Brief paper

Subsystem identification of multivariable feedback and feedforward systems

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Abstract

We present a frequency-domain technique for identifying multivariable feedback and feedforward subsystems that are interconnected with a known subsystem. This subsystem identification algorithm uses closed-loop input–output data, but no other system signals are assumed to be measured. In particular, neither the feedback signal nor the outputs of the unknown subsystems are assumed to be measured. We use a candidate-pool approach to identify the feedback and feedforward transfer function matrices, while guaranteeing asymptotic stability of the identified closed-loop transfer function matrix. The main analytic result shows that if the data noise is sufficiently small and the candidate pool is sufficiently dense, then the parameters of the identified feedback and feedforward transfer function matrices are arbitrarily close to the true parameters.

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1. Introduction

Subsystem identification (SSID) is the process of building empirical models of unknown dynamic subsystems, which are interconnected with known dynamic subsystems. These connections can be series, parallel, or feedback. SSID relies on measured data to identify the unknown subsystems. However, not all input and output signals to the unknown subsystems are necessarily accessible, that is, available for measurement.

This paper is concerned with closed-loop SSID of unknown feedback and feedforward subsystems interconnected with a known subsystem as shown in Fig. 1. The exogenous input \( r \) and closed-loop output \( y \) are measured, whereas internal signals \( u \) and \( v \) are not assumed to be accessible. We note that closed-loop SSID is distinct from the well-studied problem of system identification in closed loop (Forssell & Ljung, 1999; Isermann & Münchhof, 2011; Van den Hof, 1998; Van den Hof & Schrama, 1995). Specifically, in SSID, the unknown subsystems have inputs or outputs that are inaccessible.

SSID has applications in biology and physics as well as human-in-the-loop systems. For example, many biological systems are modeled by the interconnection of subsystems, which may be unknown and have inaccessible inputs and outputs (Roth, Sponberg, & Cowan, 2014). Similarly, physical systems are often modeled by a composition of subsystems, which are based on either physical laws or empirical information. For example, in D’Amato, Ridley, and Bernstein (2011), a large-scale physics-based model of the global ionosphere–thermosphere is improved by using measured data to estimate thermal conductivity, which can be regarded as an unknown feedback subsystem. In this application, the output of the unknown subsystem is inaccessible.

SSID also has application to modeling human behavior. For example, there is interest in modeling human-in-the-loop behavior for applications such as aircraft (Itoh & Suzuki, 2005; Nieuwenhuizen, Beykirch, Mulder, & Bülthoff, 2007; Nieuwenhuizen & Bülthoff, 2013; Olivari, Nieuwenhuizen, Venrooij, Bülthoff, & Pollini, 2012) and automobiles (Hellstrom & Jankovic, 2015; Macadam, 2003; Steen, Damveld, Happee, van Paasen, & Mulder, 2011). In addition, SSID methods can be used to model human behavior in motor control experiments, which study human learning (Drop, Pool, Damveld, van Paasen, & Mulder, 2013; Kiemel, Zhang, & Jeka, 2011; Laurence, Pool, Damveld, van Paasen, & Mulder, 2015; Zhang & Hoagg, 2016).

Closed-loop SSID of feedback and feedforward models is considered in D’Amato et al. (2011), Gillijns and De Moor (2006), Morozov et al. (2011) and Palanthandalam-Madapusi, Gillijns, De Moor, and Bernstein (2006). However, the identified feedback and feedforward models obtained from the methods in D’Amato et al. (2011), Gillijns and De Moor (2006), Morozov et al. (2011)
and Palanthandalam-Madapusi et al. (2006) can result in unstable closed-loop dynamics. To address closed-loop stability, Zhang and Hoagg (2016) present an SSID technique that guarantees asymptotic stability of the identified closed-loop transfer function. The approach in Zhang and Hoagg (2016) applies to single-input single-output (SISO) subsystems and requires that the measured closed-loop output $y$ is the same as the feedback $v$.

The new contribution of this paper is a closed-loop SSID method that: (i) identifies multi-input multi-output (MIMO) feedback and feedforward subsystems; (ii) allows for a measured output $y$ that is not necessarily the same as the feedback $v$; and (iii) guarantees asymptotic stability of the identified closed-loop transfer function matrix. This paper adopts techniques from Zhang and Hoagg (2016) but goes beyond the previous work by addressing MIMO subsystems and allowing for the measured output $y$ to differ from the feedback $v$. Furthermore, the discrete-time SSID approach in this paper can improve computational efficiency relative to the continuous-time approaches in Zhang and Hoagg (2016).

In this paper, the feedforward subsystem model is parameterized as a finite impulse response (FIR) transfer function matrix, which can improve computational efficiency as discussed in Section 7. To accomplish (i)-(iii), we use a candidate-pool approach. Our main analytic result shows that if the data noise is sufficiently small and the candidate pool is sufficiently dense, then the parameters of the identified feedback and feedforward transfer function matrices are arbitrarily close to the true parameters.

### 2. Notation

Let $\mathbb{F}$ be either $\mathbb{R}$ or $\mathbb{C}$. Then, $x_{(i)}$ denotes the $i$th component of $x \in \mathbb{F}^n$, and $A_{(i,j)}$ denotes the $(i,j)$ entry of $A \in \mathbb{F}^{m \times n}$. Let $\| \cdot \|$ be a norm on $\mathbb{F}^m$, and let $\| \cdot \|$ be the two-norm on $\mathbb{F}^n$. Next, let $A^*$ denote the complex conjugate transpose of $A \in \mathbb{F}^{m \times n}$, and define $|A|_F = \sqrt{tr A^*A}$, which is the Frobenius norm of $A \in \mathbb{F}^{m \times n}$. Let $A^+$ denote the adjugate of $A \in \mathbb{F}^{m \times n}$.

Let $A$ be the vector in $\mathbb{F}^m$ formed by stacking the columns of $A \in \mathbb{F}^{m \times n}$ and $B \in \mathbb{F}^{k \times l}$. Let $\mathbb{R}[z]$ denote the set of polynomials with coefficients in $\mathbb{R}$, and let $\mathbb{R}^{m \times n}[z]$ denote the set of $m \times n$ polynomial matrices, that is, the set of matrix functions $P : \mathbb{C} \rightarrow \mathbb{C}^{m \times n}$ whose entries are polynomials $P \in \mathbb{R}[z]$. The degree of the polynomial $p \in \mathbb{R}[z]$ is denoted by $deg(p)$, and the degree of the polynomial matrix $P \in \mathbb{R}^{m \times n}[z]$ is denoted by $deg P \triangleq \max_{i,j} m_{i,j} \cdots n_{i,j}$ of degree $deg_p$.

Define the open ball of radius $\epsilon > 0$ centered at $c \in \mathbb{F}^{m \times n}$ by $B(c, \epsilon) = \{ x \in \mathbb{F}^{m \times n} : |x - c| < \epsilon \}$ and $Z_+^*$ denote the set of positive integers.

**Definition 1.** Let $\Delta \subseteq \mathbb{F}^{m \times n}$ be bounded and contain no isolated points. For all $j \in Z^+$, let $\Delta_j \subseteq \Delta$ be a finite set. Then, $(\Delta_j)_{j=1}^\infty$ converges to $\Delta$ if for each $x \in \Delta$, there exists a sequence $(x_j)_{j=1}^\infty$ such that for all $j > 0$, there exists $L \in Z^+$ such that for all $j > L$, $x_j \in B(x, \epsilon)$.

### 3. Problem formulation

Let $G_f : \mathbb{C} \rightarrow \mathbb{C}^{n \times m}$ and $G_b : \mathbb{C} \rightarrow \mathbb{C}^{L \times m}$ be real rational transfer function matrices, and consider the linear time-invariant system with impulse response $\alpha(n)$.
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