Contents

***Abstract*—This manual is an introduction to control systems based on GATE problems.Links to sample Python codes are available in the text.**

Download python codes using

0.1. State the general model of a state space system specifying the dimensions of the matrices and vectors.
Solution: The model is given by

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \tag{0.1.1}$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) \tag{0.1.2}$$

0.2. Find the transfer function $\mathbf{H}(s)$ for the general system.
Solution: Taking Laplace transform on both sides we have the following equations

$$\begin{aligned} s\mathbf{I}\mathbf{X}(s) - \mathbf{x}(0) &= \mathbf{A}\mathbf{X}(s) + \mathbf{B}\mathbf{U}(s) \\ (s\mathbf{I} - \mathbf{A})\mathbf{X}(s) &= \mathbf{B}\mathbf{U}(s) + \mathbf{x}(0) \\ \mathbf{X}(s) &= (s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}\mathbf{U}(s) \\ &\quad + (s\mathbf{I} - \mathbf{A})^{-1}\mathbf{x}(0) \end{aligned}$$

and

$$\mathbf{Y}(s) = \mathbf{C}\mathbf{X}(s) + D\mathbf{I}\mathbf{U}(s) \tag{0.2.1}$$

Substituting from (0.2.1) in the above,

$$\begin{aligned} \mathbf{Y}(s) = (\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + D\mathbf{I})\mathbf{U}(s) \\ + \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{x}(0) \end{aligned} \tag{0.2.2}$$

0.3. Find $H(s)$ for a SISO (single input single output) system.
Solution:

$$H(s) = \frac{Y(s)}{U(s)} = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + D\mathbf{I} \tag{0.3.1}$$

0.4. Given

$$H(s) = \frac{1}{s^3 + 3s^2 + 2s + 1} \tag{0.4.1}$$

$$D = 0 \tag{0.4.2}$$

$$\mathbf{B} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \tag{0.4.3}$$

find $\mathbf{A}$ and $\mathbf{C}$ such that the state-space realization is in *controllable canonical form.*
Solution:

$$\because \frac{Y(s)}{U(s)} = \frac{Y(s)}{V(s)} \times \frac{V(s)}{U(s)}, \tag{0.4.4}$$

letting

$$\frac{Y(s)}{V(s)} = 1, \tag{0.4.5}$$

results in

$$\frac{U(s)}{V(s)} = s^3 + 3s^2 + 2s + 1 \tag{0.4.6}$$

giving

$$U(s) = s^3V(s) + 3s^2V(s) + 2sV(s) + V(s) \tag{0.4.7}$$

so equation 0.1.13 can be written as

$$\begin{pmatrix} sV(s) \\ s^2V(s) \\ s^3V(s) \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -2 & -3 \end{pmatrix} \begin{pmatrix} V(s) \\ s(s) \\ s^2V(s) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} U \tag{0.4.8}$$

So

$$\mathbf{A} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -2 & -3 \end{pmatrix} \tag{0.4.9}$$

$$Y = X_1(s) = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} V(s) \\ sV(s) \\ s^2V(s) \end{pmatrix} \tag{0.4.10}$$

$$\mathbf{C} = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \tag{0.4.11}$$

0.5. Obtain $\mathbf{A}$ and $\mathbf{C}$ so that the state-space realization in in *observable canonical form.*
Solution: Given that

$$H(s) = \frac{1}{s^3 + 3s^2 + 2s + 1} \tag{0.5.1}$$

$$\frac{Y(s)}{U(s)} = \frac{1}{s^3 + 3s^2 + 2s + 1} \tag{0.5.2}$$

$$U(s) = Y(s) \times (s^3 + 3s^2 + 2s + 1) \tag{0.5.3}$$

$$U(s) = s^3Y(s) + 3s^2Y(s) + 2sY(s) + Y(s) \tag{0.5.4}$$

$$s^3Y(s) = U(s) - 3s^2Y(s) - 2sY(s) - Y(s) \tag{0.5.5}$$

$$Y(s) = -3s^{-1}Y(s) - 2s^{-2}Y(s) + s^{-3}(U(s) - Y(s)) \tag{0.5.6}$$

let $Y = aU + X_1$
by comparing with equation 1.5.6 we get a=0 and so from above equation 1.5.6 and 1.5.7

$$
\begin{aligned}
X_1(s) &= -3s^{-1}Y(s) - 2s^{-2}Y(s) \\
&\quad + s^{-3}(U(s) - Y(s)) \\
sX_1(s) &= -3Y(s) - 2s^{-1}Y(s) \\
&\quad + s^{-2}(U(s) - Y(s))
\end{aligned}
$$

$$sX_1(s) = -3Y(s) + X_2(s) \tag{0.5.7}$$

where

$$X_2(s) = -2s^{-1}Y(s) + s^{-2}(U(s) - Y(s)) \tag{0.5.8}$$

$$sX_2(s) = -2Y(s) + s^{-1}(U(s) - Y(s)) \tag{0.5.9}$$

$$sX_2(s) = -2Y(s) + X_3(s) \tag{0.5.10}$$

where

$$X_3(s) = s^{-1}(U(s) - Y(s)) \tag{0.5.11}$$

$$sX_3(s) = U(s) - Y(s) \tag{0.5.12}$$

$$X_3(s) = U(s) - Y(s) \tag{0.5.13}$$

so we get four equations which are

$$sX_1(s) = -3Y(s) + X_2(s) \tag{0.5.14}$$

$$sX_2(s) = -2Y(s) + X_3(s) \tag{0.5.15}$$

$$sX_3(s) = U(s) - Y(s) \tag{0.5.16}$$

sub $Y = X_1(s)$ in 1.5.19,1.5.20,1.5.21 we get

$$sX_1(s) = -3X_1(s) + X_2(s) \tag{0.5.17}$$

$$sX_2(s) = -2X_1(s) + X_3(s) \tag{0.5.18}$$

$$sX_3(s) = U(s) - X_1(s) \tag{0.5.19}$$

so above equations can be written as

$$\begin{pmatrix} sX_1(s) \\ sX_2(s) \\ sX_3(s) \end{pmatrix} = \begin{pmatrix} -3 & 1 & 0 \\ -2 & 0 & 1 \\ -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} X_1(s) \\ X_2(s) \\ X_3(s) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} U \tag{0.5.20}$$

So

$$\mathbf{A} = \begin{pmatrix} -3 & 1 & 0 \\ -2 & 0 & 1 \\ -1 & 0 & 0 \end{pmatrix} \tag{0.5.21}$$

$$Y(s) = X_1(s) = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} X_1(s) \\ X_2(s) \\ X_3(s) \end{pmatrix} \tag{0.5.22}$$

$$\mathbf{C} = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \tag{0.5.23}$$

0.6. Find the eigenvaues of **A** and the poles of $H(s)$ using a python code.
Solution: The following code codes/ee18btech11004.py gives the necessary values. The roots are the same as the eigenvalues.

0.7. Theoretically, show that eigenvaues of **A** are the poles of $H(s)$.
Solution: As we know that the characteristic equation is det(sI-A)

$$\mathbf{sI} - \mathbf{A} = \begin{pmatrix} s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & s \end{pmatrix} - \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -2 & -3 \end{pmatrix} \tag{0.7.1}$$

$$= \begin{pmatrix} s & -1 & 0 \\ 0 & s & -1 \\ 1 & 2 & s+3 \end{pmatrix} \tag{0.7.2}$$

therefore

$$det(sI - A) = s(s^2 + 3s + 2) + 1(1) \tag{0.7.3}$$

$$= s^3 + 3s^2 + 2s + 1 \tag{0.7.4}$$

so from equation 1.6.2 we can see that characteristic equation is equal to the denominator of the transfer function

1 Stability

1.1 Second order System

2 Routh Hurwitz Criterion

3 Compensators

4 Nyquist Plot