CHAPTER 2

LITERATURE REVIEW

In this chapter, the literature surveys conducted on sliding mode control, chattering reduction techniques, second order sliding mode control, and super-twisting sliding mode control are presented.

2.1 Survey on Sliding Mode Control

Variable structure control with sliding mode control was proposed and developed by several researchers from the former Russia starting from the sixties. The ideas were restricted only in Russia until a book by Itkis (1976) and a survey paper by Utkin (1977) were published in English. Thereafter, sliding mode control has developed into a general control method and has been used for different types of systems, including non-linear systems, time-variant systems, MIMO systems and large scale systems. In recent years, sliding mode control (SMC) has been widely used for the control of dynamic uncertain systems because of its attractive features.

Sliding mode control (SMC) is a particular type of variable structure control systems (VSCS), which is characterized by a discontinuous control structure that switches as the system crosses certain manifold in the state space to force the system state to reach, and thereafter to remain on a specified surface within the state space called the sliding surface. The system dynamics when confined to the sliding surface is termed as an ideal sliding motion and represents the controlled system behaviour, which results in reduced order dynamics with respect to the original plant. This reduced order
dynamics provides attractive advantages, such as insensitivity to parameter variations and matched uncertainties and disturbances, making sliding mode control an appropriate scheme for robust control. As the control law is not a continuous function, the sliding mode can be reached in finite time (Perruquetti and Barbot 2002, Raviraj and Sen 1997, Utkin 1993, Utkin et al. 2009, Young et al. 1999). Hsu et al. (2004) demonstrated the effectiveness of sliding mode controller for stabilizing uncertain non-linear systems with multiple inputs containing non-linearities and uncertainties. The controller guarantees the reaching condition of the sliding mode in uncertain systems. The controller is robust and stable. Utkin et al. (2009) demonstrated the effectiveness of sliding mode control through the application to electric drives.

Even though, sliding mode control is a powerful control method that can produce a very robust closed-loop system under plant uncertainties and external disturbances, it suffers from many disadvantages. In ideal sliding mode control, the switching of control occurs at infinitely high frequency to force the trajectories of a dynamic system to slide along the restricted sliding mode subspace. In practice, it is not possible to change the control infinitely fast because of the time delay for control computations and physical limitations of switching devices. As a result, the sliding mode control action can lead to high frequency oscillations called chattering which may excite unmodeled dynamics, energy loss, and system instability and sometimes it may lead to plant damage (Levant 2007, Perruquetti and Barbot 2002, Sira-Ramirez 1992, Utkin 1993, Utkin et al. 2009, Young et al. 1999). Another disadvantage of sliding mode control is that sliding mode controllers fail to deal with unmatched uncertainties. A study on the active reliable
control issues for a class of second order non-linear uncertain systems using a sliding mode control strategy presented by Liang et al. (2012) shows that sliding mode control scheme can completely reject the matched uncertainties, but fails in case of unmatched uncertainties.

Another main disadvantage of the conventional sliding mode control scheme is that the performance of the controller heavily depends on the sliding surface. If the sliding surface of sliding mode controller is not designed properly, it may lead to unacceptable performance. The selection of optimum sliding surface is tedious and a complicated task (Eksin et al. 2002, Tokat et al. 2003).

Many researchers have proposed time-varying sliding surface for the conventional sliding mode control scheme to improve the dynamic performance. Choi et al. (1994) proposed a time-varying sliding surface for the sliding mode control to achieve fast and robust tracking in a class of second order dynamic uncertain systems. In their approach, the sliding surface initially passes arbitrary initial states and subsequently moves towards a predetermined surface. The existence of sliding mode with the time-varying sliding surface is proved. They illustrated the advantages of the proposed method using a second order non-linear system subjected to parameter variations and external disturbances. However, if the movement of the sliding surface is not done carefully, it may result in undesirable chattering. Park and Choi (1999) proposed a fuzzy logic control based time-varying sliding surface for the second order variable structure control system. The conditions for rotating or shifting are investigated and the fuzzy algorithm is formulated with the values of the sliding surface function and the total discontinuity gain as input variables and the variation of the sliding
surface function as the output variable. The efficiency of the proposed algorithm is illustrated by applying it to the position control problem of an electro-hydraulic servomechanism. This approach results in fast and robust control responses of the second order VSCS. Tokat et al. (2003) proposed two approaches for online tuning of the sliding surface slope of sliding mode controllers for improving the dynamic performance. The one approach is based on an empirical formula derived based on some approximate rules and the other based on fuzzy logic control. They proved that both approaches improve the dynamic performance in terms of a decrease in the reaching and settling times compared with the conventional sliding mode controller with a fixed sliding surface, but fuzzy logic control based approach is better compared with the empirical formula based approach. In their approach, a multiple input-single output fuzzy logic controller is used for sliding surface slope adjustment and used a rule base with 49 rules. The rule base is complex and takes considerably large computation time.

Eksin et al. (2002) proposed a fuzzy sliding mode controller with a time-varying sliding surface, in which the slope of the sliding surface is updated continuously by a time-varying coefficient based on error variables. Because of time-varying sliding surface used in the approach, the controller improves the dynamic performance in terms of a decrease in the reaching and settling times compared with fuzzy logic sliding mode controller with a fixed sliding surface. However, the method of sliding surface adjustment is based on an empirical formula derived based on some approximate rules. Since the formula used is derived based on trial and error method to satisfy approximate rules, the performance is not the best. Eksin et al. (2002a) proposed a fuzzy sliding mode controller with a fuzzy logic control based
time-varying sliding surface, in which the slope of the sliding surface is updated continuously by a time-varying coefficient generated based on error variables using fuzzy logic. Because of time-varying sliding surface used in the approach, the controller improves the dynamic performance in terms of a decrease in the reaching and settling times compared with fuzzy logic sliding mode controller with a fixed sliding surface. In their approach, a multiple input-single output fuzzy logic controller is used for sliding surface slope adjustment and used a rule base with 81 rules. The rule base is complex and takes considerably large computation time. Kim and Jeon (2004) presented a sliding mode controller with a fuzzy logic controller tuned sigmoid function for non-linear interpolation in the boundary layer. The fuzzy controller tunes the parameters of the sigmoid function based on the sliding variable and a measure of chattering. The tuning is done such that the boundary layer thickness is reduced and results in superior tracking performance compared with the linear interpolation method using saturation function. However, tuning is a complicated task. Yagiz and Hacioglu (2005) proposed a sliding mode controller with a fuzzy logic control based moving sliding surface for a planar robot control. This approach improves the dynamic response and robustness compared with the conventional sliding mode controller with a fixed sliding surface. The effectiveness of the approach is demonstrated by its application to a planar robot control. Zong et al. (2010) proposed a sliding mode control (SMC) with a self-tuning law algorithm for uncertain non-linear systems. The method uses finite time stabilization based on geometric homogeneity and integral SMC. A bipolar sigmoid function online adaptation and an adjustable control gain tuning approach without high frequency switching are developed. This approach gives good dynamic performance and robustness. However, the self-tuning algorithm of this
scheme is complex. Piltan et al. (2011) proposed a sliding mode fuzzy logic controller with an adaptive sliding surface for robot manipulators. The adaptation of the sliding surface is based on error variables. They proved that sliding mode fuzzy logic controller with an adaptive sliding surface outperforms sliding mode fuzzy logic controller with a fixed sliding surface in terms of speed of response. However, sliding mode fuzzy logic controller with an adaptive sliding surface suffers from chattering in the presence of uncertainties.

Fallaha et al. (2011) proposed a sliding mode control approach with a moving exponential sliding surface to improve the dynamic performance of sliding mode control, while keeping high tracking performance in the steady-state regime. The effectiveness of the controller is demonstrated by an experimental study on a robot arm with three degrees of freedom. Durmaz et al. (2012) proposed a sliding mode control design with adaptive sliding surfaces for a class of affine time-variant non-linear systems. The sliding surfaces are designed to be moving with varying slopes and offsets by solving the state-dependent Riccati equations online during the control process. Thus, the sliding surfaces are adaptive to cope with the non-linearities and uncertainties of the system. The effectiveness of adaptive sliding mode control method developed is verified using a simulation of longitudinal control of generic hypersonic aircraft. However, this method is very complex and suffers from chattering. Komurcugil (2012) proposed an adaptive sliding mode controller for single phase UPS inverters. The approach utilized time-varying slope in the sliding surface function. He proved that the sliding line with the time-varying slope can be rotated such that the tracking time of the output voltage can be improved during load
variations. The adjustment of the time-varying slope is achieved by using a simple linear function of error variables of the system which is obtained using piecewise linear approximation of the input-output relationship of a single input-single output fuzzy logic controller operating on the error variables. The simulation results confirm the effectiveness of the proposed approach in terms of the improvement of the dynamic response and the rejection of load disturbances.

Though, the above mentioned methods using time-varying sliding surface can improve the dynamic performance of the controller, they suffer from the dangerous chattering effect.

### 2.2 Survey on Chattering Reduction Techniques

The chattering can be eliminated by introducing a boundary layer around the sliding surface. This can be done by continuous approximation of the discontinuous control of sliding mode control using saturation function, tanh function etc. (Husain et al. 2008, Young et al. 1999). However, Slotine and Li (1991) pointed out that this method results in loss of invariance property as the control signal is a linear function of the distance between the actual state and the sliding surface within the boundary layer. Hence, the system possesses robustness that is a function of boundary layer width. This method is highly sensitive to the unmodeled fast dynamics and may lead to unacceptable performance. Also, this method results in a steady-state error that is proportional to the boundary layer thickness (Slotine and Li 1991). Slotine and Li (1991) proposed a class of functions with time-varying parameters to find a compromise between the chattering reduction and the
loss of invariance of sliding mode control. However, the tuning of the parameters is cumbersome. Husain et al. (2008) proposed a sliding mode controller with an exponentially decaying function to replace the discontinuous function of the conventional sliding mode controller to reduce chattering while retaining asymptotic stability and robustness. The effectiveness of the proposed approach is verified using its application for stabilization of an active magnetic bearing system. However, the performance of the approach depends on the proper tuning of the exponential function parameters. The tuning of parameters in this method is based on trial and error method. If the parameters are not tuned properly, the method results in unsatisfactory performance.

Another approach to reduce chattering is to use fuzzy logic in the design of sliding mode controllers. In this approach, fuzzy logic control is used to introduce a boundary layer around the sliding surface by fuzzifying the relationship between control signal and the distance between the actual state and the sliding surface, i.e., the sliding surface is fuzzified. As the sliding surface is fuzzified, it is not a hyper-plane anymore. In the two-dimensional case, the sliding surface becomes a band of sliding area, thus introducing a boundary layer around the sliding surface. The control signal changes non-linearly inside the band, thereby retaining the invariance property and robustness. Therefore, this approach reduces the chattering of sliding mode control approach without compromising robustness (Efe et al. 2000, Kaynak et al. 2001, Tao et al. 2010). Palm (1994) proposed a fuzzy logic based sliding mode controller for uncertain systems in which scaling factors of fuzzy variables and rule base are derived using sliding mode control principle. This approach combines the advantages of fuzzy logic
control and sliding mode control. The controller assures tracking quality even in the presence of high level of model uncertainties. The chattering in this method is very less compared with sliding mode controller. However, the response and stability of the controller are very difficult to predict. Dotoli (2003) proposed a fuzzy sliding mode controller for a class of second order systems based on a piecewise linear sliding manifold. The controller is robust in the presence of saturated control input and exhibit smooth dynamics without chattering. The effectiveness of the controller is demonstrated through its application for inverted pendulum control. However, fuzzy logic based approaches for eliminating the chattering effect of sliding mode control suffers from the disadvantage of the trial and error design method of the conventional fuzzy logic control. If not designed properly, it may lead to adverse effects. Moreover, the response and the stability of the system with fuzzy logic controllers are not easy to predict (Raviraj and Sen 1997).

2.3 Survey on Second Order Sliding Mode Control

formulation is applicable only to single input systems with particular types of uncertainties. They modified this approach to extend for multiple input systems having uncertainties of more general, covering a wide range of real processes. Bartolini and Punta (2000) presented a second order sliding mode control algorithm for the stabilization problem for a mechanical system as a solution to the chattering elimination problem as well as robust against discontinuous disturbances such as friction. The method is effective in avoiding complex stick-slip phenomenon as no oscillations or overshoot take place during the transients. Bartolini et al. (2004) proposed a second-order sliding-mode control approach by explicitly taking into account the presence of measurement error with an unknown upper bound. They presented simulations to highlight the high robustness and the chattering reduction of the proposed approach. Bartolini et al. (2009) presented the implementation of a second sliding mode control algorithm for a class of systems in which the sign of the constant high frequency gain is unknown. The controller is able to deal with uncertain sign and exhibit robust performance. Capisani et al. (2009) presented the effectiveness of second order sliding mode controller as a robust controller for robot manipulators. The controller exhibit good tracking performance. The controller is robust to model uncertainties and perturbations and reduces chattering compared with the conventional sliding mode control. However, the conventional second order sliding mode control suffers from the disadvantage that its implementation demands the increasing information in terms of the first time derivative of the sliding variable in addition to the sliding variable compared with the standard first order sliding mode control (Gonzalez et al. 2012).
2.4 Survey on Super-twisting Sliding Mode Control

In recent years, the super-twisting sliding mode control theory has become very popular and therefore, it has been studied widely for the control of dynamic uncertain systems. It is a second order sliding mode control and allows for finite time convergence of the sliding variable and also its time derivative to zero. Hence, super-twisting sliding mode controller maintains the distinctive robust features of sliding mode techniques, while providing a control signal smoother than that obtained through the conventional first order sliding mode controller, thereby resulting in less chattering compared with the conventional first order sliding mode control. Moreover, super-twisting sliding mode controller can support a larger class of uncertain systems compared with the conventional sliding mode controller. Super-twisting sliding mode controller supports systems with unbounded perturbations, but with a bounded time derivative whereas the conventional sliding mode controller does not support systems with unbounded perturbations. Moreover, super-twisting sliding mode control method offers a simple algorithm for the easy implementation as it does not require the time derivative of the sliding variable compared with the conventional second order sliding mode controllers (Alt and Svaricek 2011, Gonzalez et al. 2012). Moreno and Osorio (2008) presented the stability analysis and reaching time estimation of super-twisting sliding mode controller using a strong Lyapunov function. The method guarantees a finite-time convergence and the robustness of super-twisting sliding mode controller. The introduction of a Lyapunov function allows not only to study more deeply the known properties of finite time convergence and robustness to uncertainties and perturbations, but also to obtain an explicit relation of the
controller design parameters. Polyakov and Poznyak (2009) presented the stability analysis and reaching time estimation of super-twisting sliding mode controller using a Lyapunov function based on resolving of the first order partial differential equation of a special type. This method guarantees the finite time convergence of super-twisting sliding mode controller. The formula for the reaching time is derived. The method makes it possible to obtain an explicit relation of the controller design parameters. Davila et al. (2009) presented a class of quadratic-like strong Lyapunov functions for super-twisting algorithm design and formula to estimate the convergence time for each of them. They also presented a methodology to select the Lyapunov function for obtaining the minimal convergence time. Moreno (2012) presented a class of Lyapunov function for the design of super-twisting sliding mode controller to guarantee a finite time convergence and the robustness. Pico et al. (2013) proposed a simple method of designing super-twisting sliding mode controller by decoupling the stability analysis problem and that of finite time convergence. This allows simple design methods and stability proofs in a wide set of uncertainties and perturbations. They proved that super-twisting sliding mode controller achieves finite time convergence by means of a continuous action, thereby reducing the chattering. Also, super-twisting sliding mode controller does not use the information about the time derivative of the sliding variable (Gonzalez et al. 2012).

Many researchers proposed super-twisting sliding mode controller for the control of uncertain systems. Derafa et al. (2010) presented the design and implementation of super-twisting control algorithm for the behaviour tracking of a four-rotors helicopter known as quadrotor. Super-twisting
sliding mode control algorithm ensures the robustness with respect to modeling errors and external disturbances while reducing the chattering phenomenon caused by the conventional first order sliding mode controllers. The stability and finite time convergence characteristics of the algorithm are proved by means of Lyapunov functions. Chiang et al. (2011) presented the design and implementation of super-twisting sliding mode controller for a synchronous reluctance motor. Super-twisting sliding mode controller exhibits robustness for variations in the motor parameters and has reduced chattering. Djemai et al. (2011) presented the design and implementation of super-twisting sliding mode controller for the speed regulation of a DC motor using a multi-cellular converter. The controller exhibit good dynamic response and robustness. Pukdeboon (2012) presented the application of super-twisting sliding mode controller for the two-spacecraft formation flying system subjected to external disturbances in the space environment. The controller exhibits robustness for the external disturbances and reduce chattering. Kunusch et al. (2009) presented the application of super-twisting sliding mode strategy to control the breathing sub-system of a polymer electrolyte membrane fuel cell stack for transportation applications. The approach provides good dynamic characteristics and robustness to uncertainties and disturbances. The feasibility of the approach is demonstrated using simulations. Koo et al. (2012) presented super-twisting sliding mode controller for the control of the superheat ratio of refrigeration system.

Even though, super-twisting sliding mode controller is an effective second order sliding mode control scheme for the control of uncertain systems as it reduces the chattering phenomenon of the classical
first order sliding mode controller and guarantees higher accuracy in the presence of system imperfections and uncertainties, super-twisting sliding mode controller with a fixed sliding surface has the disadvantage that the system performance heavily depends on the sliding surface. It is tedious to find the optimum sliding surface and it is a complicated task. A successful sliding surface design method for improving the controller performance is to use time-varying sliding surface instead of constant one. Thus, the method of adjusting sliding surface online is an important topic in the super-twisting sliding mode controlled systems.

2.5 Summary of Literature Review

From the literature review, it is concluded that sliding mode control scheme is a well known robust control scheme for dynamic uncertain systems. However, sliding mode control suffers from the dangerous chattering effect which prevents them from being extensively used in practice. Also, the performance of sliding mode control depends heavily on the sliding surface. If the sliding surface is not designed properly, it may lead to adverse effects. Though, there are many methods in the literature to improve the performance of sliding mode controller using time-varying sliding surface, including fuzzy logic control based time-varying sliding surface, these methods do not address the problem of the chattering effect. Second order sliding mode control scheme is an effective scheme for eliminating the chattering effect. However, the increased information demand in terms of the time derivative of the sliding variable is the main disadvantage which prevents the conventional second order sliding mode control scheme from being extensively used in practice. Super-twisting
sliding mode control scheme is a modified approach which solves the increased information demand of the conventional second order sliding mode controller. Super-twisting sliding mode control scheme does not require the time derivative of the sliding variable and eliminates the chattering effect. However, the performance of super-twisting sliding mode control heavily depends on the sliding surface. If the sliding surface of super-twisting sliding mode controller is not designed properly, it may lead to unacceptable performance. The selection of optimum sliding surface is tedious and a complicated task. Thus, the method of adjusting sliding surface online is an important topic in the super-twisting sliding mode controlled systems.