Preface

The method of "integrator backstepping" emerged around 1990 as a robust version of feedback linearization for nonlinear systems with uncertainties. Backstepping was particularly inspired by situations in which a plant nonlinearity, and the control input that needs to compensate for the effects of the nonlinearity, are in different equations. An example is the system

$$\begin{aligned}\dot{x}_1 &= x_2 + x_1^3 d(t),\\ \dot{x}_2 &= x_3,\\ \dot{x}_3 &= u\,,\end{aligned}$$

where $x = (x_1, x_2, x_3)$ is the system state, u is the control input, and $d(t)$ is an unknown time-varying external disturbance. Note that for $d(t) \equiv 1$ this system is open-loop unstable (with a finite escape time instability). Because backstepping has the ability to cope with not only control synthesis challenges of this type but also much broader classes of systems and problems (such as unmeasured states, unknown parameters, zero dynamics, stochastic disturbances, and systems that are neither feedback linearizable nor even completely controllable), it has remained the most popular method of nonlinear control since the early 1990s.

Around 2000 we initiated an effort to extend backstepping to partial differential equations (PDEs) in the context of boundary control. Indeed, on an intuitive level, backstepping and boundary control are the perfect fit of method and problem. As the simplest example, consider a flexible beam with a destabilizing feedback force acting on the free end (such as the destabilizing van der Waals force acting on the tip of the cantilever of an atomic force microscope (AFM) operating with large displacements), where the control is applied through boundary actuation on the opposite end of the beam (such as with the piezo actuator at the base of the cantilever in the AFM). This is a prototypical situation in which the input is "far" from the source of instability and the control action has to be propagated through dynamics—the setting for which backstepping was developed.

Backstepping has proved to be a remarkably elegant method for designing controllers for PDE systems. Unlike approaches that require the solution of operator Riccati equations, backstepping yields control gain formulas which can be evaluated using symbolic computation and, in some cases, can even be given explicitly. In addition, backstepping achieves stabilization of unstable PDEs in a physically appealing way, that is, the destabilizing terms are eliminated through a change of variable of the PDE and boundary feedback. Other methods for control of PDEs require extensive training in PDEs and functional analysis.

Backstepping, on the other hand, requires little background beyond calculus for users to understand the design and the stability analysis.

This book is designed to be used in a one semester course on backstepping techniques for boundary control of PDEs. In Fall 2005 we offered such a course at the University of California, San Diego. The course attracted a large group of postgraduate, graduate, and advanced undergraduate students. Due to the diversity of backgrounds of the students in the class, we developed the course in a broad way so that students could exercise their intuition no matter their backgrounds, whether in fluids, flexible structures, heat transfer, or control engineering. The course was a success and at the end of the quarter two of the students, Matthew Graham and Charles Kinney, surprised us with a gift of a typed version of the notes that they took in the course. We decided to turn these notes into a textbook, with Matt's and Charles' notes as a starting point, and with the homework sets used during the course as a basis for the exercise sections in the textbook.

We have kept the book short and as close as possible to the original course so that the material can be covered in one semester or quarter. Although short, the book covers a very broad set of topics, including most major classes of PDEs. We present the development of backstepping controllers for parabolic PDEs, hyperbolic PDEs, beam models, transport equations, systems with actuator delay, Kuramoto–Sivashinsky-like and Korteweg–de Vries-like linear PDEs, and Navier–Stokes equations. We also cover the basics of motion planning and parameter-adaptive control for PDEs, as well as observer design with boundary sensing.

Short versions of a course on boundary control, based on preliminary versions of the book, were taught at the University of California, Santa Barbara (in Spring 2006) and at the University of California, Berkeley (in Fall 2007 and where the first author was invited to present the course as a Russell Severance Springer Professor of Mechanical Engineering).

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