A Review on Sliding Mode Control: An Approach for Robust Control Process

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Abstract: ***The main objective of this paper is to review various research works related to the modelling of Sliding Mode Controller (SMC) for process control carried out by different researchers for designing high-performance nonlinear controller in the presence of uncertainties. The effects of the controller over non-linear process have made it the most adaptive type to any uncertainties in it. Although it has its own problem, referred to as the chattering phenomenon, there are the methods as discussed in this paper to eliminate it.***

Keywords: Sliding Mode Control (SMC), process control, Variable Structure Control (VSC), Robust control, Non-linear process, Chattering phenomena, Lyapunov stability

1. Introduction

A very small change in a process can have a large impact on the end result. The change in proportions, temperature, flow, tolerance, and many other factors must be carefully and persistently controlled to yield the desired end product with a very limit of raw materials and energy. Process control technology enables manufacturers to keep their operations running with specified limits and set more precise limits to maximize profitably, ensure quality and safety. The Process industries include the chemical industry, the oil and gas industry, the food and beverage industry, the water treatment and the power industry.

Process control can lower variability in the end product, thereby ensuring a consistently high-quality product. A process variable is a condition of the process fluid that can change the manufacturing process in some way. The controller is a device that receives data from a measurement instrument, compares the data to a programmed set-point, and, if necessary, signals a control element to take corrective action [20].

SMC is an important robust control approach. The class of systems for which it applies, SMC design provides a systematic approach to the problem of maintaining accuracy, robustness, stability, easy tuning, and consistent performance in the face of modelling imprecision [1]. There are two major advantages of sliding mode control. First, the dynamic behaviour of the system may be tailored by the particular choice of a sliding function. Secondly, the closed loop response becomes totally unresponsive to some particular uncertainties. Due to this property, this principle extends to model parameter uncertainties, also any disturbances and non-linearity that are bounded in the systems. From a practical point of view, an SMC enables controlling of nonlinear processes subjected to the external disturbances and heavy model uncertainties.

There are some modelling inaccuracies that can occur in these controllers. It can be classified into two major kinds- structured (or parametric) uncertainties and unstructured uncertainties (or un-modelled dynamics). The former kind corresponds to inaccuracies on the terms actually included in the model, while the later kind deals with the inaccuracies on the system order. One of the important approaches to deal with model uncertainty is robust control [1].

2. Theoretical Background

The SMC is a two-part controller design. The first part associates with the design of a sliding surface so that the sliding motion satisfies the design specifications dealt with it. The second focuses on the selection of a control law that will make the switching surface attractive to the system state [3].

One job is to investigate the variable structure control (VSC) as a high-speed switched feedback control, resulting in the sliding mode. The aim of the switching control law is to drive the nonlinear plant's state trajectory onto a pre-specified (user-chosen) surface in the state space and to maintain the plant's state trajectory on this surface for a subsequent time, the surface being termed a switching surface. When the plant's state trajectory is "above" the surface, the feedback path has some gain, which is different if the trajectory drops "below" the surface. This surface helps us to define the rule for proper switching. This surface is also called a sliding manifold. Ideally, once intercepted, the switched control retains the plant's state trajectory on the surface for all the successive time and the plant's state trajectory slides along this surface. The most crucial task is to develop a switched control that will drive the plant state to the switching surface and maintain it on the surface upon interception [1].

If we can control and restrict the dynamics of the system to lie on a well-behaved surface, then the control problem is greatly simplified. It is defined in such a way that the error dynamics are exponentially stable when the system is restricted to lie on this surface. The control problem, which minimizes the problem of driving the system to this surface, and then ensuring that it stays on this surface all the time [2], a Lyapunov approach is used to characterize this task. The Lyapunov method is usually used to determine the stability properties of an equilibrium point without solving the state equation. Let $V(x)$ is a continuously differentiable scalar function defined in a domain D that contains the origin. A function $V(x)$ is said to be positive definite if $V(0) = 0$ and $V(x) > 0$ for x. It is said to be negative definite if $V(0) = 0$ and $V(x) > 0$ for x. The Lyapunov method is to assure that the function is positive definite when it is negative and function is negative definite when it is positive. In that way, the stability is assured. For each chosen switched control structure, particular "gains" can be selected so that the derivative of this Lyapunov function is negative definite, thus assuring the motion of the state trajectory to the surface. After the proper design of the surface, a switched controller is developed with the tangent vectors of the state trajectory pointing towards the surface so that the state is driven to and maintained on the sliding surface. Such controllers introduces discontinuous closed-loop systems [1].

Let us consider a single input nonlinear system, defined as

$$x^{(n)} = f(x,t) + b(x,t)u(t) \qquad \text{........... (1)}$$

Here, $x(t)$ is a state vector, $u(t)$ is a control input and x is the output state of the interest [1]. The other states in the state vector are the higher order derivatives of x up to the $(n\text{-}1)^{th}$ order. The superscript n on $x(t)$ shows the order of differentiation. $f(x,t)$ and $b(x,t)$ are generally nonlinear functions of time and states. The function $f(x)$ is not exactly known, but the extent of the imprecision on $f(x)$ is upper bounded by a known, continuous function of x; similarly, the control gain $b(x)$ is not exactly known, but is of known sign and is bounded by known, continuous functions of x.

A time-varying surface $s(t)$ is defined in the state space by equating the variable $s(x,t)$, defined below, to zero.

$$s(x;t) = \left(\frac{d}{dt} + \delta\right)^{n-1} \tilde{x}(t) \qquad \text{.................. (2)}$$

Here, δ is a strict positive constant, taken to be the bandwidth of the system,

$\tilde{x}(t) = x(t) - x_d(t)$ is the error in the output state, where is the desired state.

The strategy to converge to the sliding mode is that we can add something to $u(t)$, which will drive us to the sliding mode in a finite time. In summary, the motion consists of a reaching phase during which trajectories starting off the manifold $s(t)$ move toward it and reaches it in finite time, followed by a sliding phase during which the motion is confined to the manifold $s(t)$ and the dynamics of the system are represented by the reduced-order model. The manifold $s(t)$ is called the sliding manifold and the control law $u(x)sgn(s)$ is called sliding control mode [2].

Moreover, bounds on s can be directly translated into bounds on the tracking error vector $\tilde{x}(t)$, and therefore the scalar s represents a true measure of tracking performance.

The corresponding transformations of performance measures assuming $\hat{x}(0) = 0$ is:

$$\forall t \geq 0, |s(t)| \leq \phi \Rightarrow \forall t \geq 0, \left|\hat{x}^{(i)}(t)\right| \leq (2\delta)^i \varepsilon, \quad i = 0,1,\ldots\ldots,n-1 \qquad \text{........................... (3)}$$

where $\varepsilon = \phi/\delta^{\,n-1}$

In this way, an n^{th} order tracking problem can be replaced by a first-order stabilization problem.

The simplified first-order problem of keeping the scalar s at zero, can now be achieved by choosing the control law u of Eqn. (1) such that outside of $s(t)$

$$\frac{1}{2}\frac{d}{dt}s^2 \leq -\eta|s| \qquad \text{...................... (4)}$$

Eqn . (4) states that the squared "distance" to the surface, as measured by s^2, reduces along all system trajectories. Thus, it constraints trajectories to point towards the surface $s(t)$. In particular, once on the surface, the system trajectories are maintained on the surface. Strictly speaking, satisfying the sliding condition makes the surface an invariant set (a set for which any trajectory starting from an initial condition within the set, remains in the set for all future and past times). Furthermore, Eqn. (4) also denotes that some disturbances or dynamic uncertainties can be tolerated while still keeping the surface an invariant set.

Finally, satisfying Eqn. (2) guarantees that $x(t = 0)$ is actually off x^d $(t = 0)$, the surface $s(t)$ will be reached in a finite time smaller than $|s(t = 0)|/\eta$.

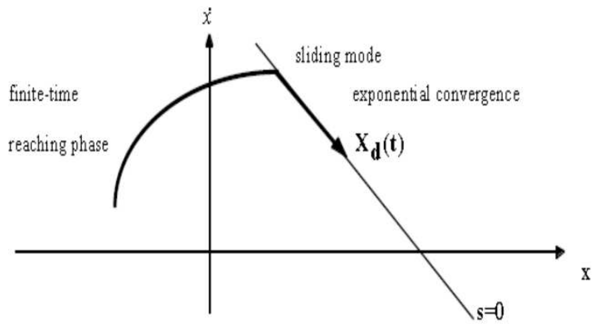


Figure 1: Graphical interpretation of Eqns. (2), (4) (for n = 2) [19]

3. Controller Design

The controller design procedure can be divided in two steps. In the first step, a feedback control law ***u*** is selected to verify the sliding condition in Eqn. (4). But, in order to account for the presence of modelling imprecision and of disturbances, the control law has to be discontinuous across $s(t)$. Since the implementation of the corresponding control switching is imperfect, this leads to chattering (Figure 2), which is undesirable in practice as it involves high control activity and may excite high-frequency dynamics neglected in the course of modelling [1]. Hence, in the second step, the discontinuous control law ***u*** is suitably smoothed to achieve an optimal trade-off between control bandwidth and tracking precision. The first step accomplishes robustness for parametric uncertainty; the second step achieves robustness to high-frequency unmodeled dynamics.

Consider a simple second order system,

$$\ddot{x}(t) = f(x,t) + u(t) \quad \text{........................ (5)}$$

where $f(x,t)$ is generally nonlinear and/or time-varying, and can be estimated as $\hat{f}(x,t)$; $u(t)$ is the control input; $x(t)$ is the state to be controlled such that it follows the desired trajectory $x_d(t)$ [1]. The estimation error on $f(x,t)$ can be assumed to be bounded by some known function $F = F(x,t)$, so that

$$\left|\hat{f}(x,t) - f(x,t)\right| \leq F(x,t) \quad \text{.................. (6)}$$

We define a sliding variable according to Eqn. (2).

$$s(t) = \left(\frac{d}{dt} + \gamma\right)\tilde{x}(t) = \dot{\tilde{x}}(t) + \gamma\tilde{x}(t) \quad \text{............ (7)}$$

Differentiation of the sliding variable yields

$$\dot{s}(t) = \ddot{x}(t) - \ddot{x_d}(t) + \gamma\dot{\tilde{x}}(t) \quad \text{....................... (8)}$$

Substituting Eqn. (5) in Eqn. (8), we have

$$\dot{s}(t) = f(x,t) + u(t) - \ddot{x_d}(t) + \gamma\dot{\tilde{x}}(t) \quad \text{............. (9)}$$

The approximation of control law $\hat{u}(t)$ to achieve $\dot{s}(t) = 0$ is:

$$\hat{u}(t) = -\hat{f}(x,t) + \ddot{x_d}(t) - \gamma\dot{\tilde{x}}(t) \quad \text{................ (10)}$$

$\hat{u}(t)$ can be thought of as the best estimate of the equivalent control.

To accommodate uncertainty in f while satisfying the condition

$$\frac{1}{2}\frac{d}{dt}(s(t)^2) \leq -\eta|s(t)|, \quad \eta > 0 \quad \text{.................... (11)}$$

The control law can be taken as:

$$u(t) = \hat{u}(t) - k(x,t)\, sgn(s(t)) \quad \text{................... (12)}$$

By selecting $k(x,t)$ large enough, such as

$$k(x,t) = F(x,t) + \eta$$

ensures the satisfaction of condition in Eqn. (11), since

$$\frac{1}{2}\frac{d}{dt}(s(t)^2) = \dot{s}(t)s(t)$$

$$= \left(f(x,t) - \hat{f}(x,t)\right)s(t) - k(x,t)|s(t)| \leq -\eta|s(t)|, \quad \eta > 0 \quad \text{.. (13)}$$

Hence, by using Eqn. (12), we ensure that the system trajectory will take a finite time to reach the surface $s(t)$, after which the errors will exponentially reduce to zero.

Now considering another second order system in the form of

$$\ddot{x}(t) = f(x,t) + b(x,t)u(t) \quad \text{.............................. (14)}$$

where $b(x,t)$ is bounded as

$$0 \leq b_{min}(x,t) \leq b(x,t) \leq b_{max}(x,t)$$

The control gain $b(x,t)$ and it's bound can be time-varying or state dependent. Because the control input is multiplied by the control gain in the dynamics, the geometric mean of the lower and upper bound of the gain is an acceptable estimate:

$$\hat{b}(x,t) = \sqrt{b_{min}(x,t)b_{max}(x,t)}$$

Then, bounds can be written as

$$\beta^{-1} \leq \frac{\hat{b}}{b} \leq \beta \text{ where } \beta = (b_{max}/b_{min})^{1/2}$$

Since the control law will be designed to be robust to the bounded multiplicative uncertainty, β is called the gain margin of the design.

It can be proved that the control law

$$u(t) = \hat{b}(x,t)^{-1}[\hat{u}(t) - k(x,t)sgn(s(t))] \quad \text{..... (15)}$$

with

$$k(x,t) \geq \beta(x,t)(F(x,t) + \eta) + (\beta(x,t) - 1)|\hat{u}(t)| \quad \text{.......... (16)}$$

satisfies the sliding condition.

4. Chattering Reduction

An ideal sliding mode occurs only when the state trajectory $x(t)$ of the controlled plant agrees with the desired trajectory at every $t \leq t_1$ for some t_1 . This may require infinitely fast switching. In real systems, a switched controller has inadequacy which limits switching to a finite frequency. The representative point then oscillates within a neighbourhood of the switching surface. This oscillation, called chattering [1], is illustrated in Figure 2.

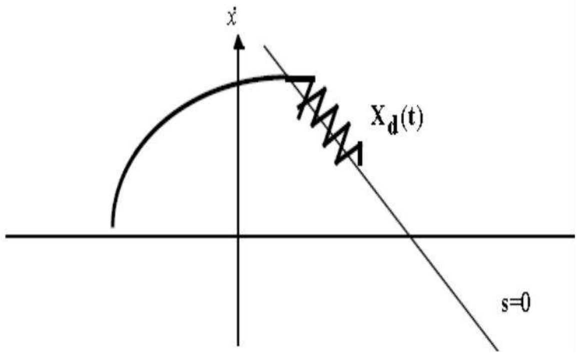
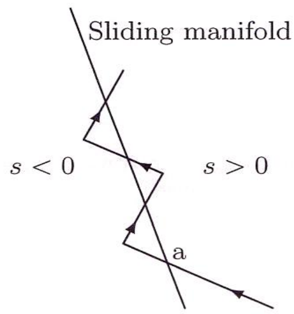


Figure 2: Chattering as a result of imperfect control switching [19]

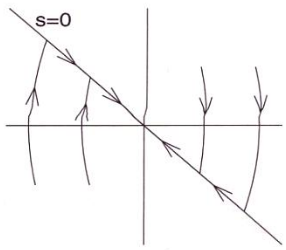
We have to note that the controller is discontinuous at $s(t)$. Due to the effects of sampling, switching and delays in the devices used to implement the controller, respectively in the simulation engines used when modelling the controlled system, sliding mode control suffers from chattering The next figure shows how delays can cause chattering. It depicts a trajectory in the region $s(t)$ heading toward the sliding manifold $s(t)$. It first hits the manifold at a point a. In ideal sliding mode control, the trajectory should start sliding on the manifold from a point a. In reality, there will be a delay between the time the sign of s changes and the time the control switches. During this delay period, the trajectory crosses the manifold into the region $s(t)$ [2].

There are many strategies used to avoid chattering; e.g., you can introduce a boundary layer. Here, the ***sgn*** function is made continuous by using a piecewise linear approximation. Within the boundary layer, you have exponentially convergence to the sliding mode. You rely on continuity arguments to show that the system will still converge [2].

Chattering results in low control accuracy, high heat losses in electrical power circuits and high wear of moving mechanical parts. It may also excite unmodeled high-frequency dynamics, which degrades the performance of the system and may even lead to instability [2].



3(a)



3(b)

Figure 3: (a) When s < 0 and s > 0
(b) When s = 0 [2].

Control laws which satisfy the sliding condition in Eqn. (4) and lead to "perfect" tracking in the face of model uncertainty, are discontinuous across the surface $s(t)$, thus causing control chattering. Chattering is undesirable as it involves extremely high control activity and besides, may excite high-frequency dynamics neglected in the course of modelling. Chattering must be reduced (or eliminated completely if possible) for the controller to perform properly. This can be achieved by smoothing out the control discontinuity in a thin boundary layer neighbouring the switching surface.

$$B(t) = \{x, |s(x;t)| \leq \phi\} \qquad \phi > 0$$

where ϕ is the boundary layer thickness, and
$\varepsilon = \phi / \lambda^{n-1}$ is the boundary layer width.

That means, outside of $B(t)$, we choose control law as mentioned earlier, which assures that the boundary layer is attractive, hence invariant. All the trajectories starting inside $B(t = 0)$ remain inside $B(t)$ for all $t \geq 0$, and then u is interpolated inside $B(t)$; e.g., $sgn(s)$ in Eqn. (12) can be replaced by $\frac{s}{\phi}$ inside $B(t)$.

5. Existing Case Studies

In a research done by Ruben Rojas, Oscar Camacho and Luis Gonzalez [4], a first order plus dead time model of the process for controlling open-loop unstable systems. The proposed controller has a simple and fixed structure with a set of tuning equations as a function of the desired performance. Both linear and non-linear models were used to study the controller performance by computer simulations.

In the research by Oscar Camacho and Carlos A. Smith [5], has shown the synthesis of a sliding mode controller based on a FOPDT model of the actual process. The controller obtained is of the fixed structure. A set of equations obtains the first estimates for the tuning parameters. The examples presented indicate that the SMC performance is stable and quite satisfactory in spite of non- linearity over a wide range of operating conditions.

In the research work by Chyi-Tsong Chen and Shih-Tien Peng [6], a novel and systematic sliding mode control system design methodology is proposed, which integrates an identified Second-Order Plus Dead-Time (SOPDT) model, an optimal sliding surface and a delay-ahead predictor. Besides, with the concept of delay equivalent, the proposed sliding mode control scheme can be utilized directly to the regulation control of a non-minimum phase process.

In the research by B. B. Musmade, R. K. Munje and B. M. Patre [7], a simple SMC strategy is designed based on the linearization of the nonlinear process model. This method is applied for the continuous yeast fermentation process. To broaden the scope of this method applications are extended to non-minimum phase behaviour processes. In conclusion, the proposed sliding mode controller can yield a better dynamic performance than conventional controllers. It is proved that the performance of the sliding mode controller is more robust against set-point changes and disturbances compared to conventional strategies.

In the research work by Hossein Nejatbakhsh Esfahani and Seyed Mohammad Reza Sajadi [8], SMC is developed for a class of nonlinear multi-input multi-output disrupted systems. In order to overcome the chattering problem and to ensure the tracking of desired trajectories, the authors proposed to combine an adaptive PD controller with the sliding mode. Based on the Lyapunov stability approach, the researchers suggested that their proposed adaptive sliding mode control scheme could guarantee global stability and the robustness of the closed-loop system with respect to disturbance.

In the research work by S. Mahieddine Mahmud, L. Chrifi-Alaoui, V. Van Assche and P. Bussy [9], the authors proposed a non-linear SMC with mismatch disturbances. The proposed method attenuates the effect of both uncertainties, external disturbances and eliminates the chattering phenomenon. The model of a hydraulic system is used to test the procedure.

The work by Aamir Hashim Obeid Ahmed [10] addresses controlling the speed of a separately excited DC motor. A separately excited DC motor is generally controlled by Proportional plus Integral (PI) controller. PI controller is simple but sensitive to parameter variations and external disturbance. Hence, for the robustness of Sliding Mode Control (SMC), especially against parameters variations and external disturbances, and also its ability in controlling linear and nonlinear systems; a separately excited DC motor sliding mode speed control technique is proposed in this paper. The simulation results showed that SMC is a superior controller than PI controller for speed control of a separately excited DC motor.

In the research work by Giuseppe Fedele [11], an identification method to estimate the parameters of a first order plus time delay model is proposed. Such a method directly obtains these parameters using a new linear regression equation. No iterations in the calculation are needed. A simple true/false criterion to establish if the hypothesis on the process type is correct can be easily derived. The proposed method shows acceptable robustness to disturbance and measurement noise as it is confirmed by several simulated experiments.

The work by Farzin Piltan, Sara Emamzadeh, Zahra Hivand, Forouzan Shahriyari and Mina Mirzaei [12], demonstrates the MATLAB/SIMULINK realization of the PUMA 560 robot manipulator position control methodology. This research focuses on two main areas, namely robot manipulator analysis and implementation, and design analyzed and implemented nonlinear Sliding Mode Control (SMC) methods. At present, robot manipulators are used in an unknown and unstructured situation and caused to provide complicated systems, consequently strong mathematical tools are used in new control methodologies to design a robust nonlinear controller with satisfactory performance (e.g., minimum error, good trajectory, disturbance rejection).

In the research by Sarah Spurgeon in the year 2014 [13], various canonical forms to facilitate design, have been described, and many numerical examples have been presented to reinforce the theoretical discussions. Of particular importance is the case of digital implementation, or indeed digital design, of sliding mode controllers.

In continuous time, discontinuous control strategies fundamentally rely upon very high frequency switching to ensure the sliding mode is attained and maintained. The introduction of sampling is disruptive. For example, switching of increasing amplitude can take place about the sliding surface.

In the research work by R. Saravana Kumar, K. Vinoth Kumar and Dr. K. K. Ray [14], the main objective was aimed at controlling the position of a field-oriented Induction Servo motor drive for a given reference input signal in a very efficient way. Their work was primarily focussed on designing a complete sliding-mode control system which would be insensitive to uncertainties, including parameter variations and external disturbances in the whole control process. They analyzed the design of an adaptive sliding- mode control system, which could adjust the bound of uncertainties in real time and also could reduce the chattering phenomena in the control effort using a simple adaptive algorithm.

The research by Chintu Gurbani and Dr. Vijay Kumar [15], addresses the designing of a controller using various types of sliding mode control strategies. Sliding mode control uses discontinuous control laws to drive the system state trajectory onto a specified surface in the state space, the so-called sliding or switching surface, and to maintain the system state on this manifold for all the subsequent times. For achieving the control objective, the control input must be designed with authority sufficient to overcome the uncertainties and the disturbances acting on the system.

In the research by Pushkin Kachroo and Masayoshi Tomizuka [16], a boundary layer around the switching surface was used to reduce chattering in sliding-mode control, and a continuous control was adapted within the boundary. The effects of various control laws within the boundary layer on chattering and error convergence in different systems were examined. New functions for chattering reduction and error convergence inside the boundary layer were suggested, which are discontinuous in magnitude only but not in sign. The internal model principle has been applied to generalize the design for the class of nonlinear systems being considered.

The research work by Yong Feng, Xinghuo Yu and Zhihong Man in 2002 [17], presents a global non-singular terminal SMC for rigid manipulators. A new terminal sliding mode manifold is first proposed for the second-order system to enable the wiping out of the singularity problem associated with conventional terminal SMC. The time taken to reach the equilibrium point from an initial state is guaranteed to be finite time. The proposed terminal SMC is then applied to the control of n-link rigid manipulators. Simulation results are presented to validate the analysis. a global non-singular TSM controller for second-order nonlinear dynamic systems with parameter uncertainties and external disturbances has been proposed. The time taken to reach the manifold from an initial system states and the time taken to reach the equilibrium point in the sliding mode have been proved to be finite. The new terminal sliding mode manifold proposed can enable the elimination of the singularity problem associated with conventional terminal sliding mode control. The global NSTM controller proposed has been used for the control design of an n-degree-of-freedom rigid manipulator. They presented simulation results to validate the analysis. The proposed controller can be easily applied to practical control of robots as given the advances of the microprocessor and the variables with fractional power can be easily built into control algorithms.

In the research by Goran Golo and Cedomir Milosavljevic [18], a new control algorithm based on discrete-time VSC theory was proposed. The basic feature of the algorithm is that trajectories reach the sliding manifold in a finite time, without chattering. Apart from stability, the robustness of the algorithm w.r.t. parameter uncertainties, as well as foreign disturbances, is considered. The authors established that robustness could be improved by reducing the sampling period. The theory was illustrated on a DC servo-position system. The realization of the proposed law requires knowledge of the state vector x. The control law has two modes. The first, non-linear mode ensures the reaching of the vicinity of the sliding hyperplane, in a finite number of steps. The second, linear mode ensures that the system reaches the sliding hyperplane in one step in the absence of external disturbances and parameter uncertainties. The linear mode is obtained by the state feedback pole-placement technique. The main feature of the proposed algorithm was robustness with respect to disturbances and parameter variations. Moreover, since a continuous function is in the vicinity of the control law, the system will be chattering free.

6. Future Directions

It has been established that SMC can be made useable in any type of non-linear process. So, future research in this regard can be an efficient process controller for industrial processes using SMC. The SMC can be effectively used in controlling the errors in industrial processes.

7. Conclusion

This review paper gives an overview of the concept of Sliding Mode Controller with a bibliographical survey of relevant background, practical requirements, the present state, and techniques. It is based on many research articles published from the past years. The citations listed here provide a representative sample of current engineering thinking pertaining to the wheeling of process control of non-linear systems.

The different process control techniques discussed here can be used for SMC. Process control systems (PCS) are pieces of equipment along the production line that can collect and transmit data during the manufacturing process. With its robustness properties, sliding mode controller can solve two major design difficulties involved in the design of a braking control algorithm: (i) The vehicle system is highly nonlinear with time-varying parameters and uncertainties; (ii) The performance of the system depends strongly on the knowledge of the tire/road surface condition [1].

For a class of systems to which it applies, a sliding controller design provides an organized approach to the problem of retaining stability and consistent performance in the face of modelling imprecision. For the wheel slip control system, the vehicle and brake system are highly nonlinear and time-varying systems. That makes a sliding mode controller ideal candidate for the application.

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