	Lee　Jae-kwan
氏　　　　　名	李　載寛
授　与　学　位	博士（工学）
学位授与年月日	平成１０年３月２５日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）電気・通信工学専攻
学位論文題目	Study on Robust Adaptive Control of Nonlinear Systems （非線形系のロバスト適応制御に関する研究）
指　導　教　官	東北大学教授 阿部 健一
論文審査委員	主査　東北大学教授　阿部 健一　東北大学教授　豊田 淳一 東北大学教授　樋口 龍雄　東北大学教授　川又 政征 東北大学助教授　吉澤　誠

論文内容要旨

1 Introduction

The control objective of servomechanism is to achieve the plant output to asymptotically track prescribed trajectories under any influence of unwanted disturbances or uncertainties. Because most of plants do not only have linear but also nonlinear properties in many practical situations, the output tracking is usually difficult to be derived from the modern linear control theories which rely on the assumption of small range operation for the linear models to be valid. At the eighties, generalizations of pole placement and observer design techniques for nonlinear systems were obtained by using differential geometric nonlinear theory. More recently, we were confronted with more realistic problems that were caused by various uncertainties about either plants or disturbances. Adaptive versions of nonlinear systems were announced starting from 1986 and have been recently expanded in works of Lee, Krstić, Kanellakopoulos, Kokotović, Morse, Annaswamy and Baillieul. On the other hand, several authors like Isidori, Nam, Khalil, Marino and Tomei have studied theories for robust versions of nonlinear systems with structurally stable regulation, treating with regulation properties preserved under general time-varying parameters case, and robust regulation, having robustness in terms of a priori fixed bounds. The above-illustrated nonlinear control approaches studied in the above paragraph were based on some restrictive conditions for exact cancellation of the nonlinear properties, i.e., exact feedback linearization. In contrast with these schemes, approximate feedback linearization was to approximately linearize nonlinear systems by relaxing one or more of these restrictions. Moreover, this technique has been researched into adaptive versions for nonlinear systems affected by only unknown constant parameters, by Ghanadan and Blankenship, and expanded to robust adaptive versions for nonlinear systems affected by not only unknown constant parameters but also unmodeled dynamics, by Lee and Abe.

The most attention of this thesis is paid to the problem of achieving output tracking for nonlinear systems including system uncertainties, such as unknown constant parameters and unmodeled dynamics, via feedback linearization. Therefore, the control schemes to be developed in this thesis can be simply explained as deriving robust adaptive control schemes for uncertain nonlinear systems. The organization of this thesis is divided into two major parts, i.e., *exact input-output feedback linearization* and *approximate input-output feedback linearization*. As the nonlinear control schemes derived from the *exact feedback linearization*, Chapter 2 is used to introduce adaptive nonlinear control as a method for controlling nonlinear systems with unknown constant parameters and Chapter 3 deals with the robustness issues in adaptive nonlinear control when unmodeled dynamics is present in the nonlinear systems. On the contrary, Chapter 4 is devoted to the design and analysis of (robust) adaptive output tracking for a class of *approximate linearizable plants.* To confirm the utility of the control schemes to be developed, we use the ***single-link rigid robot*** in Chapters 2 and 3, and the familiar ***ball and beam plant*** in Chapter 4, as computer experiments. Lastly, in Chapter 5, we conclude the performance results of our control schemes and prospect some future works to be solved.

2 Adaptive Output Tracking via Exact Feedback Linearization

It may contain that the nonlinear systems are exactly modeled but depend on physical parameters whose exact values are not known. In such cases, the ideal nonlinear control techniques developed in Section 2.2 do not apply since they require no uncertainties and exact knowledge of parameters and nonlinearities. Hence, we shall discuss the design of adaptive output tracking for a class of single-input, single-output nonlinear systems with unknown constant parameters, together with the full-state measurable assumption and the clean outside condition. The plant that is to be controlled will be completely represented by a single-input, single-output nonlinear system as described by the differential equations

$$\begin{aligned} \dot{x} &= f(x,\theta) + g(x,\theta)\,u, \qquad x \in R^n, u \in R, \theta \in R^p \\ y &= h(x), \qquad y \in R \end{aligned} \tag{1}$$

in which x is the state vector, u is the control input, θ is an unknown constant parameter vector, y is the output, $h : R^n \to R$ is a C^∞ output function and $f,\ g \neq 0$ are C^∞ vector fields dependent on θ. In this section, we assume that the unknown constant parameter vector θ is parameterized linearly in the vector fields f and g:

$$\begin{aligned} f(x,\theta) &= \sum_{i=1}^{p} \theta_i\ f_i(x) \\ g(x,\theta) &= \sum_{i=1}^{p} \theta_i\ g_i(x) \end{aligned} \tag{2}$$

with unknown constant parameters θ_i and C^∞ nonlinear functions $f_i,\ g_i : R^n \to R$, $i = 1, \cdots, p$.

Here, under an assumption on the input vector field $g(x,\theta)$, we will introduce two kinds of indirect adaptive control schemes based on the exact input-output feedback linearization which has a well-defined relative degree r as shown in Subsection 2.1.2. The first method, adaptive nonlinear control with indirect feedback linearization, will be formed by combining an on-line parameter estimator (or adaptive law, parameter update law), which provides estimates of unknown constant parameters at each instant, with a feedback linearizable controller, which is motivated from the known parameter case. In the other method, adaptive nonlinear control with direct feedback linearization, the on-line parameter update law will be designed in a state observer system derived from feedback linearization procedure, so as to assure the stability of the closed-loop system.

Our control goal is the design of adaptive nonlinear feedback control to force the output y to track the same trajectory $y_m(t)$ satisfying

$$\|y_m^{(i)}\| \leq \epsilon_{y_m}, \qquad i = 0,\ 1, \cdots, r \tag{3}$$

where $\epsilon_{y_m} > 0$ and r is the relative degree introduced in Section 2.1. In order to design this adaptive controller, the feedback linearizable control law must be designed on a local domain of both the state variables x and parameter estimate $\hat{\theta}$ for θ, together with the stability of all the closed-loop signals with $\hat{\theta}$.

3 Robust Adaptive Output Tracking via Exact Feedback Linearization

The adaptive laws and control algorithms designed and analyzed in the previous chapter are based on a class of nonlinear systems which are free of unmodeled dynamics. These schemes are to be implemented on actual plants that most likely deviate from the plant models on which their design is based. The effect of the discrepancies between the plant model and the actual plant on the performance of the adaptive control schemes dealt in Chapter 2 may raise system instability and parameter drift phenomenon. In this chapter, we present the design and analysis of control schemes which can be applied to more complex plant models that include a class of uncertainties such as unknown constant parameter and unmodeled dynamics, i.e., ***robust adaptive control schemes*** for exact feedback linearizable systems with both unknown constant parameter and unmodeled dynamics, as one important effect of this thesis. Here, we shall consider the same single input, single output uncertain nonlinear systems (1). However, in contrast with Chapter 2, we assume that the vector field f is affected by the unmodeled dynamics Δf, that is, (1) is remodeled into an approximate nonlinear model

$$\begin{aligned} f(x,\theta) &= \sum_{i=1}^{p} \theta_i f_i(x) + \Delta f(x) \\ g(x,\theta) &= \sum_{i=1}^{p} \theta_i g_i(x) \end{aligned} \tag{4}$$

with the unknown constant parameters θ_i and C^∞ nonlinear functions $f_i,\ g_i : R^n \to R,\ i = 1, \cdots, p$.

Our objective, under any influence of uncertainties Δf and θ, is the design of nonlinear feedback control to force the output y to approximately track the same reference signal y_m considered in Chapter 2. For this, the control law and the parameter update law must be also designed on the local domain of state variables x and parameter estimate $\hat{\theta}$ as shown in Chapter 2, together with robustness of all the closed-loop signals including parameter estimate $\hat{\theta}$ which may be drifted to infinity due to the unmodeled dynamics Δf. Let $\bar{f}(x,\hat{\theta})$ be $\sum_{i=1}^{p} \hat{\theta}_i\ f_i(x)$ in (4) and x_e be the equilibrium point. Moreover, we assume that $\Delta f(x_e) = 0$ and $h(x_e) = 0$ at x_e. Through this chapter, two control approaches are presented with the assumption on the input vector field g as illustrated in Chapter 2.

4 Output Tracking via Approximate Feedback Linearization

In contrast to the exact feedback linearizable control schemes in Chapters 2 and 3 requiring some restrictive condition on relative degree, i.e., exact cancellation of nonlinear terms, let us consider the design and analysis of output tracking for a class of nonlinear systems violating the existence of well-defined relative degree in this chapter, that is, the output $y(t)$ approximately tracks $y_m(t)$ with this condition

$$||y_m^{(i)}|| \le \epsilon_{y_m}, \quad i = 0,\ 1,\ \cdots,\ \gamma \tag{5}$$

with the robust relative degree γ introduced in Section 4.1.

In this chapter, let us consider the plant model (1) and (4) dealt in Chapter 3. However, since it is assumed that the system (1) does not have a definite relative degree, it is clear that the complex problem can not be solved by only control concepts of Chapter 3. To solve such a complex problem, this chapter introduces a class of nonlinear feedback control schemes which lead to robust adaptive output tracking for nonlinear systems affected by both the unknown constant parameters θ and the unmodeled dynamics Δf, via ***approximate input-output feedback linearization.*** The control schemes presented in Chapter 4 can be explained with the following two block diagrams.

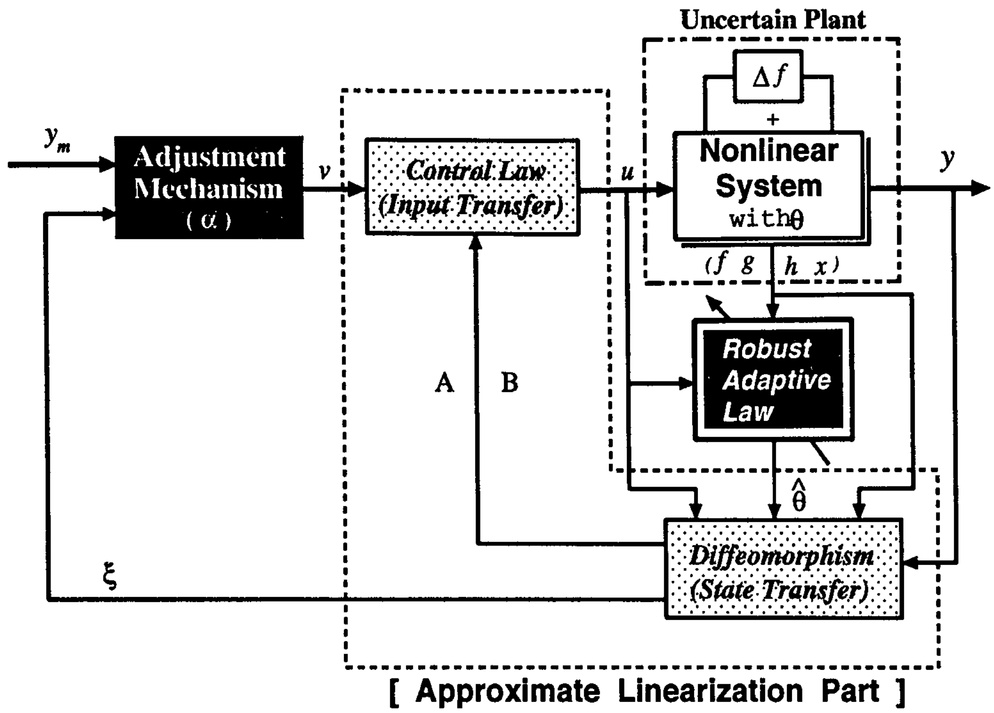

Figure 1: Robust adaptive control with indirect linearization

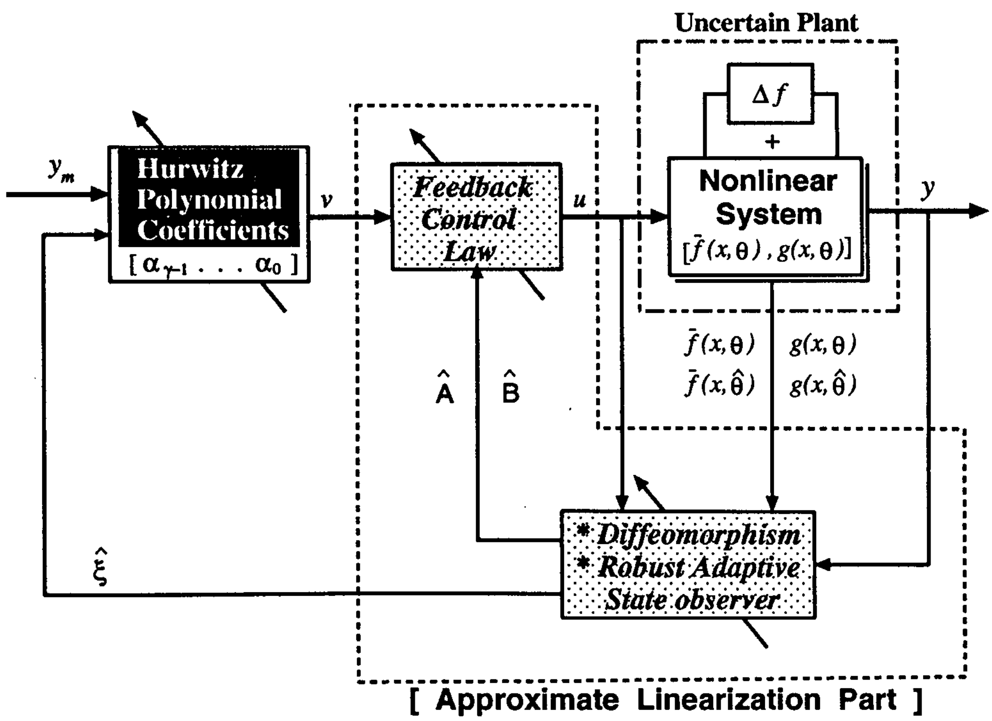

Figure 2: Robust adaptive control with direct linearization

5 Conclusions and Prospects

In this thesis, we introduce a class of (robust) adaptive nonlinear control schemes for single-input, single output nonlinear systems in the presence of unknown constant parameters (and unmodeled dynamics), via two input-output feedback linearizations, i.e., exact and approximate feedback linearization. For this, we assume that the nonlinear systems satisfy smooth (or equivalently, C^∞) vector field properties, the state variables are available for measurement, the unknown constant parameters are parameterized linearly in the nonlinear functions, the unmodeled dynamics is bounded in a known compact set, the zero dynamics derived from feedback linearization is locally exponentially stable and the relative degree for the given systems is not well defined in Chapter 4. Then, the main contributions of this thesis can be summarized as shown below. First, it is noted that all the (robust) adaptive laws developed in this thesis do not lead to any overparameterization for parameter identification. Second, it is shown that the systematic designs for the (robust) adaptive laws are similar to those for uncertain linear systems. Third, it is also important to note that these control methods lead to the stability of all the closed-loop system with the (robust) adaptive laws. Lastly, the design and analysis of control schemes presented can be explained from exact linearization concept of Chapters 2 and 3, and approximate linearization concept of Chapter 4.

However, because the control schemes developed are designed on some restrictive assumptions, such as the full-state measurable condition, the local domain of the state variables and parameter estimate, and the single-input, single-output nonlinear systems, we need to study the prospective works like output feedback control, global control and multi-input, multi-output control, based on the control schemes presented in this thesis. Moreover, the research efforts resulted have to be motivated by the more demanding performance required in robotics, motor drives, automobile engine, aircraft and spacecraft control which typically involve nonlinear dynamics.

審査結果の要旨

近年，非線形制御系に関し，微分幾何学の方法を用いた線形化理論の研究が活発になされ，その実システムへの応用が試みられつつある。しかし，モデル化誤差を許容するロバスト制御の確立には，なお解決すべき課題が数多く残されている。本論文は，１入力１出力の非線形系に対し，微分幾何学の方法による厳密線形化と近似線形化の理論を用いて，モデル化誤差が存在する場合のロバスト適応制御法を導出し，その有効性をシミュレーションによって検証したもので，全編５章からなる。

第１章は序論であり，本研究の背景と目的について述べている。

第２章では，本論文の基礎となる非線形系の厳密線形化について述べている。まず，本論文で対象とする，制御入力に関しては線形な非線形系（アファイン非線形系）について，これまでに得られている状態フィードバック線形化と入出力線形化に関する基本的な諸結果を示し，ついで，厳密線形化を用いた適応制御法を例題を交えて概観している。

第３章では，未知パラメータをもち，かつ付加的なモデル化誤差が存在するアファイン非線形系のトラッキング問題を対象として，厳密線形化に基づく２つのロバスト適応制御法を提案している。まず，制御入力の項に未知パラメータを含まない系について，未知パラメータの推定ののち線形化を行ってトラッキングのためのフィードバック制御を行う間接型の適応制御法を与えている。ついで，制御入力の項に未知パラメータを含み，その直接推定が不可能なより一般の系について，線形化ののち状態オブザーバを用いて未知パラメータを推定しフィードバック制御を行う直接型の適応制御法を与えている。いずれも，Lyapunov 関数の解析を通して，モデル化誤差を許容するロバストな適応制御が実現できることを示しており，優れた着想である。

第４章では，厳密線形化法が適用できない非線形系に対するロバストな適応制御法を提案している。第３章の議論は，系の相対次数が定義されることが前提となるが，相対次数が定義できない，すなわち厳密線形化が不可能な非線形系が数多く存在する。そこで，ロバスト相対次数の概念を使って入出力近似線形化を行う方法を用い，第３章の間接法と直接法のそれぞれを拡張したロバスト適応制御法を導いている。また，本適応制御法を，ビーム上で玉を周期的に転がすトラッキング問題に適用してシミュレーション実験を行い，よい追従性が達成できることを検証している。本手法は，より広いクラスの非線形系の有効な適応制御を可能としたもので，高く評価できる。

第５章は結論である。

以上要するに本論文は，未知パラメータとモデル化誤差が存在する非線形系のトラッキング制御問題に，厳密線形化および近似線形化の方法を適用してロバストな適応制御法を導き，その有効性を種々のシミュレーション実験により明かにしたもので，制御工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。