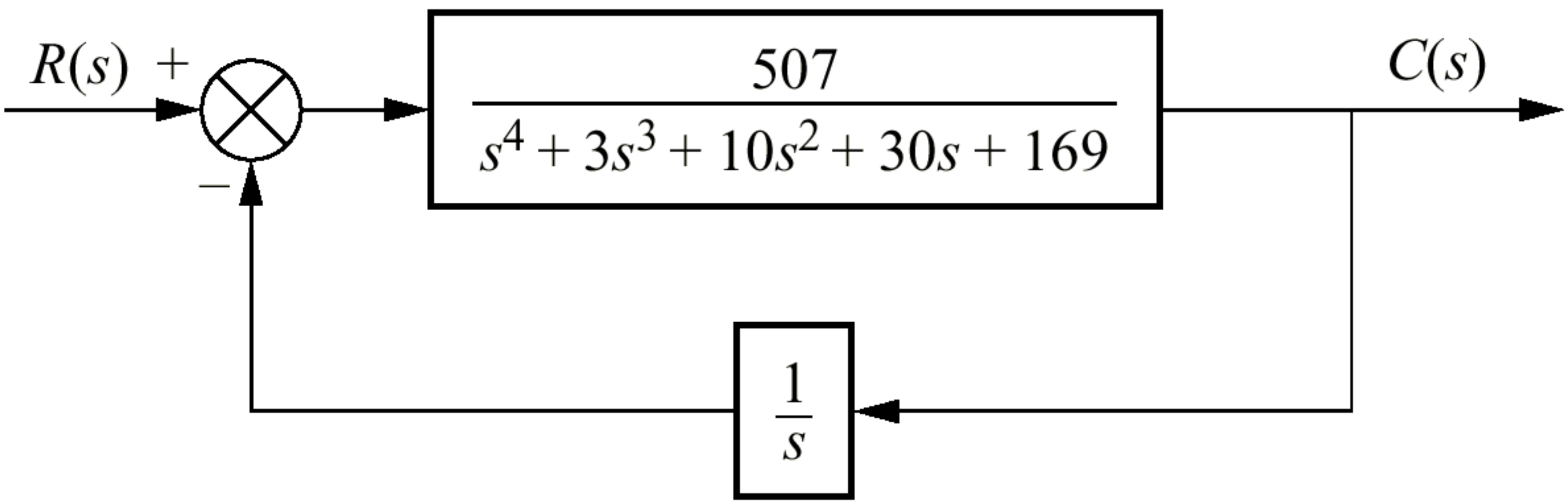


Figure P6.6

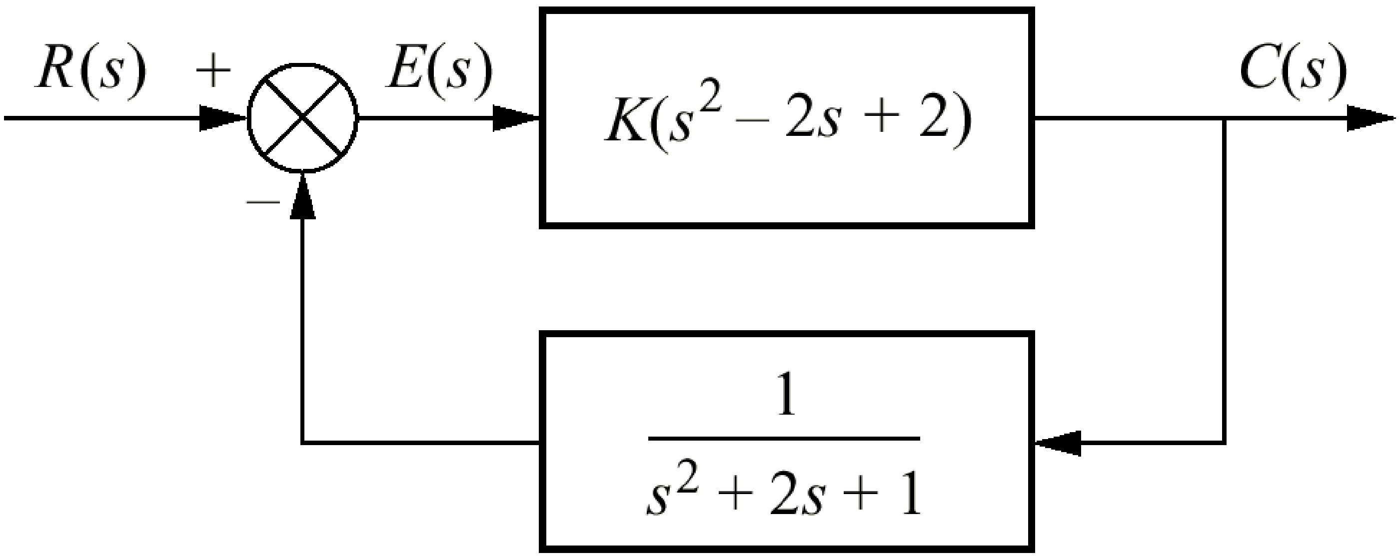


Figure P6.7

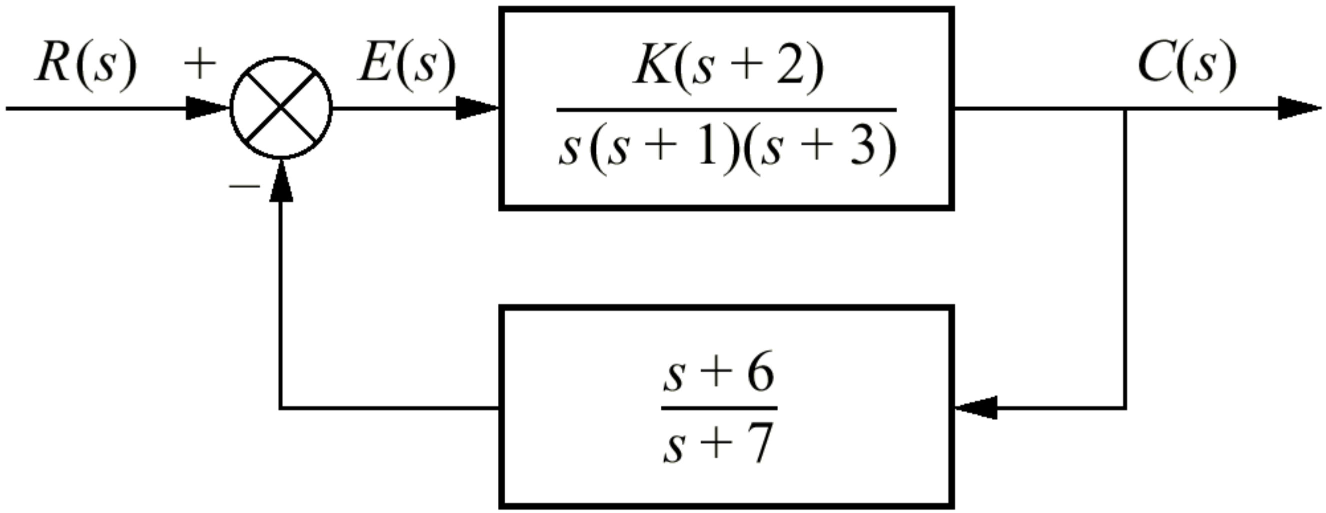
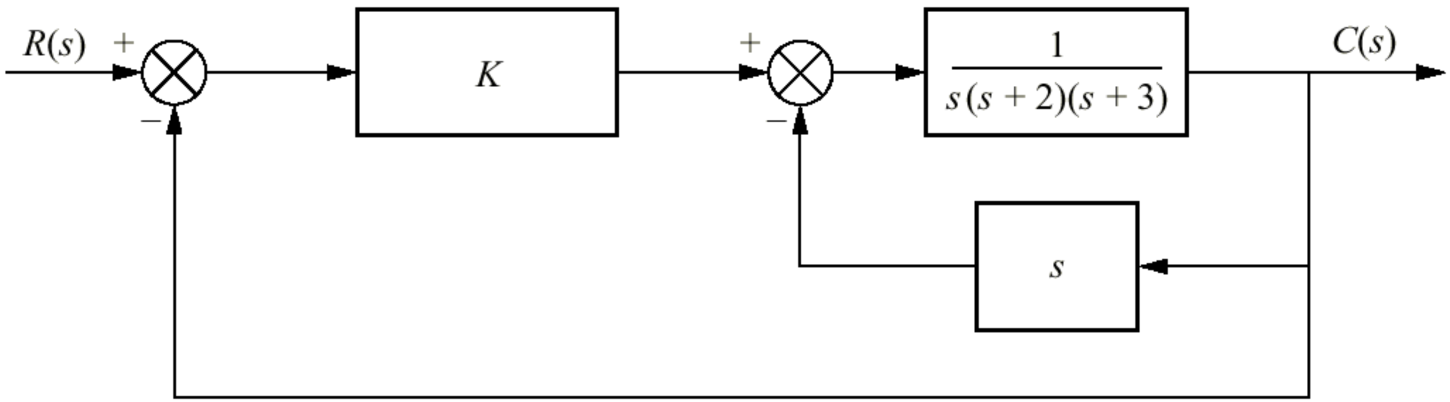


Figure P6.8



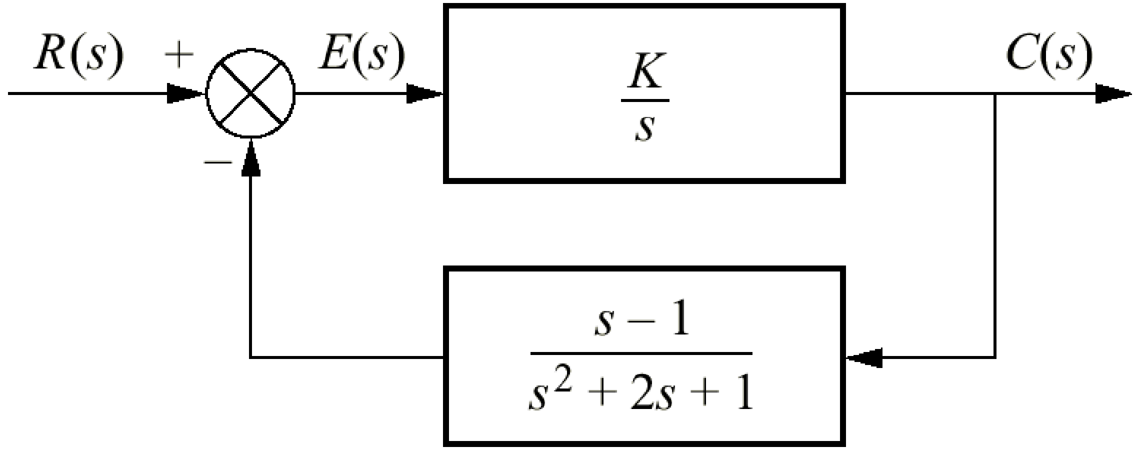
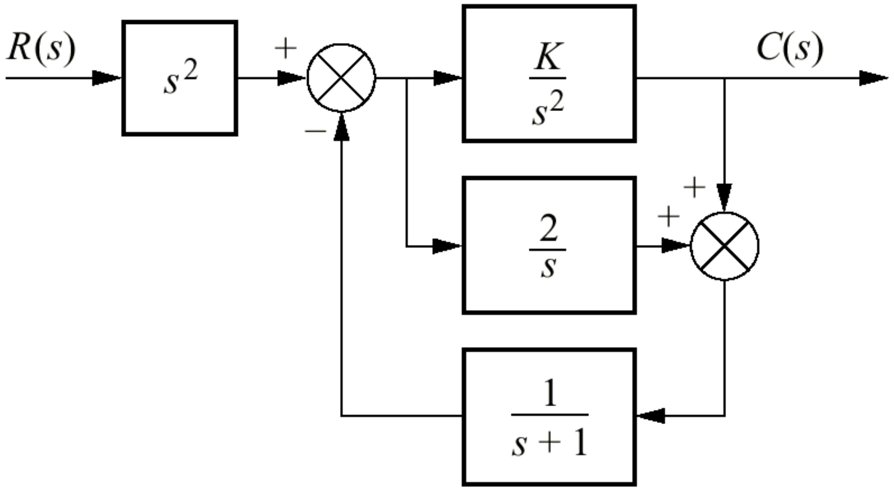


Figure P6.9

Figure P6.10
Closed-loop system
with pole plot



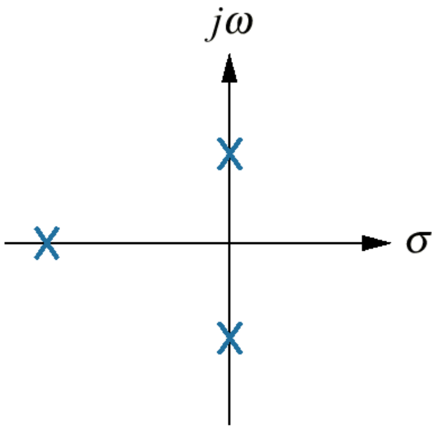


Figure P6.11
Aircraft pitch loop model

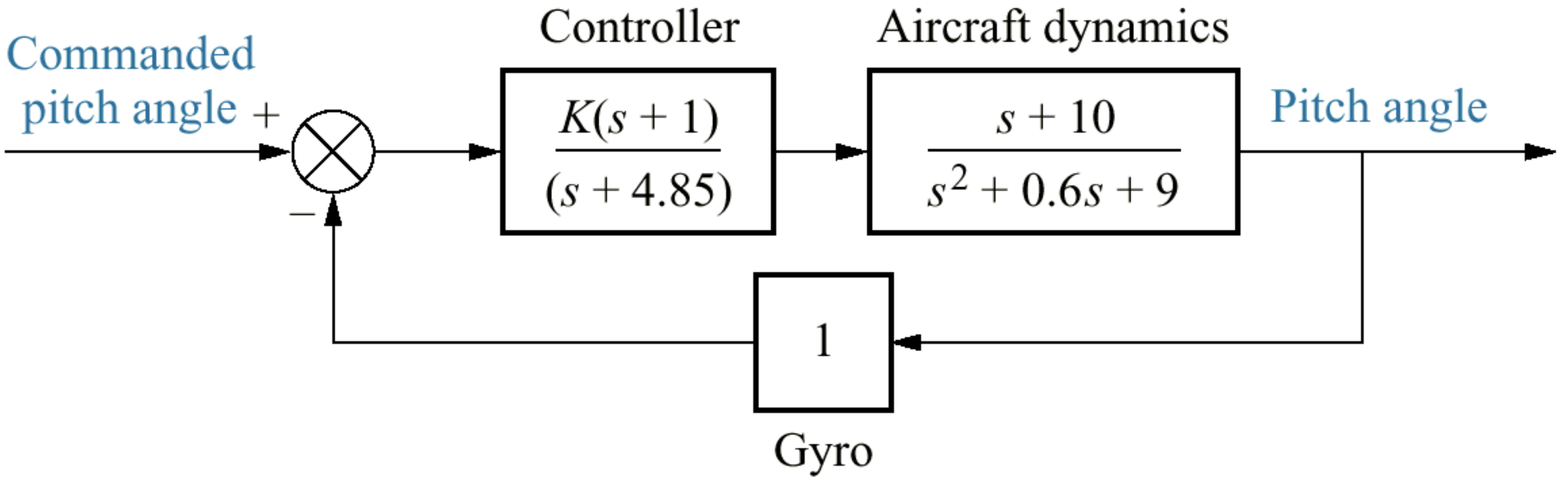
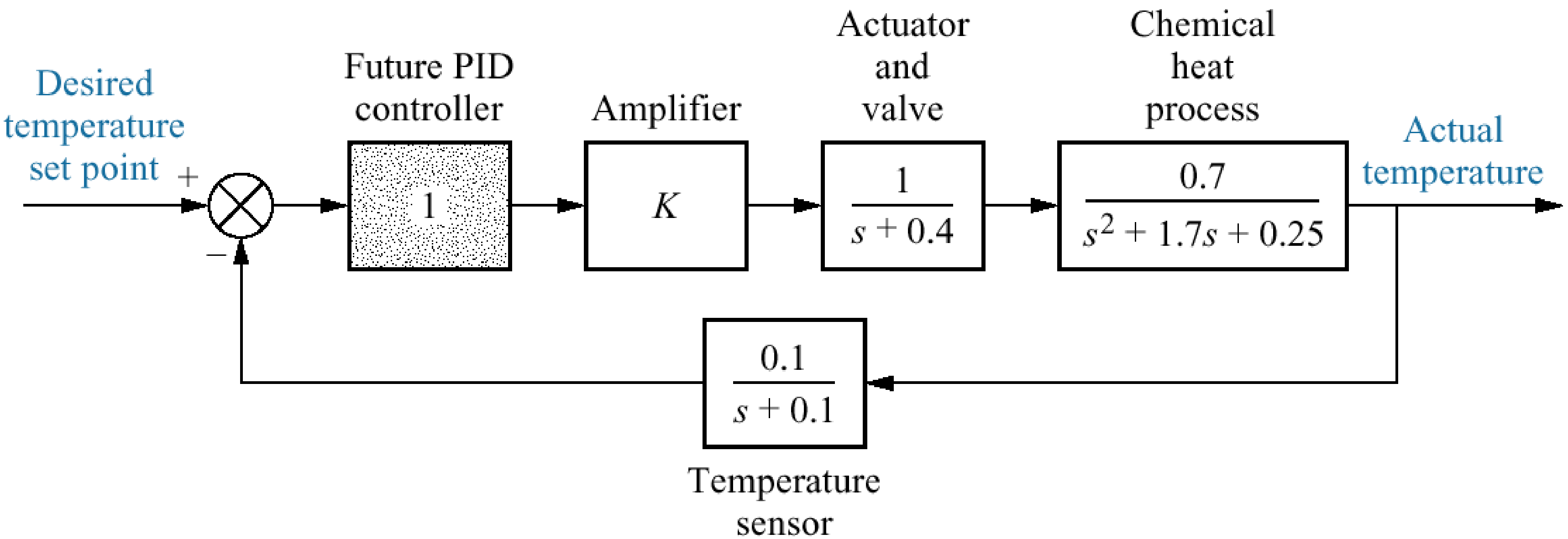
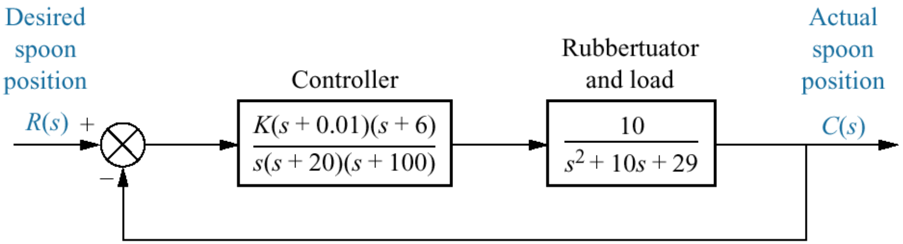


Figure P6.12
Block diagram of a chemical process-control system



Courtesy of Kazuhiko Kawamura, Vanderbilt University.

(*a*)



(*b*)

Figure P6.13
a. *Soft Arm* used for feeding;
b. simplified block diagram

Figure P6.14
Towed vehicle roll
control

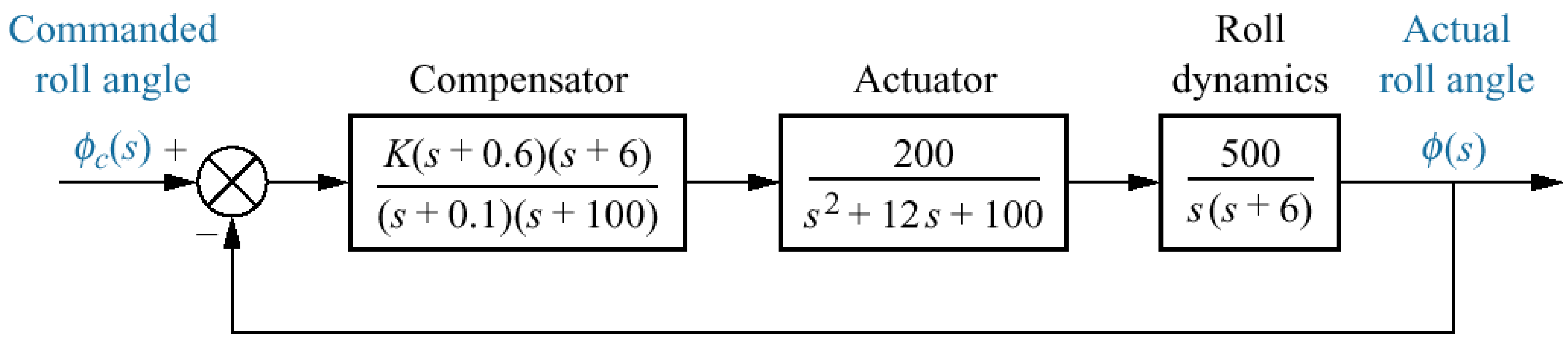


Figure P6.15
Cutting force control system

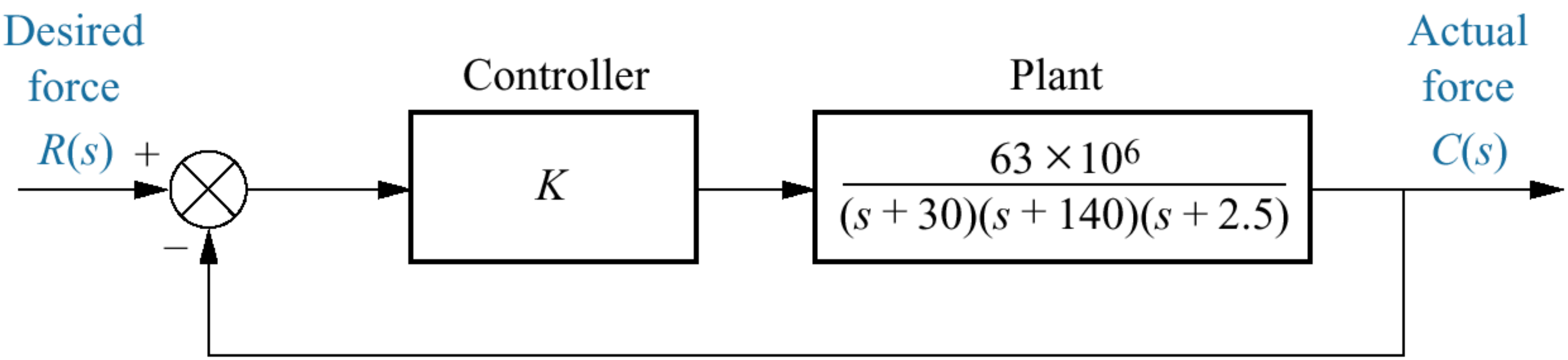
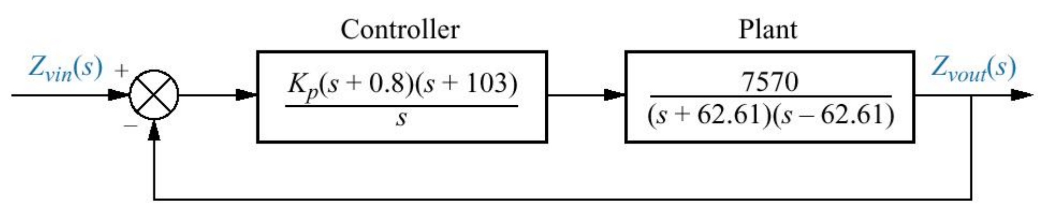


Figure P6.16
a. A magnetic levitation transportation system;
b. simplified block diagram (©1998 IEEE)

(*a*)



(*b*)