Brief note on match and miss-match uncertainties

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ABSTRACT

The appearance of uncertainties and disturbances often effects the characteristics of either linear or nonlinear systems. Plus, the stabilization process may be deteriorated thus incurring a catastrophic effect to the system performance. As such, this manuscript addresses the concept of matching condition for the systems that are suffering from miss-match uncertainties and exogeneous disturbances. The perturbation towards the system at hand is assumed to be known and unbounded. To reach this outcome, uncertainties and their classifications are reviewed thoroughly. The structural matching condition is proposed and tabulated in the proposition 1. Two types of mathematical expressions are presented to distinguish the system with matched uncertainty and the system with miss-matched uncertainty. Lastly, two-dimensional numerical expressions are provided to practice the proposed proposition. The outcome shows that matching condition has the ability to change the system to a design-friendly model for asymptotic stabilization.

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1. INTRODUCTION

Dealing with dynamical systems with uncertainties is trivial. Uncertainties may introduce nonlinarity and need linearization to facilitate stabilization process [1]. Considering a mechanical rotational system in practice, the uncertainties in the modeling may be contributed by the backlash in the gearing teeth [2]. Many stabilization approaches available in the literature can be opted to perform tracking tasks as well as regulation tasks for such systems. However, the presence of uncertainties and disturbances make the objectives a challenging task. Among the approaches, a classical [3], [4], optimal, and robust approaches are common.

Among the robust stabilization approaches, backstepping [5], [6] and variable structure system (VSS) [7]-[9] are known to be prevalent. Both techniques adopt the Lyapunov stability criteria [10]. VSS is a discontinuous nonlinear system. As a time-invariant system is normally denoted as $\dot{x} = \varphi(x)$ with a state vector $x \in \mathcal{R}^n$, VSS on the other hand can be denoted by a piecewise function $\dot{x} = \varphi(x, t)$ with $t \in \mathcal{R}$. A concept discussed in [8], [9] and the references therein state that a variable structure control has become the established method to control or regulate VSS. A sliding mode approach has become the main subset to a variable structure operation. Sliding mode is one of the established nonlinear management methods which is robust to parameter uncertainties. As such, sliding mode concept is suitable to stabilize a system with uncertain parameters [11]. Nevertheless, few shortcomings of sliding mode that can be compromised by designers are the chattering phenomenon, and it difficultness in handling miss-match uncertainties [12]. To overcome miss-match uncertainties in the mathematical expression, one may augment back-stepping calculation to the sliding mode approach [13].

This manuscript discusses about the uncertainties and disturbances thoroughly. As such, the rest of the manuscript begins with thorough review on the class of uncertainties and disturbances. The distinguishing features between match and miss-match uncertainties are discussed in detail. Then, a numerical example on the match and mismatch handling will be presented to replenish understanding.

2. UNCERTAINTIES AND DISTURBANCES

One of the key reasons for designing a controller is to combat with the adverse effect of uncertainty that may appear in different forms as disturbances or as other imperfections in the system model. Uncertainty is classified into two categories namely disturbance signals and dynamic perturbations. Disturbance signal includes sensor noise (see aircraft noise in [14]), actuator noise [15] and exogenous disturbance such as intermittent wind flow in wind turbine [16] and gust on aircraft [17]. Dynamic perturbations due to un-modelled dynamics (usually high frequency dynamics) is known as unstructured uncertainty [18], [19]. Neglected nonlinearities in the system model and variations in system parameters are known as parametric uncertainty [18], [19]. The unstructured uncertainty constitutes the lumped dynamic perturbations that may occur in different parts of a system. For linear time invariant systems, the configuration of unstructured uncertainty can be additive perturbation, inverse additive perturbation (see the application in wind farms in [20]), input multiplicative perturbation, output multiplicative perturbation, inverse input multiplicative, inverse output multiplicative perturbation, left coprime factor perturbations and right coprime factor perturbations [19]. On the other hand, the parametric uncertainties affect the low-frequency range performance that are normally caused by dynamic perturbations due to variations of certain system parameters. In a dynamical system model, the uncertain term can be matched with the control input, mismatched with the control input or mixed matched-mismatched with the control input. Hence, emerge a class of system so-called matched uncertainty, mismatched uncertainty, and matched-mismatched uncertainty [21], [22].

There is a large volume of published studies describing the method to solve a dynamical system with uncertainty. Numerous studies in [21]-[23] have attempted to solve matched uncertainty using a sliding mode control (SMC) and a variable structure control (VSC). A method to solve nonlinear system with matched uncertainty using Lyapunov redesign are discussed in [24], [25].

Mismatched and mixed matched-mismatched uncertainty are rather hard to handle as they require matching condition such that the uncertain term matched with the control input. An early matching condition using a Lyapunov min-max approach can be reviewed in [26]. Choi [27], [28], Lee and Mau [29] proposed SMC to stabilize linear dynamical system with mismatched uncertainty. For a system with nonlinearity and input matrix uncertainty, the approach has been proposed by Choi in [30]. To date, very little literature proposed a control approach for nonlinear system with matched-mismatched uncertainty. Amongst them, Park *et al*. [31] proposed VSC for linear system with matched-mismatched uncertainty. In Kamarudin *et al*. [5], proposed back-stepping and Lyapunov redesign approach to stabilize nonlinear system with matched-mismatched uncertainty. To compensate the uncertainty in the design therein, the nominal back-stepping controller is augmented with nonlinear damping function.

As for linear systems, numerous studies have been revealed. For example, studies in [32] reported the use of linear matrix inequalities (LMI-based) approach to the analysis and design of closed-loop system under linear state feedback laws to maximize the disturbance rejection capability. Several studies thus far have linked the use of LMI-based method to the problem of disturbance tolerance and rejection for a family of linear systems subject to actuator saturation and L_∞-disturbances [33], [34], L_2-disturbance [35]-[37] or L_∞/L_2-disturbance [38]. More practical treatments on the uncertainties have been discussed by Jamri [39], and overview in power system. Figure 1 summarizes the uncertainties phenomena and they classification.

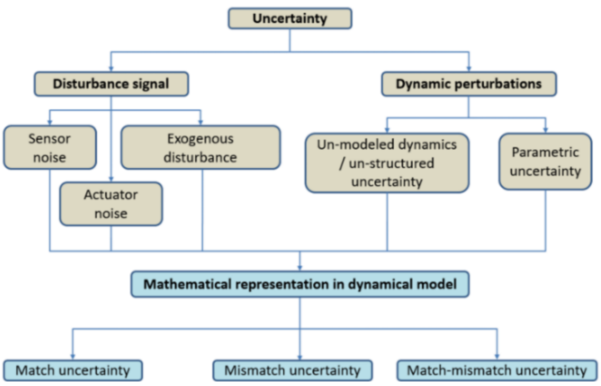

Figure 1. Class of uncertainties and disturbances

3. MISS-MATCH HANDLING

Miss-match (or un-match) uncertainties are rather hard to handle. In certain occasion, system with miss-match uncertainties needs structural condition and complex mathematical manipulation. Simple continuous time-invariant system with miss-match exogenous disturbance is shown in (1).

$$\dot{x} = F(x) + G(x)u + H(x)\mathcal{w} \tag{1}$$

Where $F(\cdot)$, $G(\cdot)$ and $H(\cdot)$ are continuous functions, u is the control input, and $\mathcal{w}$ is the disturbance input. The conceptual diagram for the system is depicted in Figure 2.

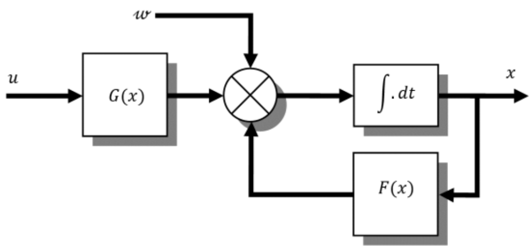

Figure 2. Conceptual diagram for system in (1)

It is clearly shown in both (1) and Figure 2 that $\mathcal{w}$ is miss-match to u; and u does not affine in $\dot{x}(F, H)$. As such, one might simply design a stabilizing function u under assumption that nominal system in (1) is stabilizable and the state is available for feedback; that is $Y(x) = \{x\}$ for output $Y(x)$. However, omitting $\mathcal{w}$ in the stabilizing function u may not realize the stabilization if $\mathcal{w}$ dominate the function and has no constraint. Though $\mathcal{w}$ constraint the closed unit ball ($\mathcal{w} \equiv \mathcal{B}$), the unconstrained control function ($u \equiv \mathcal{U}$) unable to dominate $\mathcal{w}$. In this case, one might ponder a structural condition for (1) as portrayed in proposition 1.

3.1. Proposition 1

Assume that there exists a continuous function $E(x)$ that satisfies structural condition $H(x) = G(x)E(x)$. Then the matching condition can be applied to the system (1).

$$\dot{x} = F(x) + G(x)[u + E(x)\mathcal{w}] \tag{2}$$

Through proposition 1, u and $\mathcal{w}$ become affine in $G(x)$, and $\mathcal{w}$ is said to be matched with the control input u. Thus $\mathcal{w}$ can be combated easily provided that $\mathcal{w}$ is available and observable. In case $\mathcal{w}$ is unobservable, one might use disturbance estimator provided that the bounded of $\mathcal{w}$is known (perhaps within a closed unit ball $\mathcal{w} \equiv \mathcal{B}$). Figure 3 shows affine function (2) where $\mathcal{w}$ enters through the same input channel as u.

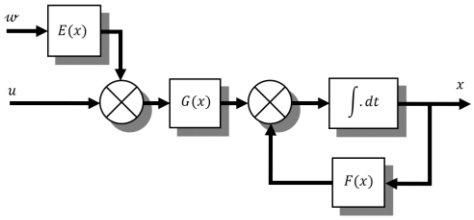

Figure 3. System in (1) after matching condition

3.1.1. Miss-match versus match uncertainties

To replenish the understanding towards the method, two numerical systems are shown in (3) and (4).

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= u + x_1^3\mathcal{w} \end{aligned} \tag{3}$$

$$\begin{aligned} \dot{x}_1 &= x_2 + x_1^3\mathcal{w} \\ \dot{x}_2 &= u \end{aligned} \tag{4}$$

Note that both systems in (3) and (4) possess identical dynamic (system matrix $\begin{bmatrix}0 & 1\\0 & 0\end{bmatrix}$) and input matrix ($[0 \quad 1]^T$). The only difference between the two is the attribute of matrix associated with w. To this end, system in (3) satisfies the matching condition because the disturbance can be re-grouped into a function $f(u, w, x_1)$. Whereas, system in (4) does not satisfy the matching condition. To visualize the issue, let us plug the numerical dynamics into the system. With simple matrix algebra, one would reach clearer visualization between match and miss-match appearance in the system at hand. Hence, system (3) becomes:

$$\begin{bmatrix}\dot{x}_1\\\dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\0 & 0\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix} + \begin{bmatrix}0\\1\end{bmatrix}[u + x_1^3 w] \tag{5}$$

Whereas system (4) turns into:

$$\begin{bmatrix}\dot{x}_1\\\dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\0 & 0\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix} + \begin{bmatrix}0\\1\end{bmatrix}u + \begin{bmatrix}1\\0\end{bmatrix}x_1^3 w \tag{6}$$

System (5) portrays a matched uncertainty. Whereas system (6) reveals miss-match uncertainty that is identical to the priorly defined system in (1). At glance, we can control the 1st state. The system is controllable if we consider the controllable matrix denotes as:

$$C_m \triangleq [B \quad AB] = \begin{bmatrix}0 & 1\\1 & 0\end{bmatrix} \tag{7}$$

That gives the rank 2 matrix. As the systems are known to be autonomous, the null input matrix results in unobservable states. As both systems (5) and (6) are controllable, let design the feedback gain K that will produce the control energy $u = -Kx$ under the nominal condition (that is $w = 0$). To simplify the process, let us place the closed loop aigenvalues $(A - BK)$ in stable region, for instance $eig(A - BK) \equiv [-1 \quad -2]$. The judicious choice of $eig(A - BK)$ leads to the feedback gain $K = [2 \quad 3]$. The history of the states trajectory is depicted in Figure 4. With the judicious K-value, both states return to equilibria within 3 seconds with initial condition $x(0) = [1 \quad 1]$. Figure 5 shows the control law for system in (6) with matched disturbance w appeared in the system. Despite the disturbance, the system is stabilizable with only slight distortion in the trajectory, as depicted in Figure 6.

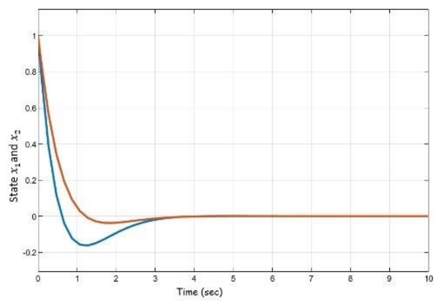

Figure 4. State trajectory for system (6) without disturbance w with state feedback

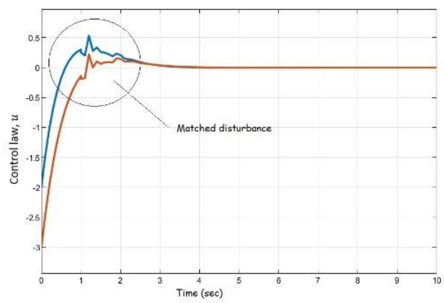

Figure 5. Control law u for system (6) when disturbance w occurred

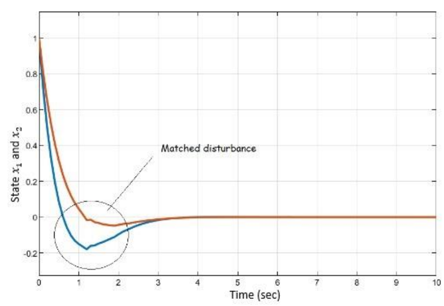

Figure 6. State trajectory for system (6) with disturbance w and state feedback

3.1.2. Example of matching condition

To illustrate the concept of structural matching condition more literally, let consider two-dimensional nonlinear system of the form.

$$\dot{X} = f(X) + g(X)y + h(X)\xi(X,t) \tag{8}$$

$$y = u \tag{9}$$

Where $\begin{bmatrix} X \\ y \end{bmatrix} \in \mathcal{R}^{n+1}$ are the system states with $X \in \mathcal{R}^n$, $X \in \mathcal{R}$ is the single control input, $\xi(X,t)$ is the sum of uncertainties and time varying exogenous disturbances, $f(\cdot)$, $g(\cdot)$ and $h(\cdot)$ are smooth functions. As compared with one dimensional system in (2), the control problem for system (8) and (9) become more complicated as the control command u does not directly influence x_1. In addition, $\xi(X,t)$ is mismatches to y and u. Therefore, it needs structural matching condition prior to the design steps. By using proposition 1, we introduce a continuous function $p(X)$ that satisfies structural condition $h(X) = g(X)P(\text{X})$. Then the matching condition can be applied to the system (8), (9). The dynamic equation in subsystem (10) eases the elimination of $p(X)\xi(X,t)$-term via a virtual control y. To this end, the design objective is to eliminate $\xi(X,t)$ by a control law (not to be discussed in this work).

$$\dot{X} = f(X) + g(X)[u + p(X)\xi(X,t)] \tag{10}$$

$$y = u \tag{11}$$

4. CONCLUSION

The necessity of matching condition is emphasized in the existence of unmatched uncertainties (or mismatched) and exogeneous disturbances. Beforehand, the matching case and unmatching case were distinguished with example. The outcome showed that the structural matching condition is able to simplify the systems in order to facilitate control design. In the future, the application of control design will be presented in conjunction to the matching process discussed in this manuscript.

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