CHAPTER 2

LITERATURE SURVEY

The present chapter narrates an overall classification of the control techniques prevailing in practice and how a transition occurred from classical control to mathematically enriched Systems Theory. A brief note on the need for a shift in the existing control strategy is mentioned here. A survey on the concept of evolution of Active Disturbance Rejection Control, its analysis and engineering applications that utilised this notion are also reported in this chapter.

2.1 Control techniques - A broad classification

Existing control techniques can be broadly classified into

1. Error based technique (Empirical Approach)
2. Model based technique (Modern Control Approach)

2.1.1 Error based empirical approach

The design of such controllers is not based on any information of the dynamics of the system. i.e., a mathematical model of the system is not required for its design. The controller design is purely based on observation of the behaviour of the plant. Practitioners in control industry follow such an error based approach for control of processes. They tune these controllers using lookup tables and trial and error techniques which they gained from their vast industrial experience. Hence the name empirical approach. Here the practical design aims in developing a control law that
minimises the error between the process variable and reference tracking signal. The control action largely depends on the present error, the accumulated errors over an interval of time and the prediction of the error variations in the future. PID controller belongs to this category of controllers. The mathematical equations that describe the operation of the established PID controller is empirically deduced without a mathematical system model.

\[ u = K_p e + K_i \int e \, dt + K_d \frac{de}{dt} \]  

(2.1)

The three parameters of Equation 2.1 are manually tuned to achieve the desired performance. However, it requires tuning of three parameters and the tuning process need to be repeated for varied operating conditions.

### 2.1.2 Model based modern control approach

The control law for these controllers is designed to suit the model devised for the system. State feedback controllers belong to this category. Their performance primarily depends on the extent to which the mathematical model matches with the actual system. Though the design of these controllers results in acceptable range of performance, they do not often exhibit optimal operating behaviour, primarily due to this model mismatch.

Consider a mathematical relation governing an electromechanical system as given below.

\[ \ddot{y} = f(y, \dot{y}, w, t) + bu \]  

(2.2)

In this model based design, we assume that the required dynamics of the plant is

\[ \ddot{y} = g(y, \dot{y}) \]  

(2.3)
Assuming the system as a disturbance free and linearised one, we can write

\[ f(y, \dot{y}, w, t) \approx \bar{f}(y, \dot{y}) \]  (2.4)

This reduces equation (2.2), resulting in the control law of (2.5)

\[ u = -\bar{f}(y, \dot{y}) + g(y, \dot{y}) \]  (2.5)

In equation (2.5), the effectiveness of the control law \( u \) depends much on the closeness of the term \( -\bar{f}(y, \dot{y}) \), to the actual dynamics of the system. In short, modern control paradigm can be summarised in the following steps:

1. An accurate mathematical model is required to describe the process (2.2).
2. Another mathematical model is required to define the design requirements (2.3). This can even be a cost function to be minimised.
3. A control law is formulated combining the above two (2.5).

### 2.2 From automatic control to Systems Theory

Most of the early engineering processes were naturally described by Ordinary Differential Equations (ODE). Hence the classical approaches in control theory mainly relied on Linear Ordinary Differential Equations, with constant coefficients. Mathematical control theory had its origin when people started using many mathematical techniques to a large extent, to put the principles of control theory into practice. This is true in all the control systems developed till date: beginning from Watt’s steam engine governor to present day autopilots in air planes. By the middle of 20th century, the world of mathematical control theory opened appreciably for researchers. In this context, we cannot forget the remarkable contributions made by a few great mathematicians. These include Dynamic Programming by Richard E. Bellman (1954),
Pontryagin’s principle by Lev.S. Pontryagin (2018) and Linear System Theory by Rudolf E. Kalman et al. (1969). During the development of modern control theory, it was noticed that the real world was too complex and the mathematical models in use till then, failed to accurately describe the dynamics of the system. Modelling of complex, nonlinear, uncertain, real world systems were beyond the scope of studies till then. Researchers concentrated on bringing a solution to this issue, and many responses to this problem can be found in the literature. Among these are the remarkable contributions of modern control era,

1. Robust Control - A control technique that requires a priori information of the plant dynamics and the bound of uncertainties (Veselý, 2013). In this case, the control law is not changed. The contributions of the Russian control theorist Vladimir Kharitonov (1979) marked a turning point for the developments in robust control. Some examples of robust control techniques are high gain feedback control, Sliding Mode Control (SMC), Variable Structure Control (VSC), loop transfer recovery technique, $H_\infty$ control etc.

2. Adaptive Control - A control technique that does not require a priori information of the plant dynamics and the bound of uncertainties (Landau et al., 2011). In this case, the control law automatically gets adapted to system variations. Some examples of adaptive control techniques commonly used in practice are Deterministic and Stochastic Adaptive Controls, Feedback and Feedforward Adaptive Controls and Model Reference Adaptive Control. Apart from this, different state-of-the-art adaptive control methods are also reported in literature (Anavatti et al., 2015).

Control theory, thus, started under the name “Automatic Control” gradually moved to a mathematically enriched new phase under the name “Systems Theory”. Modern control presumed that mathematical models could be used to effectively describe the dynamics of the plant. Subsequently, the control law was formulated from mathematical descriptions of the plant/process. Obviously, the performance and accuracy
of the controller depend much on the extent to which the mathematical model resembles the system. Thus, the performance of the controller was adversely affected by the uncertainties that were not included in the system model. This made researchers think in the direction of developing some method by which the uncertainties of the system could be adequately tracked. They wanted to make easily tunable, robust and model independent controllers that could compensate unknown dynamics of the plant and the actual disturbances in real time. The conflict between the established modern control theories and primordial practices led to the unabating theory Vs practice hassle. It was this irritating theory-practice gap that kindled the minds of Jingqing Han and triggered him to answer the question of “need for a paradigm shift” (Gao, 2006a).

2.3 The need for a paradigm shift

It was Thomas Kuhn, the American historian and philosopher of science who introduced the term “paradigm shift” for scientific revolutions. According to Kuhn, “paradigms prove to be constitutive of the research activity”. He ascertained that “when paradigms change, there are usually significant shifts in the criteria determining the legitimacy, both of problems and of proposed solutions” (Kuhn and Hawkins, 1963). Mathematics is all about manipulation of abstracts. Hence, as long as we fail to develop a perfect mathematical model of the system under study, the precision of mathematics fails. The words of Albert Einstein perfectly match this context -“As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality”.

Modern Control Paradigm depended too much on mathematical models, whereas the Empirical Design Paradigm proved inappropriate in uncertain environments, as it is rather an intuitive approach. In short, model-based and error based techniques had their limitations in solving the cardinal issue of uncertainties in feedback con-
trol systems. This reinforced the need for a paradigm shift in control theory.

2.4 The evolution of the new concept of ADRC

Unmodelled dynamics, parameter variations due to failure in components and external disturbances largely exist in the processes in nature. These demanded “disturbance rejection” and “control of systems with uncertainty” as a fundamental issue to be solved by researchers working in the field of control systems in recent years. Active Disturbance Rejection Control (ADRC) evolved as a fruitful control technique, that could handle uncertainties of any nature, be it internal or external. Here, the total disturbances are included in an extended state variable which is estimated using an Extended State Observer (ESO). The control mechanism, thereby, remains unaffected by any discrepancies in the modelling, as it includes all uncertainties as the extended state variable. Uncertainty reduction and a kind of robustness make this method an interesting solution to problems, in cases where full knowledge of the system is not available.

The concept of ADRC was pioneered by Jingqing Han and contributed through many of his Chinese transcripts, before his last publication (Han, 2009). The term Active Disturbance Rejection Control was systematically used for the first time in English literature and opened to the research world by Zhiqiang Gao in the year 2001 (Gao et al., 2001b). Active Disturbance Rejection Control (ADRC) is a robust control strategy, which encompasses the features of, error driven PID and state observer. Here the observer model of the system is extended with a new state variable, which includes all parameter variations, disturbances and internal dynamics that are left unnoticed in the normal plant description. The key idea behind this principle lies in the canonical representation of the Extended State Observer (ESO). The online estimation of this new state is performed using a state observer called ESO, which is used to separate the system and uncertainties, which in turn indirectly
simplifies the closed loop system to a large extent. Due to the real time compensa-
tion of the uncertainty, issues in modelling are satisfactorily eliminated. Thus the
control mechanism, more or less remains unaffected even in the presence of model
discrepancies, parameter variations and external disturbances.

2.5 A review on the theoretical justifications related to ADRC

In the early days of its progress, analysis of ADRC took a slow pace due to its
very structure with nonlinear gains. However, studies on convergence of nonlinear
ADRC for Single Input Single Output systems (Zhao and Guo, 2016) and Mul-
tiple Input Multiple Output systems (Guo and Zhao, 2013) are reported in litera-
ture. In the initial years, research attempts resulted only in approximate frequency
response of nonlinear ADRC to analyse the extent of disturbance rejection (Gao
et al., 2001a). A frequency response analysis of Nonlinear ADRC (NLADRC) was
carried out using describing function approach. These studies show that NLADRC
exhibited higher control efficiency for linear plants, but with lesser stability (Wu
and Chen, 2013).

The linear reduction and gain parameterisation of ADRC by Gao (2006b) simplified
the approach and paved the way for many justifications on its potential capabili-
ties. Later, the stability analysis of the ADRC with this linear topology was studied
(Zheng et al., 2007c,b). This paper gives an analytical approach that establishes the
performance of Linear ADRC (LADRC) achieved in varied classes of plants like
nonlinear, time-varying and plants with unknown dynamics. Two extreme cases are
considered here.

1. For plants with accurate mathematical model, asymptotic stability is detailed
and derived.
2. For plants with unknown dynamics, upper bounds of tracking error and estimation error are defined.

The exponential stability of nonlinear time variant systems with LADRC (Zhou et al., 2009) is dealt with by decomposing the original one into slow subsystem and a fast subsystem. Zhao and Huang (2012) discuss the performance of LADRC in linear time invariant Single Input Single Output minimum phase systems with unknown orders, uncertain relative degrees, and unknown input disturbances. Investigations had been extended to study the performance of LADRC in systems with long dead time and with right half-plane zeros, unstable and of distributed parameters (Chai et al., 2011).

However, a frequency response analysis was inevitable for ADRC to be appreciated by practicing engineers. An initial step in this line on analysing the extent of stability and performance of linear ADRC, through frequency response using a transfer function approach, on highly uncertain linear time invariant systems was justified by Tian and Gao (2007). Csank and Gao (2008) used frequency response approach to explore the disturbance rejection property of linear ADRC. The reports of Xue and Huang (2013a) give a better insight on frequency response analysis of ADRC for uncertain systems. The discussion on the link between time domain and frequency domain characteristics of ADRC solidifies its capability for engineering applications (Xue and Huang, 2013b; Zheng and Gao, 2016). An overall time domain and frequency domain performance analysis of LADRC for plants with uncertain dynamics proves the extent of robustness and ability of disturbance rejection of this promising concept (Xue and Huang, 2015).

It is noticed that the design framework of ADRC applies to all categories of systems like linear, nonlinear, time invariant, time variant, Single Input Single Output (SISO) as well as Multiple Input Multiple Output (MIMO) Systems. The review reports of Huang and Xue (2014) consolidate all facets of the methodology and theoretical aspects of ADRC.
Table 2.1: A consolidated review of the studies on ADRC conducted so far

<table>
<thead>
<tr>
<th>Type of plant</th>
<th>Objective of study</th>
<th>Topology</th>
<th>Nature of study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>convergence</td>
<td>NLADRC</td>
<td>Time domain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LADRC</td>
<td>Frequency domain</td>
</tr>
<tr>
<td>SISO</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>MIMO</td>
<td>convergence</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Nonlinear plants</td>
<td>stability, tracking performance</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Nonlinear time varying with unknown dynamics</td>
<td>stability</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Nonlinear plants</td>
<td>exponential stability</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Linear SISO minimum phase systems with unknown order</td>
<td>performance and stability</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Linear time invariant</td>
<td>performance and stability</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Linear time invariant</td>
<td>robustness</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Critical bandwidth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The research gap was identified after consolidating the above review. The study is tabulated in Table 2.1. The blank spaces represents the research gaps, while ‘x’ represents the availability of literature.

Along with the developments of ADRC, its various constituents were also the subject of interest for researchers. Theoretical research on the convergence for a second order linear tracking differentiator with any differentiable input signal and nonlinear tracking differentiator is discussed in literature (Guo et al., 2002). The studies by Yang and Huang (2009) and Yoo et al. (2007) show significant performance level of Extended State Observer pillaring ADRC. Some simulation studies on the convergence of Linear ESO (LESO) associated with ADRC for nonlinear systems are reported in discrete time domain by Yoo et al. (2006) as well as in continuous time domain by Guo and Zhao (2011).
A procedure based tuning method for a second order LADRC for a variety of systems like low order and high order was also developed by taking settling time as the performance specification (Chen et al., 2011). Rather than time domain specifications, frequency domain specifications are the matter of interest for practicing engineers. Since ADRC was developed as a transformative control strategy for industrial control applications, tuning based on frequency specifications is highly recommended. But elaborate studies in this perspective are hardly noted in literature.

In short, the major highlights of this intuitive technology are robustness and uncertainty reduction. It is understood that ADRC is a potential replacement for the deeply rooted PID technology in industries and had become an attractive area for applied researchers. In the next section some applications are reported where the principle of ADRC is tried and implemented in engineering applications by various research groups across the globe.

2.6 A review on applications of ADRC

Even though there are some gaps in the theoretical aspects of ADRC, it had been effectively implemented in some major industrial applications. This section lists a few of this kind.

2.6.1 Motion control

The research group of The Applied Control Research Laboratory of Cleveland State University initiated the studies on ADRC based motion control systems (Gao et al., 2001a). The search for the best control law for a motion control problem converged to Linear ADRC (LARDC) among control algorithms like PID control, PID with leadlag compensation, PID with velocity feedforward control, parameterized loop
shaping control and LADRC (Zheng and Gao, 2005; Goforth, 2004). The results of about 168 benchmark tests on an industrial motion control platform that characterises the performance of both ADRC and existing industrial controllers show the prospective future of ADRC as a feasible solution in manufacturing industry (Tian and Gao, 2009).

2.6.2 MEMS gyroscope

Automotive industry and navigation systems largely rely on gyroscopes. With the advent of microelectromechanical systems (MEMS), the conventional gyroscopes were replaced by MEMS gyroscopes. Eventually, the control techniques of MEMS gyroscopes too invaded the research field of control theory. A major challenge in the control aspect of MEMS gyroscopes is its time varying rate of rotation which is normally discarded in studies. Researchers took this as an opportunity to apply the technique of Active Disturbance Rejection Control, to handle this issue in the model dynamics of MEMS gyroscopes. It is found that ADRC could successfully eliminate the vibrations in the sense axis of MEMS gyroscopes resulting in an easier and precise estimation of the rotation rate. This establishes the high tracking performance of ADRC (Zheng et al., 2007a). An economic solution for counteracting the structural and fabrication imperfections and improving the rotation rate sensing of MEMS gyroscopes was addressed by (Dong et al., 2008b). The stability analysis with encouraging results proves the theoretical establishment of ADRC in MEMS gyroscopes where the underlying issue is disturbance rejection (Dong et al., 2008a; Zheng et al., 2008; Zheng and Gao, 2011).

2.6.3 Web tension regulators

The web tension control problem is a highly dynamic and complex case due to large amount of uncertain parameter variations, which requires special concern in
industrial control situations. Different control techniques were tried to solve the issue of rejecting changing dynamics due to “tension transfer” between nearby web spans, changes in working temperature, defects in physical framework etc. ADRC provided an encouraging solution in this case too (Hou et al., 2001; Zhou and Gao, 2007).

2.6.4 Other applications

Apart from the areas mentioned above, the concept of ADRC had been successfully applied in solving a variety of interesting issues related to human postural sway (Kotina et al., 2011), the disturbances and unmeasured dynamics associated with chemical processes (Chen et al., 2007), load changes and system uncertainties in power system containing both thermal and hydraulic turbines (Dong and Zhang, 2010), integrated flight-propulsion control scheme (Wang et al., 2010) and the like. Zheng et al. (2011) address the disturbance rejection as the key annoying issue in thermal power plants and proposes ADRC as a meaningful solution. It is found that this control strategy gives convincing results in the field of power electronics (Sun and Gao, 2005), space power management (Ping and Gao, 2005), electric power assist steering system (Dong et al., 2010), iron and steel processes (Wang et al., 2011) and airships under uncertain wind disturbances (Kim et al., 2003). The areas of application can be extended to systems whose accurate mathematical models are not fully demystified like high precision machining processes, high altitude flight control problems, uncertain power plant contingencies etc.