Survey

Nicole Gehring*, Abdurrahman Irscheid, Joachim Deutscher, Frank Woittennek, and Joachim Rudolph

Control of distributed–parameter systems using normal forms: An introduction

Abstract: This paper gives an overview of the control of distributed-parameter systems using normal forms. Considering linear controllable PDE-ODE systems of hyperbolic type, two methods derive tracking controllers by mapping the systems into a form that is advantageous for the control design, analogous to the finite-dimensional case. A flatness-based controller makes use of the hyperbolic controller canonical form that follows from a parametrization of the system's solutions. A backstepping design exploits the strict-feedback form of the system to recursively stabilize and transform the subsystems.

Keywords: distributed-parameter systems, state feedback, backstepping, flatness, canonical forms

1 Introduction

In control theory, a normal or canonical form usually refers to a special state-space representation of a dynamical system that is well-suited for a certain analysis or synthesis purpose. Thereby, the label canonical is usually used if a form is unique. The basic idea of a controller design using normal forms is sketched in Figure 1. For linear finite-dimensional single-input single-output (SISO) systems, the pioneering work [20] introduced the controller canonical form (CCF) and the observer canonical form (OCF) that are also sometimes called the controllable and observable canonical form, respectively. While any observable system can be mapped into OCF, the CCF

$$\dot{\eta} = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ \vdots & & \ddots & \ddots & \vdots \\ \vdots & & & \ddots & 0 \\ 0 & & \cdots & 0 & 1 \\ -a_0 & -a_1 & \cdots & & -a_{n-1} \end{bmatrix} \eta + \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ 0 \\ 1 \end{bmatrix} u \quad (1)$$

exists for any controllable system. It is well known that the design of a stabilizing state feedback for (1) is straightforward as the characteristic coefficients a_i, $i = 0, \ldots, n-1$, are simply replaced by some desired ones of a stable closed-loop system (e.g. [28]). This simplicity motivates the use of normal forms for a design. As illustrated in Figure 1, instead of a potentially very involved synthesis based on the original representation, a system is first mapped into, e.g., CCF, with a stabilizing feedback of the normal form state implied by the obtained simple system structure. Together with the inverse state transformation this results in the sought feedback of the original state. This design strategy using normal forms is not limited to linear finite-dimensional systems.

The nonlinear counterpart of (1) also involves a chain of integrators, with a nonlinear function in the last differential equation (e.g. [39]). As in the linear setting, the existence of such a nonlinear CCF is closely related to the controllability of the system. Flatness or more precisely differential flatness (see, e.g., [14, 23, 27]) is a system property that can be interpreted as one possible extension of the notion of controllability to nonlinear systems. If a system is flat, there exists a (fictitious) flat output that allows to express all system variables — in particular the state and the input — in terms of the flat output and a finite number of its time derivatives. Not only is this flatness-based parametrization known to allow for an easy trajectory planning and feedforward design, but the flat output and its derivatives also form a nonlinear CCF state. Consequently, the controller synthesis for flat systems is straightforward. For example, all nonlinear SISO systems in strict-feedback form

$$\dot{\eta}_1 = f_1(\eta_1) + g_1(\eta_1)\eta_2 \quad (2a)$$

$$\dot{\eta}_2 = f_2(\eta_1, \eta_2) + g_2(\eta_1, \eta_2)\eta_3 \quad (2b)$$

$$\vdots$$

$$\dot{\eta}_n = f_n(\eta_1, \ldots, \eta_n) + g_n(\eta_1, \ldots, \eta_n)u \quad (2c)$$

(see, e.g., [21]) are flat due to their structure, with the differential equation for $\eta_i(t)$, $i = 1, \ldots, n$, only depending on $\eta_1(t), \ldots, \eta_{i+1}(t)$ (with $\eta_{n+1}(t) = u(t)$). Thus, $\eta_1(t)$ constitutes a flat output. The well-known backstepping

*Corresponding author: Nicole Gehring, Johannes Kepler University Linz, Austria

Abdurrahman Irscheid, Joachim Rudolph, Saarland University, Germany
Joachim Deutscher, Ulm University, Germany
Frank Woittennek, UMIT TIROL, Austria

Distributed Parameter Control Systems Trends And Applications

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