

Linearization

Control Theory, Lecture 11

by Sergei Savin

Spring 2024

- Taylor expansion
- Linearization
- Linearization of Manipulator equations

TAYLOR EXPANSION AROUND NODE, 1

Consider a non-linear dynamical system:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \quad (1)$$

If \mathbf{x}_0 and \mathbf{u}_0 represent a *node*, i.e. $\mathbf{f}(\mathbf{x}_0, \mathbf{u}_0) = 0$, $\mathbf{x}_0 = \text{const}$, $\mathbf{u}_0 = \text{const}$, we can consider a Taylor expansion around that node:

$$\mathbf{f}(\mathbf{x}, \mathbf{u}) \sim \frac{\partial \mathbf{f}}{\partial \mathbf{x}}(\mathbf{x} - \mathbf{x}_0) + \frac{\partial \mathbf{f}}{\partial \mathbf{u}}(\mathbf{u} - \mathbf{u}_0) + \text{H.O.T.} \quad (2)$$

Where \mathbf{x}_0 and \mathbf{u}_0 are expansion point. We define new variables \mathbf{e} and \mathbf{v} as distance from the expansion point:

$$\mathbf{e} = \mathbf{x} - \mathbf{x}_0, \quad \dot{\mathbf{e}} = \dot{\mathbf{x}}, \quad (3)$$

$$\mathbf{v} = \mathbf{u} - \mathbf{u}_0. \quad (4)$$

$$(5)$$

TAYLOR EXPANSION AROUND NODE, 2

With that we can re-write the Taylor expansion:

$$\dot{\mathbf{e}} = \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \mathbf{e} + \frac{\partial \mathbf{f}}{\partial \mathbf{u}} \mathbf{v} + \text{H.O.T.} \quad (6)$$

We can introduce notation:

$$\mathbf{A} = \frac{\partial \mathbf{f}}{\partial \mathbf{x}}, \quad \mathbf{B} = \frac{\partial \mathbf{f}}{\partial \mathbf{u}}. \quad (7)$$

If we drop higher order terms from the Taylor expansion, we obtain *linearization* of the system dynamics:

$$\dot{\mathbf{e}} = \mathbf{A}\mathbf{e} + \mathbf{B}\mathbf{v} \quad (8)$$

In this context, \mathbf{x}_0 and \mathbf{u}_0 is the *linearization point*.

TAYLOR EXPANSION ALONG A TRAJECTORY

Consider a non-linear dynamical system:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \quad (9)$$

and a trajectory $\dot{\mathbf{x}}_0 = \mathbf{f}(\mathbf{x}_0, \mathbf{u}_0)$. We can consider a Taylor expansion along this trajectory:

$$\mathbf{f}(\mathbf{x}, \mathbf{u}) \sim \mathbf{f}(\mathbf{x}_0, \mathbf{u}_0) + \frac{\partial \mathbf{f}}{\partial \mathbf{x}}(\mathbf{x} - \mathbf{x}_0) + \frac{\partial \mathbf{f}}{\partial \mathbf{u}}(\mathbf{u} - \mathbf{u}_0) + \text{H.O.T.} \quad (10)$$

Since $\dot{\mathbf{e}} = \dot{\mathbf{x}} - \dot{\mathbf{x}}_0$, we re-write:

$$\dot{\mathbf{e}} \sim \mathbf{A}\mathbf{e} + \mathbf{B}\mathbf{v} + \text{H.O.T.} \quad (11)$$

As before, we drop higher order terms and obtain linearization:

$$\dot{\mathbf{e}} = \mathbf{A}\mathbf{e} + \mathbf{B}\mathbf{v} \quad (12)$$

If we want to maintain our original variables, we can still use Taylor expansion:

$$\mathbf{f}(\mathbf{x}, \mathbf{u}) \sim \mathbf{f}(\mathbf{x}_0, \mathbf{u}_0) + \mathbf{A}(\mathbf{x} - \mathbf{x}_0) + \mathbf{B}(\mathbf{u} - \mathbf{u}_0) \quad (13)$$

Denoting $\mathbf{f}(\mathbf{x}_0, \mathbf{u}_0) - \mathbf{A}\mathbf{x}_0 - \mathbf{B}\mathbf{u}_0 = \mathbf{c}$ and dropping H.O.T. we approximate the system as affine:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{c} \quad (14)$$

Consider Manipulator equation:

$$\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g} = \tau \quad (15)$$

We will attempt to linearize it.

We begin by proposing the following new variables:

$$\mathbf{x} = \begin{bmatrix} \mathbf{q} - \mathbf{q}_0 \\ \dot{\mathbf{q}} - \dot{\mathbf{q}}_0 \end{bmatrix}, \quad \mathbf{u} = \tau - \tau_0 \quad (16)$$

$$\mathbf{q} = \mathbf{S}_q \mathbf{x}, \quad \dot{\mathbf{q}} = \mathbf{S}_v \mathbf{x} \quad (17)$$

where τ_0 is chosen such that $\mathbf{C}(\dot{\mathbf{q}}_0, \mathbf{q}_0)\dot{\mathbf{q}}_0 + \mathbf{g}(\mathbf{q}_0) = \tau_0$, and \mathbf{S}_q and \mathbf{S}_v are choice matrices.

Next, we introduce function $\phi(\dot{\mathbf{q}}, \mathbf{q}, \tau) = \ddot{\mathbf{q}}$, expressed as:

$$\phi(\dot{\mathbf{q}}, \mathbf{q}, \tau) = \mathbf{H}^{-1}(\tau - \mathbf{C}\dot{\mathbf{q}} - \mathbf{g}) \quad (18)$$

Next, we write our dynamics as a first order ODE:

$$\frac{d}{dt} \left(\begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} \end{bmatrix} \right) = \begin{bmatrix} \dot{\mathbf{q}} \\ \phi(\dot{\mathbf{q}}, \mathbf{q}, \tau) \end{bmatrix} \quad (19)$$

$$\dot{\mathbf{x}} = \begin{bmatrix} \mathbf{S}_v \mathbf{x} \\ \phi(\mathbf{x}, \tau) \end{bmatrix} \quad (20)$$

With that, we can find matrices \mathbf{A} and \mathbf{B} .

In this case, state matrices \mathbf{A} and \mathbf{B} become:

$$\mathbf{A} = \begin{bmatrix} \frac{\partial \dot{\mathbf{q}}}{\partial \mathbf{q}} & \frac{\partial \dot{\mathbf{q}}}{\partial \dot{\mathbf{q}}} \\ \frac{\partial \phi}{\partial \mathbf{q}} & \frac{\partial \phi}{\partial \dot{\mathbf{q}}} \end{bmatrix} = \begin{bmatrix} 0 & \mathbf{I} \\ \frac{\partial \phi}{\partial \mathbf{q}} & \frac{\partial \phi}{\partial \dot{\mathbf{q}}} \end{bmatrix} \quad (21)$$

$$\mathbf{B} = \begin{bmatrix} \frac{\partial \dot{\mathbf{q}}}{\partial \tau} \\ \frac{\partial \phi}{\partial \tau} \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{H}^{-1} \end{bmatrix} \quad (22)$$

Thus. our task is to find the following jacobians: $\frac{\partial \phi}{\partial \mathbf{q}}$ and $\frac{\partial \phi}{\partial \dot{\mathbf{q}}}$.

Let us find $\frac{\partial \phi}{\partial \mathbf{q}}$:

$$\frac{\partial \phi}{\partial \mathbf{q}} = \frac{\partial}{\partial \mathbf{q}} (\mathbf{H}^{-1}(\tau - \mathbf{C}\dot{\mathbf{q}} - \mathbf{g})) = \quad (23)$$

$$= \frac{\partial \mathbf{H}^{-1}}{\partial \mathbf{q}} (\tau - \mathbf{C}\dot{\mathbf{q}} - \mathbf{g}) + \mathbf{H}^{-1} \frac{\partial}{\partial \mathbf{q}} (\tau - \mathbf{C}\dot{\mathbf{q}} - \mathbf{g}) \quad (24)$$

If we evaluate $\frac{\partial \phi}{\partial \mathbf{q}}$ at the point $\mathbf{q} = \mathbf{q}_0$, $\dot{\mathbf{q}} = \dot{\mathbf{q}}_0$, $\tau = \tau_0$, we can use the fact that $\mathbf{C}(\dot{\mathbf{q}}_0, \mathbf{q}_0)\dot{\mathbf{q}}_0 + \mathbf{g}(\mathbf{q}_0) = \tau_0$ to avoid computing derivative $\frac{\partial \mathbf{H}^{-1}}{\partial \mathbf{q}}$:

$$\frac{\partial \phi}{\partial \mathbf{q}} = \mathbf{H}^{-1} \left(\tau - \frac{\partial \mathbf{C}\dot{\mathbf{q}}}{\partial \mathbf{q}} - \frac{\partial \mathbf{g}}{\partial \mathbf{q}} \right) \quad (25)$$

Let us find $\frac{\partial \phi}{\partial \dot{\mathbf{q}}}$:

$$\frac{\partial \phi}{\partial \dot{\mathbf{q}}} = \frac{\partial}{\partial \dot{\mathbf{q}}} (\mathbf{H}^{-1}(\tau - \mathbf{C}\dot{\mathbf{q}} - \mathbf{g})) = \quad (26)$$

$$= -\mathbf{H}^{-1} \frac{\partial \mathbf{C}\dot{\mathbf{q}}}{\partial \dot{\mathbf{q}}} \quad (27)$$

With that, we expressed all jacobians. The rest is the same as in the general case we studied in the first slides.

Lecture slides are available via Github:

github.com/SergeiSa/Control-Theory-2024

