Decoupling of a class of underactuated systems based on SMC Methogology

rev. 1

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1 Motivation

Consider the system

{eq:sys}
$$\dot{x} = Ax + Bu, \quad x \in \mathbb{R}^n, u \in \mathbb{R}^m \tag{Σ}$$

with one-degree of underactuation i.e., $n = m + 1$, and $A : \mathbb{R}^n \to \mathbb{R}^n, \quad B : \mathbb{R}^m \to \mathbb{R}^n$ are constants.

Objective: The goal is to design a sliding manifold $\sigma = Cx$ to stabilize the system (Σ). As requirement σ needs to be relative degree complete, i.e., n with reference to the output u.
The motivation of the objective is to solve the stabilization of a underactuated system in a simpler manner. The methodology have two main steps: Design a n-RD sliding manifold σ then, propose a n-order Continuous Sliding Mode Controller to stabilize it. Note that, if the sliding-manifold has the same order that the system (Σ), once $\sigma \equiv 0$ does not exist zero dynamics.

2 Decoupling based on SMC

First we define an output of the (Σ) as $s = Cx$, s.t,

$$\dot{s} = CAx + CBu.$$

in order to annihilate CB,

$$(CB)^{\perp}\dot{s} = (CB)^{\perp}CAx + (CB)^{\perp}CBu.$$

which can be written as

$$\frac{d}{dt}\underbrace{\begin{bmatrix} (CB)^{\perp} & 0 \\ 0 & 1 \end{bmatrix}}_{J_1}\underbrace{\begin{bmatrix} s \\ \int s\,d\tau \end{bmatrix}}_{Y_1(t)} = \underbrace{\begin{bmatrix} (CB)^{\perp}CA \\ C \end{bmatrix}}_{M_1} x(t)$$

We continue computing the derivative of $\frac{d}{dt}J_1 Y_1(t) = M_1 x(t)$ in the same manner, until rank $M_k = n$

$$\frac{d^2}{dt^2}J_1 Y_1(t) = M_1 Ax + M_1 Bu,$$

then,

$$\frac{d^2}{dt^2}(M_1B)^{\perp}J_1Y_1(t) = (M_1B)^{\perp}M_1Ax + (M_1B)^{\perp}M_1Bu.$$

$$\frac{d^2}{dt^2}\underbrace{\begin{bmatrix} (M_1B)^{\perp}(CB)^{\perp} & 0 \\ 0 & (M_1B)^{\perp} \end{bmatrix}}_{(M_1B)^{\perp}J_1}\begin{bmatrix} s \\ \int s\,d\tau \end{bmatrix} = (M_1B)^{\perp}M_1Ax.$$

That can be rewritten as

$$\frac{d^2}{dt^2}\underbrace{\begin{bmatrix} (M_1B)^{\perp}J_1 & 0 \\ 0 & 1 \end{bmatrix}}_{J_2}\begin{bmatrix} s \\ \int s\,d\tau \\ \int\int s\,d\tau dy \end{bmatrix} = \underbrace{\begin{bmatrix} (M_1B)^{\perp}M_1A \\ C \end{bmatrix}}_{M_2} x.$$

Following the same procedure we will arrive to a system of n-order,

{eq:compS}
$$\frac{d^n}{dt^n}J_{n-1}\underbrace{\begin{bmatrix} s \\ \int s\,d\tau \\ \vdots \\ \int\cdots\int s\,d\tau dy \end{bmatrix}}_{Y_{n-1}} = M_{n-1}Ax + M_{n-1}Bu \tag{1}$$

Notice that by construction J_k, $\forall\, k = 1, \ldots, n-1$ is diagonal and therefore also invertible, so, we can write (1) as,

$$\frac{d}{dt}\begin{bmatrix} s^{(n-1)} \\ \vdots \\ \dot{s} \\ s \end{bmatrix} = J^{-1}M_{n-1}\left[Ax + Bu\right] \tag{2}$$

3 Furuta Pendulum Stabilization with LTI model

Consider the linearisation of the Furuta pendulum with the matrices

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 80.3 & -45.8 & -0.93 \\ 0 & 122 & -44.1 & -1.4 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 83.4 \\ 80.3 \end{bmatrix}.$$

$$\dot{s} = CAx + CBu.$$

$$\frac{d}{dt}\begin{bmatrix} s \\ \int s \end{bmatrix} = \begin{bmatrix} CA \\ C \end{bmatrix} x.$$

$$\frac{d}{dt} Y_1(t) = M_1 x.$$

$$\frac{d}{dt}\begin{bmatrix} s \\ \int s \end{bmatrix} = \begin{bmatrix} 0 & 0 & 3 & 10 \\ 3 & 10 & 0 & 0 \end{bmatrix} x.$$

$$\frac{d^2}{dt^2} Y_1(t) = M_1 A x + M_1 B u.$$

$$\frac{d^2}{dt^2} (M_1 B)^{\perp} Y_1(t) = (M_1 B)^{\perp} M_1 A x.$$

$$\frac{d^2}{dt^2} \begin{bmatrix} (M_1B)^{\perp} & 0 & 0 \\ 0 & (M_1B)^{\perp} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} s \\ \int s \\ \int \int s \end{bmatrix} = \begin{bmatrix} (M_1B)^{\perp} M_1 A \\ C \end{bmatrix} x \tag{3}$$

$$\ddot{s} = CA^2 x + CAB.$$