Preface

The output regulation problem, or alternatively, the servomechanism problem, addresses design of a feedback controller to achieve asymptotic tracking for a class of reference inputs and disturbance rejection for a class of disturbances in an uncertain system while maintaining closed-loop stability. This is a general mathematical formulation applicable to many control problems encountered in our daily life, for example, cruise control of automobiles, aircraft landing and taking-off, manipulation of robot arms, orbiting of satellites, motor speed regulation, and so forth. Study of the output regulation problem can be traced as far back as 1769 when James Watt devised a speed regulator for a steam engine; yet rigorous formulation of this problem in a modern state-space framework was not available until the 1970s. In contrast to similar problems, such as trajectory tracking, where the trajectory to be tracked is assumed to be completely known, a distinctive feature of the output regulation problem is that the reference inputs and disturbances do not have to be known exactly so long as they are generated by a known, autonomous differential equation. In the following, the term "exogenous signals" will be used to refer to both reference inputs and disturbances when there is no need to distinguish them. The autonomous differential equation generating exogenous signals will be called the exosystem.

The output regulation problem was first studied for the class of linear systems under various names such as the robust servomechanism problem (Davison), or the structurally stable output regulation problem (Francis and Wonham). It was completely solved by the collective efforts of several researchers, including Davison, Francis, and Wonham, to name just a few. Solvability conditions for the output regulation problem were worked out either in terms of the location of the transmission zeros of the system, or in terms of the solvability of a set of Sylvester equations. A salient outcome of this research was the internal model principle which includes classical PID (proportional-integral-derivative) control as a special case. From the control theoretic point of view, the significance of the internal model principle is that it enables the conversion of the output regulation problem into the well-known stabilization problem for an augmented linear system.

At almost the same time that research on the linear output regulation problem reached its peak, in the mid 1970's, Francis and Wonham considered the output regulation problem for a class of nonlinear systems for the special case that exogenous signals are constant. They showed that a linear regulator design based on the linearized plant can solve the robust output regulation problem for a weakly nonlinear plant while maintaining the local stability of the closed-loop system. In the late 1980s, Huang and Rugh further studied this problem for general nonlinear systems using a gain scheduling approach, and related the solvability of this problem to solvability of a set of nonlinear algebraic equations.

To establish a general theory for the output regulation problem for uncertain nonlinear systems subject to time-varying exogenous signals, one must address three important issues: how to define and guarantee existence of the steady state of the system, and hence characterize the solvability of the problem; how to handle plant uncertainty when it is known that the linear internal model principle does not work for nonlinear systems in the general case; and how to achieve asymptotic tracking and disturbance rejection in a nonlinear system with arbitrarily large initial states of the plant, the exosystem, and the controller, in the presence of uncertain parameters that lie in an arbitrarily prescribed, bounded set.

None of these three issues can be dealt with by a simple extension of the existing linear output regulation theory. Because of these challenges, the output regulation problem for nonlinear systems has become one of the most exciting research areas since the 1990s. As a result of extensive work, these three issues now have been successfully addressed to certain degree.

The difficulty associated with the first issue, existence of steady state, lies in the fact that the solution of a nonlinear system is not available. Isidori and Byrnes first addressed this issue for the case where the plant is assumed to be known exactly. By introducing center manifold theory, Isidori and Byrnes found that it is possible to use a set of mixed nonlinear partial differential and algebraic equations, called regulator equations in the sequel, to characterize the steady state of the system. This discovery coupled with the zero dynamics theory of nonlinear systems leads to a solvability condition for the output regulation problem in terms of solvability of the regulator equations. It turns out that the regulator equations are a generalization of the Sylvester equations mentioned above. The solution of the regulator equations provided a feedforward control to cancel the steady-state tracking error. Based on the solution of the regulator equations, both state feedback and error feedback control laws can be readily synthesized to achieve asymptotic tracking and disturbance rejection for an exactly known plant while maintaining local stability of the closed-loop system.

The second issue is concerned with the plant uncertainty characterized by a set of unknown parameters. The feedforward control approach mentioned in the last paragraph cannot handle this case due to the presence of the unknown parameters. A design approach based on the linear internal model principle does not work either, as shown by a counterexample due to Isidori and Byrnes. Huang first revealed in 1991 that the linear internal model principle failed because, unlike the linear case, the steady-state tracking error in a nonlinear system is a nonlinear function of the exogenous signals. Based on this observation, Huang found that if the solution of the regulator equations is a polynomial in the exogenous signals, then it is possible to solve the output regulation problem for uncertain nonlinear systems by both state feedback and output feedback control. This approach effectively leads to a nonlinear version of the internal model principle. The robust output regulation problem was further pursued by Byrnes and Isidori, Delli Priscoli, and Khalil, generating various techniques and insights on this important issue.

While the first two issues have been intensively addressed since the 1990s, the investigation of the third issue, the output regulation problem with global stability, has just started and is rapidly unfolding. In the original formulation of the output regulation problem, as given by Isidori and Byrnes, only local stability is required for the closed-loop system. For this case, the stability issue can be easily handled by Lyapunov's linearization method. When a global stability requirement is imposed on the closed-loop system, the situation becomes much more complicated. Khalil studied the semi-global robust output regulation problem for the class of feedback linearizable systems in 1994. His work was further extended to the class of lower triangular systems by Isidori in 1997. The output regulation problem with global stability was solved for the class of output strict-feedback systems by Serrani and Isidori in 2000. Up to this point, the problem of output regulation with nonlocal stability was handled on a case-by-case basis, and only limited results were obtained. Recently, Huang and Chen have established a new framework that converts the robust output regulation problem for nonlinear systems into a robust stabilization problem. This new framework has offered greater flexibility to incorporate recent stabilization techniques, thus having set a stage for systematically tackling robust output regulation with global stability. This new framework has been successfully applied to solve the output regulation problem with global stability for several important classes of nonlinear systems.

The scope of research on the output regulation problem is constantly expanding, and the topic is made richer and more interesting with the injections of new ideas and techniques from other research areas such as stabilization, adaptive control, neural networks, and numerical mathematics. For example, the output regulation problem with uncertain exosystems was studied recently by Chen and Huang, Nikiforov, Serrani, Marconi and Isidori, and Ye and Huang, respectively. This scenario had not been studied previously, even for linear systems.

The output regulation problem arises from formulating daily engineering control problems. Therefore, in addition to the theoretical issues mentioned above, the application of this theory to practical design should be adequately addressed. A key issue critical to the applicability of the output regulation theory is the solvability of the regulator equations. Being a set of mixed nonlinear partial differential and algebraic equations, the solution of the regulator equations is usually unavailable. Thus it is necessary to develop approximation approaches to solving these equations. An approximation method based on Taylor series expansion was developed by Huang and Rugh in 1991, and was also considered by Krener in 1992. The effectiveness of these approximation methods has been demonstrated by many case studies, including benchmark nonlinear systems such as the Ball and Beam, the Inverted Pendulum on a Cart, and the Rotational/Translational Actuator.

This book will give a comprehensive and up-to-date treatment of the output regulation problem in a self-contained fashion. The book begins with an introduction to the linear output regulation theory in Chapter 1. Then a review of fundamental nonlinear control theory is given in Chapter 2. Chapters 3 and 4 are devoted to the output regulation problem and the approximate output regulation problem for continuous-time nonlinear systems, respectively. The robust output regulation problem for uncertain continuous-time nonlinear systems is presented in Chapters 5 and 6. In Chapter 7, the global robust output regulation is formulated and studied for uncertain continuous-time nonlinear systems. Chapter 8 presents both the output regulation problem and the robust output regulation problem for singular nonlinear systems. Finally, in Chapter 9, results on the output regulation problem and the robust output regulation problem are extended to discrete-time nonlinear systems. The author seeks to strike a balance between the theoretical foundations of the output regulation problem and practical applications of the theory. The treatment is accompanied by many examples, including practical case studies with numerical simulations based on MATLAB/SIMULINK.

The book can be used as a reference for graduate students, scientists and engineers in the area of systems and control. Readers are assumed to have some fundamentals of linear algebra, advanced calculus and linear systems. Knowledges needed for nonlinear systems have been summarized in Chapter 2. Some chapters were used in the workshops of the 1999 IEEE Conference on Decision and Control, the 2004 World Congress on Intelligent Control and Automation, and graduate seminars at the Chinese University of Hong Kong.

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