Chapter 8

Conclusions and Future Perspectives

In this chapter, we bring closure to the comprehensive body of work presented in this thesis, emphasizing its notable contributions while acknowledging its inherent limitations. Additionally, we identify prospective avenues for further exploration and investigation.

8.1 Conclusions

The primary goal of this thesis centered on formulating and applying the theory of sliding mode based on difference equation with minima tailored for discrete-time systems. By delving into the research, we aimed to address persistent challenges in the development of discrete sliding mode approaches. Each chapter of this thesis makes distinctive contributions, and we summarize the main findings below:

In the exploration detailed in Chapter 3, we introduced two reaching laws specifically designed for discrete-time systems, leveraging difference equation with minima. These reaching laws not only effectively eliminate chattering, ensuring smoother operation, but also contribute to improved system robustness. This improvement is achieved by strategically reducing the size of the quasi-sliding mode band width, without putting too much stress on the control effort. The delicate balance struck by these reaching laws showcases their efficacy in addressing nuanced challenges within discrete-time systems. Theoretical analysis and extensive simulation studies were conducted to validate the effectiveness and robustness of the proposed methodology in achieving slidng mode for unperturbed case and quasi-sliding mode for perturbed case.

Chapter 4 expanded upon the reaching laws based on the difference equation with minima, introducing a shift to rate-regulatory function-based reaching laws. The primary aim was to harness advantages related to the variable rate of change of the sliding variable, facilitated by the proportional term. This modification resulted in a significantly accelerated rate of change of the sliding variable. Notably, we demonstrated that this rate of change is effectively upper-bounded by the design parameters, offering an additional advantageous feature. We conducted the simulation on numerical example as well as on pendulum system. For pendulum system we conducted a comparative analysis among various methods and expectedly the findings revealed that the proposed method outperformed others.

Chapter 5 of the thesis set out to explore the Lyapunov characterization of discrete sliding mode based on difference equation with minima. In pursuit of this objective, we established the Lyapunov conditions for the finite-time input-to-state stability of perturbed discrete-time systems, offering insights into the settling time function. Moreover, we conducted a comparative study through simulations, highlighting the superior performance of the proposed laws in comparison to existing ones. An intriguing observation arising from this analysis is the attainment of the least ultimate bound for the sliding variable trajectory with satisfactory transient behavior.

Chapter 6 delved into the development of twisting-like and super-twisting-like algorithms, grounded in the framework of a difference equation with minima. Unlike conventional discrete-time algorithms which are often Euler-discretized, our proposed designs showcased distinctiveness. Employing these designs, we achieved the convergence of system states to an equilibrium point for unperturbed systems and to an invariant set for perturbed systems within finite time. Additionally, we extended the utility of the discrete super-twisting-like algorithm to design a super-twisting observer. This observer, in turn, robustly estimated unknown state variables for a perturbed pendulum system within a finite timeframe.

Chapter 7 centers on the application of the suggested reaching law based on a difference equation with minima, and delves into the intricacies of the applied reaching law, providing a comprehensive analysis of its performance in the context of the couple tank system. The results not only demonstrate the robustness of the proposed approach but also highlight its adaptability to real-world experimental conditions. The proposed law was successfully implemented in the couple tank system, and we showcased the outcomes through simulation and experimentation. The level control of the tank system was conducted under unperturbed and perturbed conditions. In both scenarios, the successful attainment of the desired water level underscores the efficacy of the proposed laws.

8.2 Future Perspectives

Although this thesis has significantly contributed to the field of discrete-time sliding mode control, it is crucial to recognize that the proposed design comes with certain limitations, suggesting possibilities for further progress. As a result, the subsequent sections outline these challenges and pinpoint potential avenues for future research and development:

- Exploring higher-order discrete sliding mode control stands out as a promising avenue that could significantly diminish the size of the quasi-sliding mode band and enhance the robust characteristics of sliding mode control. The implementation of higher-order discrete sliding mode involves elevating the relative degree of the sliding variable. Investigating the application of a difference equation with minima-based discrete sliding mode control, incorporating reaching laws with higher relative degrees, could prove to be an intriguing exploration. Notably, disturbances introduced in the reaching law from the r^{th} (for r^{th}-order sliding mode) time instants ago lead to the confinement of system states within a much narrower band.

- Exploring more intricate and practical system models is imperative, particularly in addressing challenges inherent in real-world scenarios. This includes investigating stochastic systems to encompass a broad spectrum of uncertain dynamical systems. The nonlinearities and uncertainties in such systems may manifest in a probabilistic manner with specific types and intensities. It becomes essential to analyze these aspects separately, taking into account the stochastic behavior of the system, in order to effectively mitigate the adverse effects resulting from these uncertainties.

- Enhancing robustness properties by narrowing the quasi-sliding mode band width is an extensively researched area and is expected to remain a focus in the years to come. The pursuit of refining proximity to the sliding manifold continues to be a significant aspect. Despite the loss of the invariance property in discrete sliding mode control, there remains room for improvement in the degree of robustness, making it a pertinent area for further exploration.

- Examining robustness properties concerning more generalized uncertainties presents an intriguing avenue for research. The uncertainties affecting system performance can fall into either matched or unmatched categories. Throughout this thesis, the assumption has been that the system is subject to matched-type bounded uncertainty, and the analysis has been specifically tailored to this case. However, the stability properties of the closed-loop system may differ, or even worse, the system could become unstable under unmatched uncertainties. Therefore, a more comprehensive analysis in this direction could provide a better understanding of the limitations inherent in the research conducted in this thesis.
- The Lyapunov characterization for the general n^{th}-order system is an obvious direction to continue this research work.