A Nonlinear Perspective to Intelligent Control Systems

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1 Introduction

In the talk, we will provide a nonlinear perspective to intelligent control and intelligent systems. At the onset, one realizes that intelligent system research is a broad theme that can have drastically different interpretations among researchers [1]. Here we discuss the issues of intelligent control systems from an angle of nonlinear studies. Nonlinear dynamical systems are the rule of nature rather than the exception. A fundamental challenge in intelligent control systems design is to contend with nonlinearity. In classical design methods and tasks, nonlinearities in feedback systems were viewed as lying somewhere between novelties and undesirable features which should avoided if at all possible [2]. We believe that one aspect of intelligent control systems should be aimed at exploiting (rather than avoiding) nonlinear

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features in designs. In other words, the control system designer needs to be *intelligent* about nonlinearity.

In fact, the important tasks of modeling and control design in intelligent control systems amount to nothing more than establishing mappings from input to state variables and/or output, and from measurement variables to control input. The so-called intelligent control approaches, including neural networks, artificial intelligence, fuzzy logic, genetic algorithm, etc., are useful mainly because they provide practical means to deal with nonlinearity in this process of modeling and control design.

In this talk, we report recent advances in two aspects of nonlinear control systems, namely, control of nonlinear dynamics, and nonsmooth feedback design. An intelligent control system is expected to deliver high performance in dynamic and uncertain environments. Control of nonlinear dynamics is intimately linked with the high performance operation of engineering systems in stressed situations. Nonsmooth feedback also aims at rendering high performance controllers for various applications.

2 High Performance Intelligent Systems and Nonlinearity

The past two decades have witnessed steadily increasing recognition and appreciation of nonlinear dynamics across a broad range of disciplines. Applications of bifurcations and chaos have appeared in many areas of engineering, physics, and natural and social sciences. All these have led to a remarkable change in the way engineers and scientists interact with nonlinear dynamics. While ten years ago nonlinear dynamics to most of us was somewhat a novelty, it has become an indispensable part of our toolkits today. The main purpose hereby is to discuss the role which nonlinear dynamics has played in high performance intelligent systems and control, emphasizing the much needed interplay between nonlinear dynamics and control designs.

Investigations of control systems issues related to nonlinear dynamics such as bifurcations and chaos began relatively recently [2]. The main motivation for the study of control of bifurcation and chaos relates to a performance vs. stability trade-off that appears in a variety of forms in various applications. It is often the case that significant improvement in performance is achieved by operation near the stability boundary. These are highly nonlinear situations occurring in the high-performance operation of a wide variety of systems. Such operations tend to exhibit nonlinear instabilities in terms of a jump to a new low-performance operating point, oscillatory behavior, chaotic behavior or system collapse in the absence of appropriate control action. Examples of the consequences of operating a system close to its inherent limits include:

- Aircraft stall in supermaneuvers;
- Blackout of a heavily loaded electric power system;
- Aircraft stall in supermaneuvers;
- Failure of a heavily loaded information network;
- Aircraft engine stall; and
- Runaway in chemical processes.

Achieving increases in performance while maintaining an acceptable safety margin is an important current engineering challenge. An essential aspect of this challenge is the design of controllers which facilitate operation of systems in nonlinear regimes with a negligible margin of stability. It is important to note that linearized models are not adequate for prediction or control of a system's response near the stability boundary.

The control problems addressed herein are characterized by two main features: 1. impact of nonlinear dynamical phenomena on system behavior; 2. achievement of control objectives via altering nonlinear dynamics. These belong to the type of problems that cannot be adequately addressed without recoursing to results from nonlinear dynamics, especially, bifurcations and chaos. We view control systems design as an enabling technology for intelligent systems in which complex nonlinear dynamics behavior arises. The ability of managing this type of behaviors intelligently can result in significant practical benefits. This might entail facilitating system operability in regimes where linear control methods break down; taking advantages of bifurcative and chaotic behavior to capture a desired steady or oscillatory state without expending much control energy; or purposely introducing a chaotic signal in a communication system to mask a transmitted signal, thereby allowing for development of new encryption technology.

Theoretical and technical problems as well as applications future in the search along this direction will be presented. Applications will be drawn from a variety of disciplines. These include thermal convection, mechanical systems, jet engine dynamics, and nonlinear cardiac dynamics.

3 Nonsmooth Feedback: Fractional Power Control

Recent interest in nonsmooth feedback design can be attributed to at least two reasons. Although most of natural and man-made systems are smooth, they may not be stabilized by smooth feedback, but can be stabilized by nonsmooth feedback. In fact, the systems having unstable noncontrollable eigenvalue of approximate linearization, cannot be stabilized using smooth feedback [3]. The well-known examples include some nonholonomic systems and under-actuated systems. Furthermore, even for the systems that can be stabilized by smooth feedback, nonsmooth control design can still be applied to improve system performance. Sliding mode control and time-optimal control are well-known examples. They may improve the transient behavior (for instance, time-optimal control can minimize overshoot) and increase the robustness properties (for instance, sliding mode control can handle unmodeled dynamics).

In fact, there are many kinds of nonsmooth feedback control: sliding mode control, piece-wise constant control, and piece-wise linear control. Here we do not intend to give a comprehensive summary about nonsmooth feedback designs. Rather we focus on a special form of nonsmooth feedback: controllers consisting of terms of factional powers, which are referred to as fractional power control (FPC). Note that FPC is continuous, though it is not smooth.

In the problem of controlling nonlinear dynamics such as bifurcations and chaos, most of the existing control designs are based on smooth feedback. By employing factional power control, new bifurcation phenomena are shown to occur with increased performance for the closed-loop system [6]. Specifically, a proposed FPC feedback law leads to a so-called trumpet bifurcation. As an application, a simple FPC design is demonstrated to be effective in the control of rotating stall in axial flow compressors. FPC can also be viable in the control of border-collision bifurcation phenomena which exist in nonsmooth dynamical systems such as impact oscillators. Similarly, control of chaos via FPC can be studied, too.

Another application of FPC is on finite-time control design, which means that with the proposed feedback control laws, the closed-loop systems are finite-time convergent to the desired states in addition to being Lyapunov stable. The finite-time control design has traditionally been studied in the context of optimality or controllability. The resulting controllers are usually discontinuous, or time-varying, or depending directly on the initial conditions. Finite-time control design via *continuous time-invariant* feedback laws has become the focal point of several recent studies. In particular, state feedback finite-time stabilization can be realized by FPC, and moreover, finite-time stabilization via dynamic output feedback, in conjunction with finite-time (convergent) observers can be obtained as well [7]. Some applications such as robot control has been considered.

Moreover, FPC usually have disturbance-rejection properties. In fact, FPC, which is continuous, can be viewed as a trade-off between discontinuous feedback and linear feedback. If carefully selected, it may enjoy the benefits of both classes of controllers and minimize their disadvantages (such as chattering phenomena).

4 Conclusion

In summary, we discuss some recent advances in control of nonlinear dynamics and nonsmooth feedback design with the emphasis on how to deal with nonlinearity in an intelligent manner in nonlinear and complex systems.

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