A Review Study of Various Control strategies for a class of Uncertain Nonlinear Systems

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Abstract: **This paper gives an overview of various control strategies for the uncertain nonlinear systems. After reviewing the basic concepts of nonlinear control, we survey the uncertainty descriptions considered in the literature, and the techniques proposed for improving stability and performance of system. The key concept of uncertainty is discussed at form of some point. In this paper also include review of wavelet neural networks and their limitation.**

***Index Terms*: Study of Adaptive observers; wavelet networks; time delay systems; Nonlinear Systems**

I. Introduction

Control process is an area of study that provides a mean to produce algorithms which make the systems (or plants) to behave in a desirable manner. It addresses the stability and performance of the system which is characterized by error size and the tendency of errors to grow or converge. However, use of these tools of control science to produce good control system designs is met by a number of obstacles. Two major difficulties to be dealt in this work are uncertainties and nonlinearities in the input-output representation of the plants [1]-[2]. Control system design relies on mathematical representations of systems that characterize how the real systems evolve in time for given situations (initial conditions) and external stimulus (inputs). For the designing of a control strategy to attain the desired performance, an accurate and precise mathematical model of the physical system is required and it is a non trivial task to obtain such an effective model for most of the physical systems, as some system characteristics are difficult to be derived mathematically with specified level of accuracy. There will typically be discrepancies between the actual plant and the mathematical model developed for controller design. These inaccuracies can be due to uncertainties regarding system dynamics, finite dimensional representation, linearization, model reduction, neglected secondary dynamics, or unforeseen system changes. In addition to uncertainty in the system dynamics, there is often also uncertainty in the environment where the system is operating. Controller designing aspects related with the control of systems having uncertain or unmodelled dynamics is being treated as a challenging issue in the control theory.

Model uncertainty can be broken down into parametric uncertainty (structured uncertainty) and unstructured uncertainty [3]. Parametric uncertainty is often easier to characterize. An example of unstructured uncertainty is unmodelled dynamics (i.e. actuator dynamics or higher flexible modes). These uncertainties play a vital role as far as the stability and other performance aspects of the system are concerned and are therefore required to be considered while designing a controller. In few cases, the statistical characterization of the uncertainties in the plant dynamics may be approximated and some norm bounded constraints may be applied to the uncertainties, however it results in a conservative controller design [3]. In many systems, the cancellation of nonlinearities is not exact due to modeling inaccuracies, uncertainties, the existence of immeasurable states and time lags. Also the linear time invariant controllers designed for the linearized model of the nonlinear systems, either through coordinate transformation or nonlinearity cancellation, do not offer an efficient and accurate control as the considerable nonlinear states are been neglected. This may have serious consequences if such hidden nonlinear modes are not adequately controlled. In such conditions intelligent controllers have to be implemented. Adaptive control has been believed as a breakthrough for realization of intelligent control systems with parametric or model uncertainties, adaptive control enables the control system to monitor the time varying changes and manipulate the controller for desired performance. The closed-loop stability of an adaptive control system is established by Lyapunov's second method. The advantages of adaptive control come from the fact that adaptive controllers can adapt themselves to modify the

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control law based on estimation of unknown parameters by recursive algorithms. Means area of adaptive control has close connections with system identification, which an area is aiming at providing and investigating mathematical tools and algorithms that build dynamical models from measured data [4]-[6].

Time delay, either in state or in control input is another serious practical problem which severely affects the performance of the dynamic systems. Time delays are found to exist in many dynamic systems e.g. chemical processes, rolling mill, biological systems, metal cutting process etc. Time delay occurs in physical systems due to so many reasons like finite capability of information processing among various parts of system, inherent phenomenon like mass transfer flow and recycling and /or byproduct of computational delay [7].Existence of time delay may lead towards the oscillations, degradation in the performance or even sometimes to instability. There may be single point delay or multiple point delay present in the system. Discussions on delays and their effect on stabilization /destabilization of control systems have attracted the interest of several researchers in recent years [8]. Mainly the results cited in the literature are based on two approaches: Lyapunov-Krasovskii theorems based approach and Razumikhin theorem based approach. The results obtained are having a variable degree of conservatism. Controller design for time delay systems have widely been considered in last few years.

In most of the practical systems, the magnitude of control signal is always limited to a certain range due to the physical input saturation on actuators. Actuator saturation is the potential problem control system which often severely limits the system performance, giving rise to inaccuracy or even leading to instability. This issue even becomes more sensitive if the control effort approaches to its maximum value and last at that value for a longer time span as it may damage the actuator. The development of adaptive control schemes for the systems having input saturations has been a task of major practical interest as well as theoretical significance. Few control strategies for the systems having input constraints are cited in the literature .These techniques are based on augmentation of base line control scheme with additional control components to deal with actuator saturation. Most of the research in this topic is focused on one of the strategies:

1. Model predictive control: Actuator saturation is dealt as constraint of optimization at each iteration [9]-[10].

2. Ant windup control: The principle controller is augmented with some additional dynamics to counteract the negative consequences of saturation [11]-[12].

Designing of tracking controller is an active area of research since last decade, the problem is addressed by several researchers for various classes of linear and nonlinear systems. Most modern nonlinear design techniques are developed assuming state feedback, which means that measurements of all states are available. However, in practical control problems, usually not all states are measured due to economical or technical reasons. Thus, observer design techniques are needed to implement state-feedback control by output feedback. For several processes only output is available for measurement due to inherent characteristics of the plant or unavailability of feasible sensor locations. In such cases, controller strategies rely on output feedback or construction of a state estimator (observers) which estimates the states of the plant. Schemes dealing with output feedback control and observer based control are cited in the literature for various classes of the systems [13]-[14]. Designing an observer is equivalent to derive a system which is driven by output measurement of original system and reconstruct the system states in an asymptotic manner to track the state of the original system.

In the field of nonlinear systems, the observer design problem is more complicated and so far there is no systematic complete solution found. However there have been constant attempts to attack the problems from different angles. Notably, there are four main approaches: Lyapunov-based observer design approach, linearization approach, structure-based high-gain observer design approach, Kazantis and Kravaris approach. Nonetheless, there is still no systematic and complete versatile approach existing to deal with general nonlinear observer design problem. Each of these approaches can only deal with certain class of systems.

Observers may broadly be classified in two categories; Full order observer and reduced order observer. Full order observer estimates all the states of the system and is useful for such systems where only the output of the system is available

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for the measurement. There exist certain systems where it is feasible to measure some of the states while the remaining ones are not measurable. Such systems need an observer design to estimate only unmeasured states so as to have high system efficiency and accuracy. For such systems, second category of observers is introduced, named as reduced order observer [15]-[18].

Designing of an observer for systems having unknown dynamics is an active area of research. Such observers, referred as adaptive observers, mainly emphasizes on simultaneously estimating the unknown states and uncertainties of a class of nonlinear systems. An adaptive observer performs the role of state estimation as well as parameter identification. It comprises two coupled algorithms for the tasks. The state estimation algorithm works under unknown parameters, where updated parameters are used for estimating state variables. The parameter identification algorithm is also based on measured outputs and estimated states. Various adaptive observer methods have been introduced for nonlinear systems with unknown parameters. The conventional design approach for adaptive observer mainly emphasizes on the designing of the observers for the systems where uncertainties follow Lipschitz condition, however it results in a conservative observer design and is applicable to limited class of systems. Designing of adaptive observers which uses approximation tools like Neural Networks (NN) or Wavelet Neural Networks (WNN) for system identification is new domain of research in the field of observer design. Use of these system identification tools relaxes the Lipschitz restriction and hence it enhances the class of uncertain nonlinear systems under consideration. Owing to the universal approximation property of these identification tools, the results provided by these observers are highly accurate in comparison to conventionally designed adaptive observers.

The problem of system identification is to estimate the underlying system characteristics using empirical input-output data from the system. Neural networks such as multilayer perceptrons have been proved as an efficient approximation tool due to their universal approximation property. They provide a generic black box functional representation and are capable of approximating any continuous function defined on a compact set in with arbitrary accuracy. Due to these attractive features, neural networks are successfully employed in the control design; however there are certain difficulties associated with NN based controller design [20]. The basic functions are generally not orthogonal or redundant, i.e. the network representation is not unique and is probably not the most efficient one. Furthermore, the convergence of neural networks may not be guaranteed. Even when it exhibits a good convergence, training procedure may still be trapped in some local minima depending on the initial settings. In addition, approximation errors and external disturbances cannot be efficiently attenuated. Hence, performance and even stability may not be guaranteed. Recently by combining the idea of neural networks and the merits of wavelets, a wavelet neural network was developed by Zhang and Benveniste. Wavelet networks are feed-forward neural networks using wavelets as activation function. In wavelet networks, both the position and the dilation of the wavelets are optimized besides the weights. Due to their space and frequency localization properties, learning capability of WNN is superior to conventional neural networks. Training algorithms for WNN converge in smaller number of iterations than for conventional neural networks [21]-[23].These WNN combines the capability of artificial neural network for learning ability and capability of wavelet decomposition for identification ability. Kreinovich has proven that wavelet neural networks are asymptotically optimal approximates for functions of one variable. Wavelet neural networks are optimal in the sense that they require the smallest possible number of bits to store for reconstructing a function within a precision. Thus WNN based control systems can achieve better control performance than NN based control systems.

The major limitation of conventional WNN is its static characteristics which appear due to its feed forward nature. So these networks are not very effective under the frequently changing operating conditions and dynamic properties as they cannot adapt rapidly under such circumstances. To overcome this problem, a feedback mechanism is inserted in conventional WNN giving rise to either Output Recurrent Wavelet Neural Network (ORWNN) or Self Recurrent Wavelet Neural Network (SRWNN).These recurrent networks combines the properties of recurrences with the

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convergence properties of WNN to solve the complex control problems [24]-[29].

II. Literature Review

The problem of state reconstruction for linear deterministic systems with known dynamic models was dealt by Luenberger [1-2] .The idea was further developed for uncertain systems by other researchers.

X. He et. al. [3] considers the problem of constructing a reliable tracking controller such that the output of resulting of closed-loop linear systems asymptotically tracking reference output. The main results are a sufficient condition for the existence of such a controller and the design method of this controller.

Z. Yun et.al. [4] Investigated the output-feedback stabilization control problem for a class of nonlinear uncertain systems. An observer is designed to estimate the system states using integral back stepping approach together with completing square technique. The output-feedback stabilization control is constructively designed such that the closed-loop system is asymptotically stable. P. Pagilla and Y. Zhu [5] proposed observer design for Lipchitz nonlinear systems. But it is applicable only to a certain class of nonlinearities which satisfies Lipchitz condition.

K. M. Chang [6] proposed a model reference adaptive control for uncertain systems with sector-like bounded nonlinear inputs, which is a conservative and bounded solution.

G. S. Chen et. [7] presented a robust control designs of a complex nonlinear system which can be modeled by a dynamic neural network. Two kinds of new H∞ control design methods are developed. One tries to attenuate both modeling error and the external disturbance to a prescribed level via the H∞ control term, the other tries to attenuate the external disturbance only via the H∞ control, whereas the modeling error is dealt with by a sliding mode control term.

E. Fridman and U. Shaked [8], and M.S. Mahmoud et. al. [9],have discussed the complexities like chaotic behavior, destabilization and other complex nonlinearities induced by the presence of delay either in state or input or in both and also presented an optimal tracking control design of for linear time delay systems.

M. Chen et. al. [10], N. Takagi et. al. [11], F. Morabito et. al.[12] and J. Zhou et.al. [13] have discussed the control strategies to deal with actuator saturation like model predictive control, antiwindup strategy and reshaping of control law to avoid saturation. The strategy proposed in [10,11] is based upon the augmentation of baseline controller with additional dynamics developed in order to recover the lost part of the system states during the saturation state of the actuator so as to avoid the detuning of controller parameters. Proposed scheme is computationally complex and somewhat better results than the proposed ones can be obtained by incorporating some intelligent tools like neural network etc. Scheme proposed in [12-13] utilizes the dynamic error based control component deal with actuator saturation basic limitations of the proposed schemes is that they require the complete knowledge of input and output of actuator, however actuator output is not available in several real time control systems.

Z. Yun et. al. [14], Y. Zhu and P. R. Pagilla proposed an observer controller strategy for nonlinear uncertain systems. The proposed observers are adaptive in nature so as to incorporate the uncertainties present in the systems. H. Bouadi, and M. Tadjine[15] and F. Abdollahi et. al. [16] verified the efficiency of the proposed adaptive nonlinear observers by implementing the design to real time systems.

The reduced order observer solutions for the uncertain nonlinear systems are proposed by V. Sundarapandian [17], Z. F. Lai and D. X. Hao and R. L. Mishkov [18]. The work in [19] is a geometric study of reduced order observer design for nonlinear systems which is applicable for Lyapunov stable nonlinear systems with a linear output equation. The error convergence for the reduced order estimator for nonlinear systems is established using the center manifold theory for flows. In [17] and [18], a reduced-order observer design method is developed under the assumption that a linear matrix inequality (LMI) has positive definite matrix solution and the reduced-order observer gain matrix is computed by the solution of LMI. By a linear transformation, a reduced-order observer which does not contain the information of the derivative of the system output is provided. G. Bartolini [20] proposed a reduced order observer design for nonlinear non-affine systems. The proposed design approaches in for adaptive observers for a class of nonlinear systems having Lipschitz nonlinearities and parametric uncertainties. Here the conservatism observed in the designing of conventional observers for nonlinear systems is relaxed to some extent but

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the proposed control strategy is applicable only to that class of nonlinearities which satisfy the linear in parameter condition.

Combining the approximation properties of neural networks with the features of wavelets, C. Cattani [20], have explored the system identification capabilities of neural networks and implemented them to the control of uncertain nonlinear systems.

R.J. Wai and H.H. Chang [22] and C.F. Hsu et.al.[23] have presented wavelet based adaptive controller strategies for various uncertain systems. Wavelet networks are used for approximating functional uncertainties. Tuning laws are proposed for online tuning of wavelet parameters. The proposed strategy uses the back stepping technique and so the design strategy is confined only to those classes of nonlinear systems where the nonlinearities are differentiable up to the required order. A. Kulkarni and S. Purwar [24] proposed a wavelet based control strategy for nonregular systems with input constraints. However, the WNN has a disadvantage that it can be used only for static problems due to its feed forward network structure. That is, the WNN is not the most suitable in solving temporal problems like predicting the behaviors of complex chaotic systems.

III. Conclusion

While this review is not complete it reflects the state of the art. It is apparent that none of the methods presented is suitable for use in industry except maybe in very special situations. The techniques are hardly an alternative to ad hoc MPC tuning based on exhaustive simulations for ranges of operating conditions. Choosing the right robust MPC technique for a particular application is an art and much experience is necessary to make it work even on a simulation case study. Much research remains to be done, but the problems are difficult. Recent finding indicates the application of tools like neural networks for approximating system nonlinearities as well as nonlinearities due to hysteresis. Application of neural network greatly relaxes the model dependencies for hysteresis. Based on the above review it has been observed that the research findings mainly emphasis on single input systems and this work can be extended to multi input systems. Secondly, performance of the system can be improved by using some advance neural network architecture like recurrent neural network or neuro fuzzy networks for system approximation.

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