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# State Estimation for Linear Impulsive Systems

Enrique A. Medina and Douglas A. Lawrence

**Abstract— In this paper, we treat the fundamental problem of state estimation for a class of linear impulsive systems with time-driven impulsive effects. We show that a *strong observability* property enables an impulsive observer to be constructed that yields uniformly exponentially stable estimation error dynamics. This approach accommodates impulsive systems with arbitrarily-spaced impulse times and singular state transition matrices in a manner reminiscent of well-known results for time-varying discrete-time linear systems. As an example, an observer is constructed for an impulsive system that produces general cubic spline signals.**

## I. Introduction

Impulsive systems evolve according to continuous-time dynamics and are also subject to impulsive effects governed by discrete-time dynamics that yield instantaneous changes. These impulsive effects may occur at prescribed time instants and/or be triggered by specified events along a particular trajectory. In this paper, we focus on state estimation for linear impulsive systems with time-driven impulsive effects specified by a set of impulse times. The main contribution is an observer construction for such systems that satisfy a *strong observability* property.

It has been shown by several researchers that state estimation and filtering for continuous-time linear systems with discrete [1], [10], mixed continuous-discrete [7], or multirate [9] measurements leads naturally to observers with an impulsive structure. Moreover, it has been shown that filter/observer gains that yield optimal estimation performance (with respect to various optimality criteria) are derived from differential Riccati equations with jumps. More general measurement schemes considered in [8] yield observers and Riccati equations described by differential equations over distributions. Here we consider systems with impulsive dynamics as well as discrete-time measurements which potentially results in a singular state transition matrix. We also accommodate impulsive systems with arbitrarily-spaced impulse times. These system characteristics significantly complicate the computation of observer gains that yield uniformly exponentially stable error dynamics. Our approach is inspired by the work of Anderson and Moore in [6] for time-varying discrete-time linear systems with singular state transition matrices.

The remainder of the paper is organized as follows. In Section II, the class of linear impulsive systems is specified for which stability and observability properties are characterized that underpin the ensuing analysis. In Section III, an impulsive observer construction is derived that achieves uniformly exponentially stable error dynamics. In Section IV, this scheme is applied to an impulsive system that produces general cubic spline signals. Concluding remarks are offered in Section V.

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## II. Preliminaries

We consider linear impulsive systems described by

$$\begin{aligned} \dot{x}(t) &= A_C x(t) + B_C u(t) && t \in \mathbb{R} \setminus \mathcal{T} \\ x(\tau_k) &= A_Z x(\tau_k^-) + B_Z w[k] && \tau_k \in \mathcal{T} \\ y[k] &= C_Z x(\tau_k^-) \end{aligned} \tag{1}$$

where $\mathcal{T}$ is a countably infinite set of strictly increasing impulse times assumed to contain a finite number of elements on any finite time interval, $x(t)$ is the continuous-time state that undergoes instantaneous changes at the impulse times, $u(t)$ is a continuous-time input, $w[k]$ is a discrete-time input, and $y[k]$ is a discrete-time measurement. The state space for (1) is denoted by $\mathcal{X}$.

Given an initial time $t_0$ and final time $t_f > t_0$, for notational simplicity we denote the subset of impulse times $\mathcal{T} \cap [t_0, t_f)$ by $\{\tau_1, \tau_2, \ldots, \tau_k\}$. We then define $\delta_0 = \tau_1 - t_0$, $\delta_i = \tau_{i+1} - \tau_i$ for $i = 1, \ldots, k-1$, and $\delta_k = t_f - \tau_k$. In terms of this, the state transition matrix of (1) is given by

$$\Phi(t_f, t_0) = e^{A_C \delta_k} A_Z e^{A_C \delta_{k-1}} A_Z \cdots A_Z e^{A_C \delta_1} A_Z e^{A_C \delta_0} \tag{2}$$

The state transition matrix is invertible for all $t_f > t_0$ if and only if $A_Z$ is invertible. In this case, $\Phi(t_0, t_f)$ can be defined via $\Phi(t_0, t_f) = \Phi^{-1}(t_f, t_0)$. The state response of (1) on $[\tau_k, \tau_{k+1})$ given $x(t_0) = x_0$ can be compactly written as

$$x(t) = \Phi(t, t_0) x_0 + \int_{t_0}^{t} \Phi(t, \tau) B_C u(\tau)\, d\tau + \sum_{j=1}^{k} \Phi(t, \tau_j) B_Z w[j]$$

In the remainder of the paper, we focus on the construction of an impulsive observer of the form

$$\begin{aligned} \dot{\hat{x}}(t) &= A_C \hat{x}(t) + B_C u(t) && t \in \mathbb{R} \setminus \mathcal{T} \\ \hat{x}(\tau_k) &= A_Z \hat{x}(\tau_k^-) + B_Z w[k] \\ &\quad + L_Z[k]\left(C_Z \hat{x}(\tau_k^-) - y[k]\right) && \tau_k \in \mathcal{T} \end{aligned} \tag{3}$$

in which the observer gain $L_Z[k]$ is to be determined in order to yield uniformly exponentially stable error dynamics

$$\begin{aligned} \dot{\tilde{x}}(t) &= A_C \tilde{x}(t) && t \in \mathbb{R} \setminus \mathcal{T} \\ \tilde{x}(\tau_k) &= \left(A_Z + L_Z[k] C_Z\right) \tilde{x}(\tau_k^-) && \tau_k \in \mathcal{T} \end{aligned} \tag{4}$$

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