Amirkabir University of Technology
(Tehran Polytechnic)

Nonlinear Control

Dynamic and High order Sliding Mode Control
(DSMC)

Supervisor
Dr. Farzaneh Andollahi

By
Alireza Ansari

February 2023

Table of Contents

Amirkabir University of Technology
Faculty of Electrical Engineering

Nonlinear Control

Chapter 01: Introduction

Necessity of Robust Nonlinear Control Strategies.

Introduction

- Necessity of Robust Nonlinear Control

  ✓ In the control methods have been reviewed so far, such as Feedback Linearization, if the model is a very accurate, control methods based on the theory of linear systems can be used.

  ✓ In practice, models do not have enough accuracy and usually have uncertainty.

Introduction

- Sliding Mode Control

  ✓ SMC is a Nonlinear Control technique featuring remarkable properties of **Accuracy**, **Robustness**, and **Easy tuning and Implementation.**

  ✓ The basic concept of sliding mode control was first introduced in the 1950s by V. M. Glushkov in the Soviet Union. However, it was not until the 1970s that the approach was developed and popularized by Vadim Utkin, a Russian control theorist.

Nonlinear Control

Chapter 02: Traditional SMC

Exploring an example and stating the limitations.

Traditional SMC

- SMC Design

  ✓ SMC Systems are designed to drive the system states onto a particular Surface(Manifold), Called **Sliding Surface**.

  ✓ Once the Sliding Surface is reached, SMC Keeps the states on the **Closed Neighborhood of the Sliding Surface**.

Traditional SMC

- SMC Principles

  ✓ The first part involves the **Design of a Sliding Surface** so that the sliding motion **satisfies Design Specification**.

  ✓ The second part is concerned with the **selection of a Control Law** that will make the **Switching Surface attractive to the system states**.

Traditional SMC

- Chattering

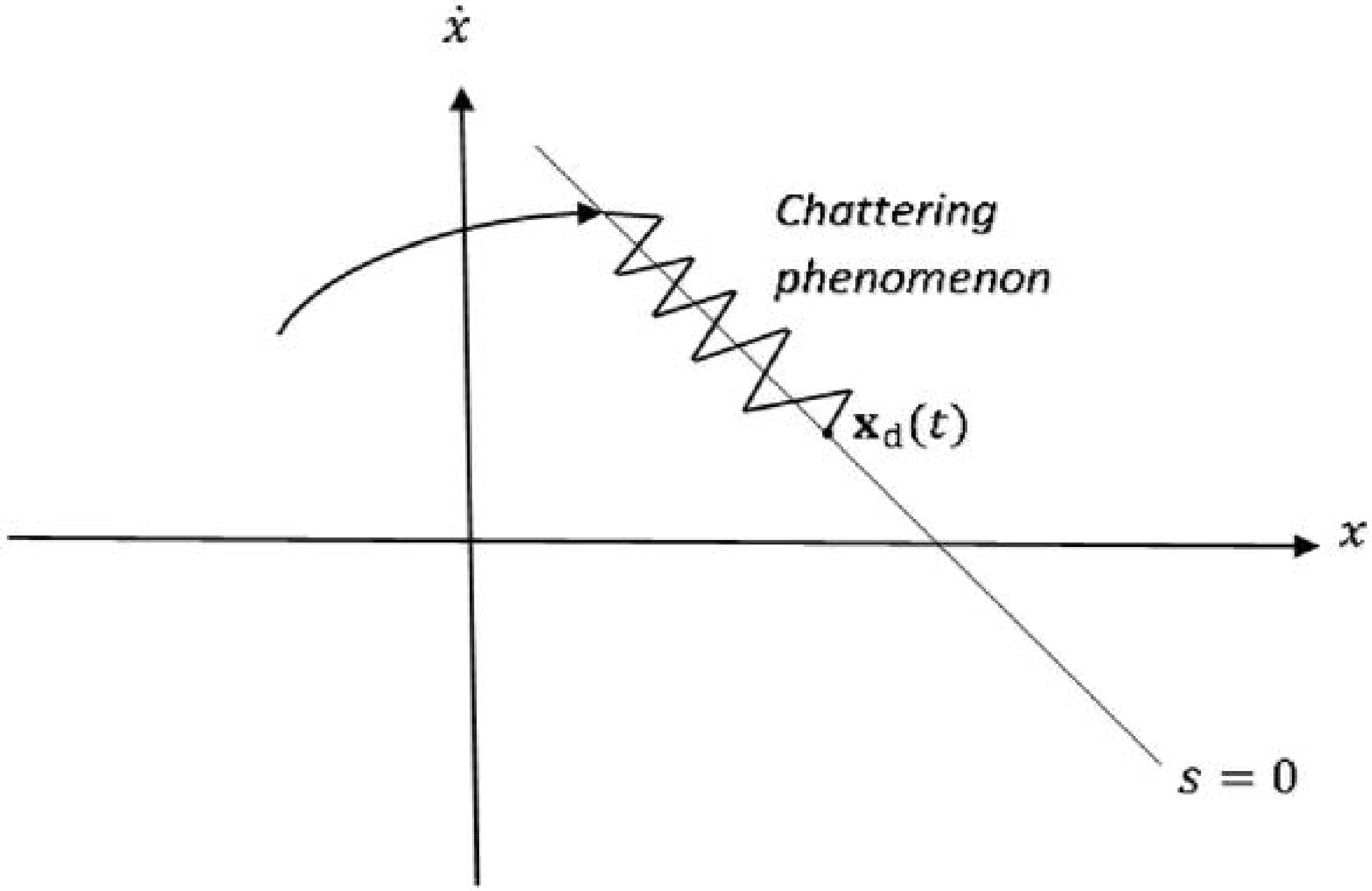
  - ✓ Chattering effect occurs in sliding mode control because of the **Discontinuous nature of the control signal**.

  - ✓ the control signal switches rapidly between two value in response to small changes in the system state.

  - ✓ The reason for this rapid switching is that the sliding mode control aims to drive the system state onto a sliding surface, which is a hyperplane in the state space. **Once the system state crosses this hyperplane**, the **control signal switches** to the opposite value, in order to drive the state back onto the sliding surface

Traditional SMC

- Chattering



Traditional SMC

- Chattering

  - ✓ Chattering effect can be particularly problematic in systems with **high-frequency dynamics or fast actuators**, as the rapid switching of the control signal can cause high-frequency oscillations that can damage the system or cause it to become unstable.

  - ✓ Boundary Layer Control Using Saturation Function and DSMC, …

Nonlinear Control

Chapter 03: Dynamic Sliding Mode Control

Examining one of the Methods for Chattering Reduction.

DSMC

- Introduction

  ✓ The main benefit of using dynamic sliding mode control over traditional sliding mode control is that it **reduces Chattering** in the system response.

  ✓ DSMC can reduce chattering effect in comparison to SMC because it **introduces a smoothing term that gradually transitions the control signal between its two values**, instead of switching abruptly.

  ✓ The Order of sliding mode control refers to the **number of times the sliding surface and its derivatives** are used in the control law.

DSMC

- Introduction

  ✓ The order of sliding mode control affects the performance of the control system. Higher-order sliding mode control laws can provide **better tracking and disturbance rejection performance**, but they can also be more difficult to design and implement.

  ✓ But they can also be **more difficult to design and implement.**

DSMC

- Introduction

  ✓ @DSMC, the control signal is computed by **adding a smoothing term to the SMC law**. The smoothing term **acts as a LPF that** filters out high-frequency oscillations in the control signal, while allowing the control signal to track the sliding surface accurately.

  ✓ A motivating example will be discussed in the next section.

DSMC

- Motivating Example

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -x_1^{\ 3} + u + d\sin(\omega t) \end{cases}$$

$$u = \boxed{-k\ \mathrm{sgn}(s)} + \boxed{h(s,\dot{s})}$$

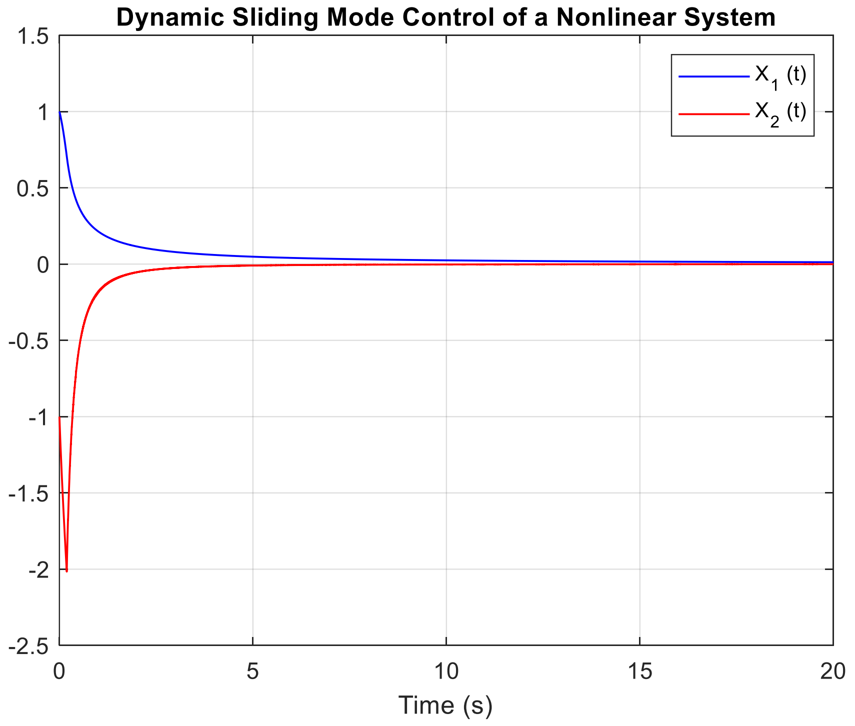
$$h(s,\dot{s}) = -k\ \mathrm{sgn}(s) - 0.5\dot{s}$$

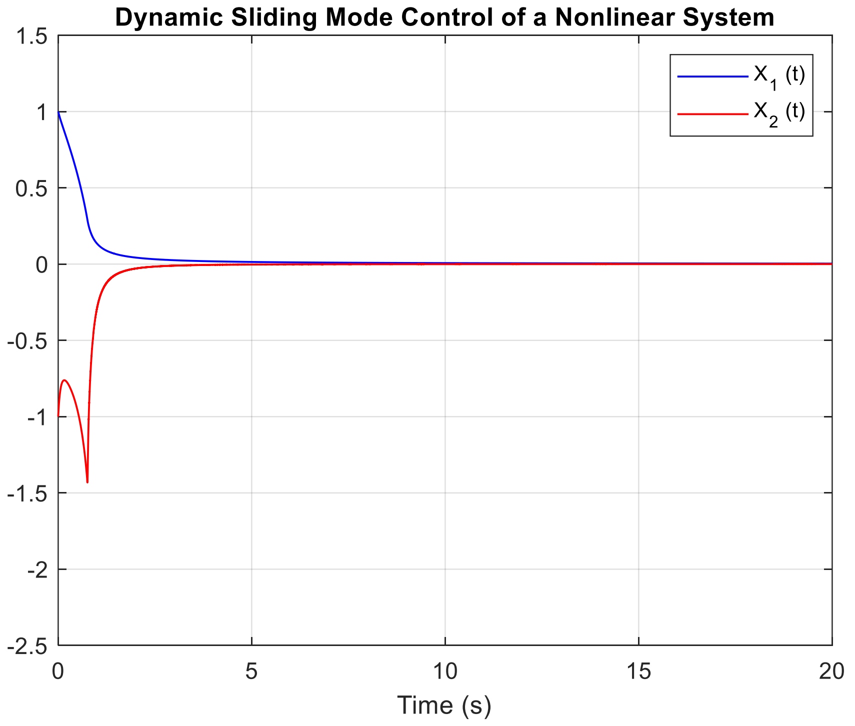
$$s = x_2 + 2\lambda x_1^{\ 2}$$

$$V(\underline{x}) = \frac{1}{2}(x_1^{\ 2} + x_2^{\ 2}) + \frac{1}{2}\lambda s^2 \longrightarrow \dot{V}(\underline{x}) = x_1 x_2 - x_1^{\ 4} - k|s|(x_2 + 4\lambda x_1 s) - \lambda s^2$$

DSMC

- Motivating Example





λ=2 **λ=8**

Nonlinear Control

Chapter 04: Case Study

Simulating a Chemical Process Model with DSMC.

Case Study

Journal of Process Control 85 (2020) 112–120

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

ELSEVIER

An approach of dynamic sliding mode control for chemical processes

Marco Herrera[a,*], Oscar Camacho[a], Hugo Leiva[b], Carlos Smith[c]

[a] *Departamento de Automatización y Control Industrial, Facultad de Ingeniería Eléctrica y Electrónica, Escuela Politécnica Nacional, Ladrón de Guevara E11-253, Quito 170517, Ecuador*
[b] *School of Mathematical Science and Information Technology, University Yachay Tech, San Miguel de Urcuqui-Imbabura, Ecuador*
[c] *Chemical Engineering Department, University of South Florida Tampa, FL 33620, United States*

Check for updates

Case Study

- Introduction

  ✓ Chemical processes have inverse behavior, and ever-present changes in disturbances. Combined with lack of precise knowledge of model parameter values, these aspects reduce the performance of conventional regulation schemes.

  ✓ For purpose of designing the controller, a process model is required. Industrial chemical processes are nonlinear in nature and present Dead-Time.

Case Study

- System Model

$$\frac{t_0\tau_m}{2}\ddot{Y}^*(t)+(\tau_m+\frac{t_0}{2})\dot{Y}^*+Y^*=k_m(\lambda-\eta)\dot{U}(t)+k_mU(t)$$

✓ Linearized Model:

$$G(s)=\frac{e^{-10s}}{(s+1)(0.5s+1)(0.25s+1)(0.125s+1)}$$

✓ FOPDT Model:

$$G(s)\cong\frac{e^{-10.68s}}{1.3s+1}$$

$$G_m(s)=\frac{k_m}{\tau_m s+1}e^{-t_0 s}\cong\frac{k_m}{\tau_m s+1}\frac{\left(1-\frac{t_0}{2}s\right)}{\left(1+\frac{t_0}{2}s\right)}$$

Case Study

- SMC Design

  ✓ Sliding Surface:

$$S(t) = sign(K)\left[-\frac{dX(t)}{dt} + \lambda_1 e(t) + \lambda_0 \int_0^t e(t)dt\right]$$

  ✓ Control Law:

$$U(t) = \left(\frac{\tau t_0}{K}\right)\left[\frac{X(t)}{\tau t_0} + \lambda_0 e(t)\right] + K_D \frac{S(t)}{|S(t)| + \delta}$$

Case Study

- DSMC Design

✓ Sliding Surface

$$\sigma = \dot{e}^*(t) + \lambda_1 e^*(t) + \lambda_0 \int e^*(t)\,dt \qquad e^*(t) = R(t) - Y^*(t)$$

✓ Reaching on Sliding Surface

$$\dot{\sigma} = (\ddot{R}(t) - \ddot{Y}^*(t)) + \lambda_1(\dot{R}(t) - \dot{Y}^*(t)) + \lambda_0 e^*(t) = 0$$

$$\dot{U}_c(t) = \frac{1}{2k_m(\lambda - \eta)}\left[(-\lambda_1 \tau_m t_0 + 2\tau_m + t_0)\dot{Y}^* + \lambda_0 \tau_m t_0 e^*(t) + 2Y^* - 2k_m U(t)\right]$$

$$\dot{U}_D(t) = k_D \,\mathrm{sgn}(\sigma)$$

Case Study

- DSMC Design

✓ Complete Control Law:

$$\dot{U}_{DSMC}(t) = \frac{1}{2k_m(\lambda-\eta)}\left[(-\lambda_1\tau_m t_0 + 2\tau_m + t_0)\dot{Y}^* + \lambda_0\tau_m t_0 e^*(t) + 2Y^* - 2k_m U_{DSMC}(t)\right] + k_D \operatorname{sgn}(\sigma)$$

$$\longrightarrow \quad U_{DSMC}(t) = \int_0^t \frac{1}{2k_m(\lambda-\eta)}\left[(\lambda_0\tau_m t_0 e^*(t) + 2Y^* - 2k_m U_{DSMC}(t)\right]dt + \int_0^t k_D \operatorname{sgn}(\sigma)dt$$

✓ Derivative of R(t) = 0:

$$\sigma = -\dot{Y}^*(t) + \lambda_1 e^*(t) + \lambda_0 \int e^*(t)dt$$

Case Study

- DSMC Design

  ✓ Parameter Variable(Due to FOPDT Model):

$$\lambda_0 \le \frac{\lambda_1^{\,2}}{4}$$

$$\lambda_1 = \frac{t_0 + 2\tau_m}{\tau t_0}$$

$$\lambda > \eta$$

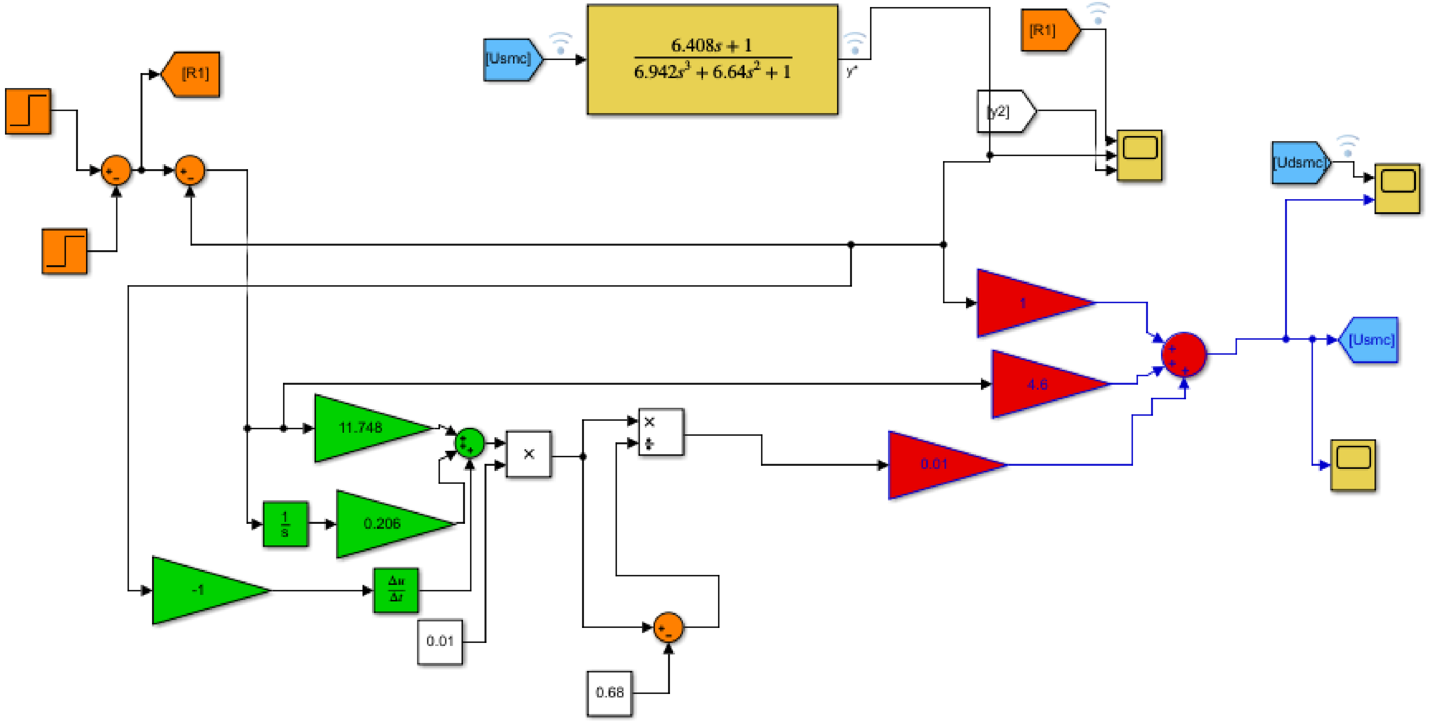
$$\lambda_0 = 0.206$$

$$\lambda_1 = 0.956$$

$$\lambda = 1.1 t_0 = 11.748$$

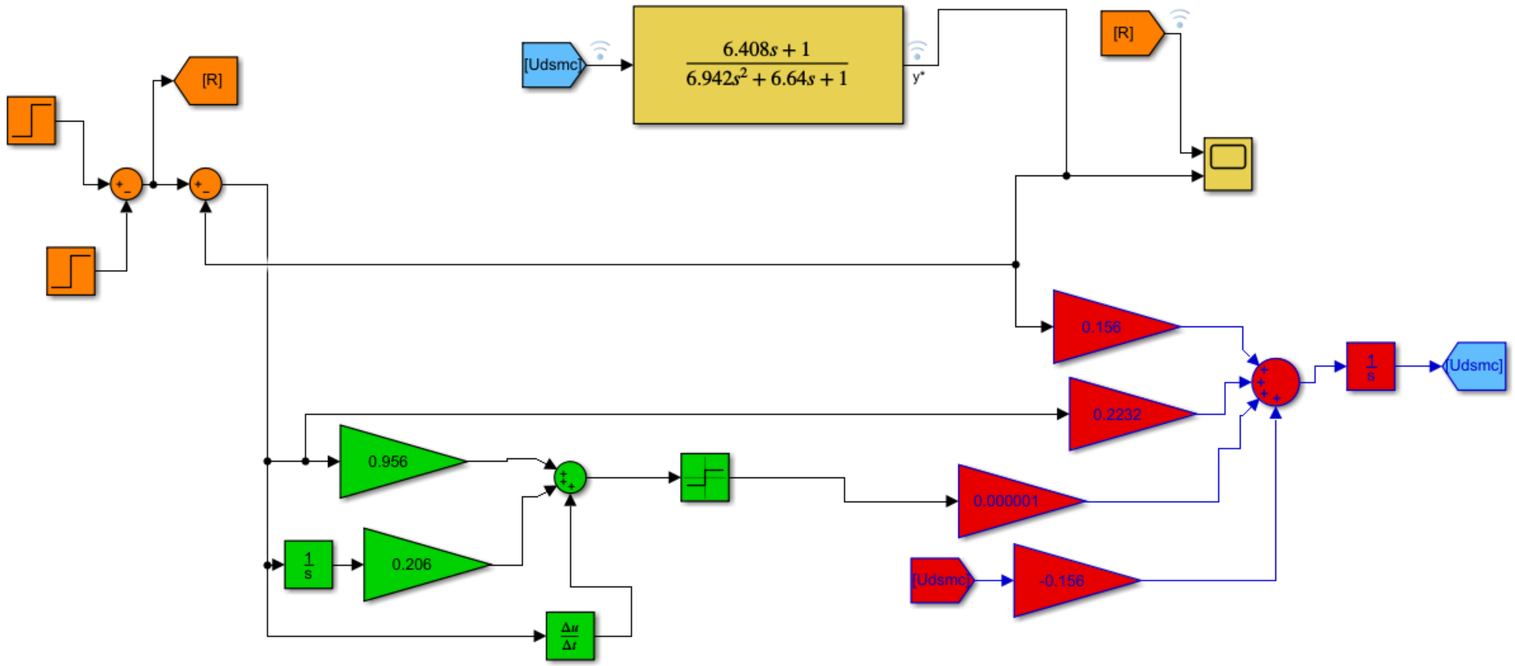
Case Study

- SMC Simulink Model:



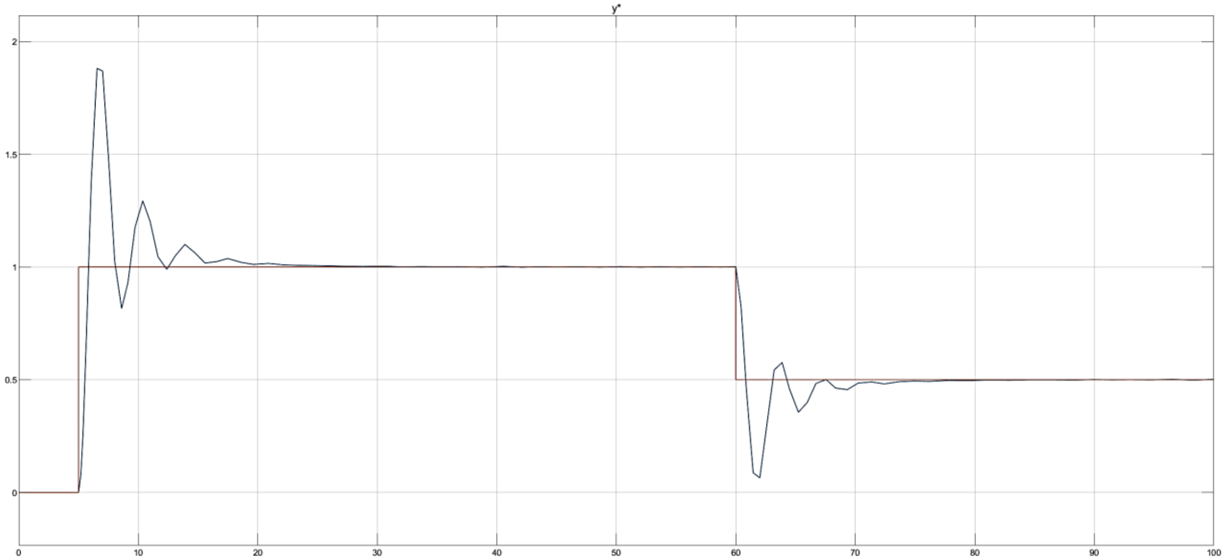
Case Study

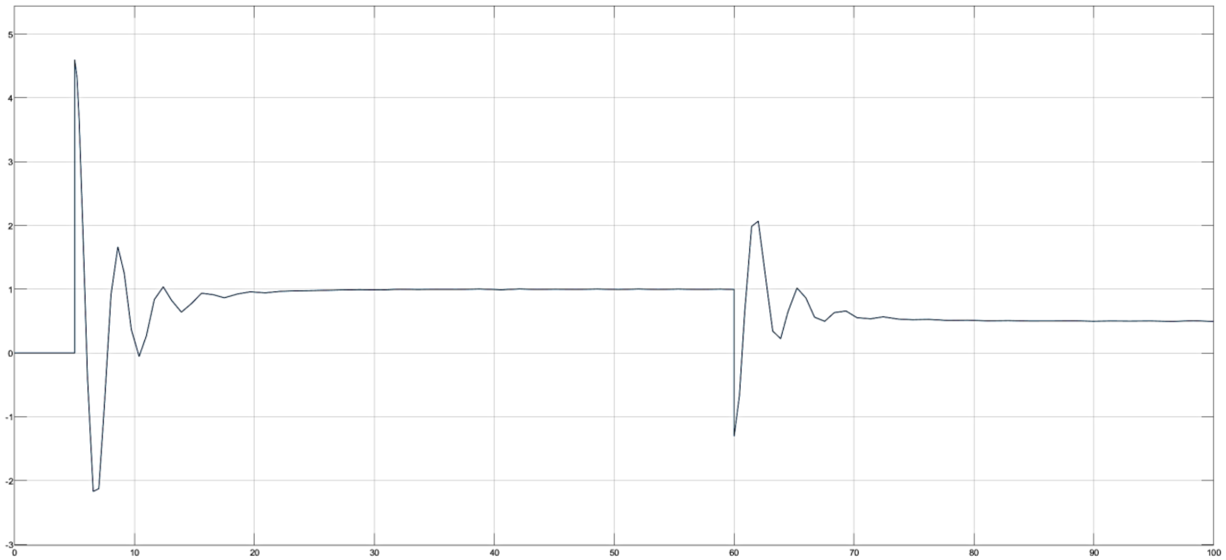
- DSMC Simulink Model:



Case Study

- Simulation Result (SMC)



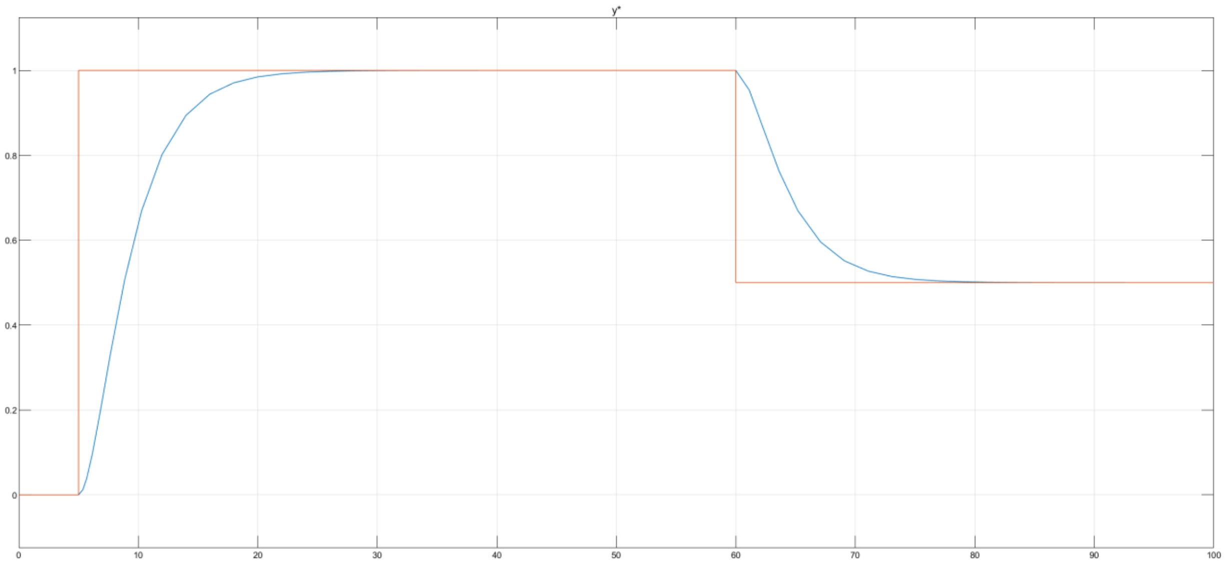


Output

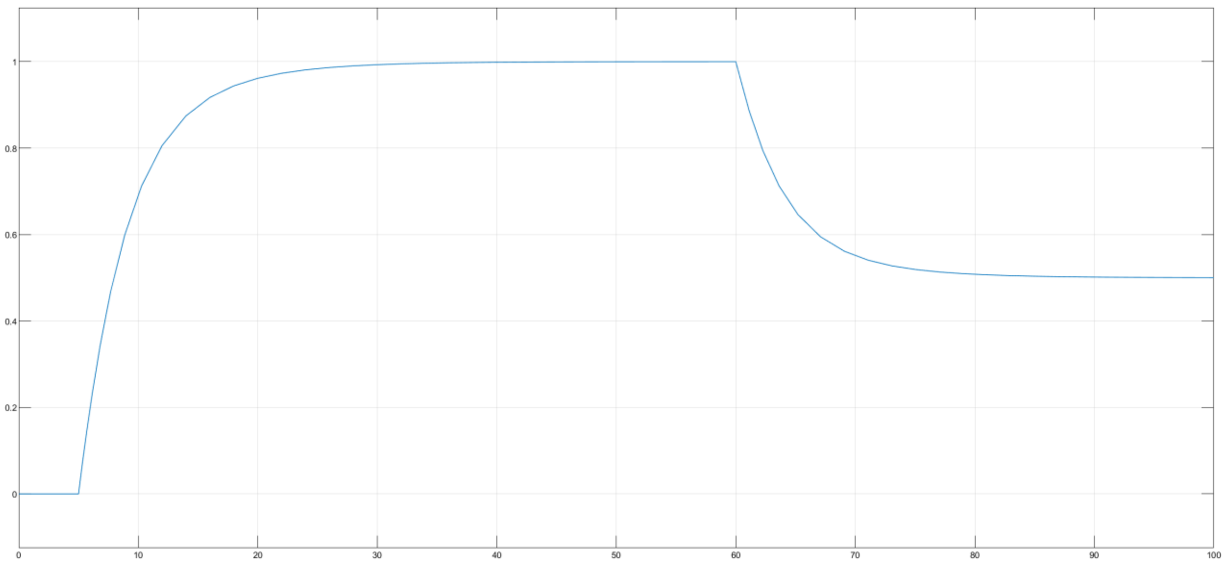
Control Effort

Case Study

- Simulation Result (DSMC)



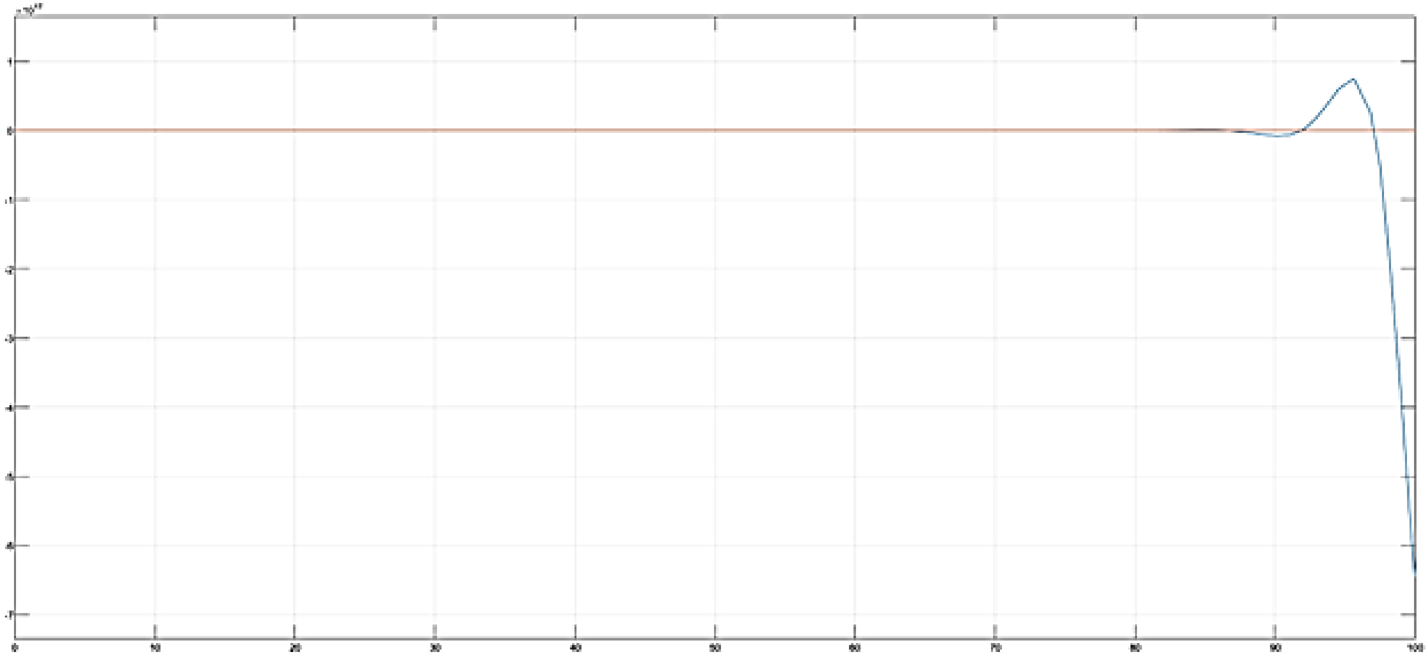
Output



Control Effort

Case Study

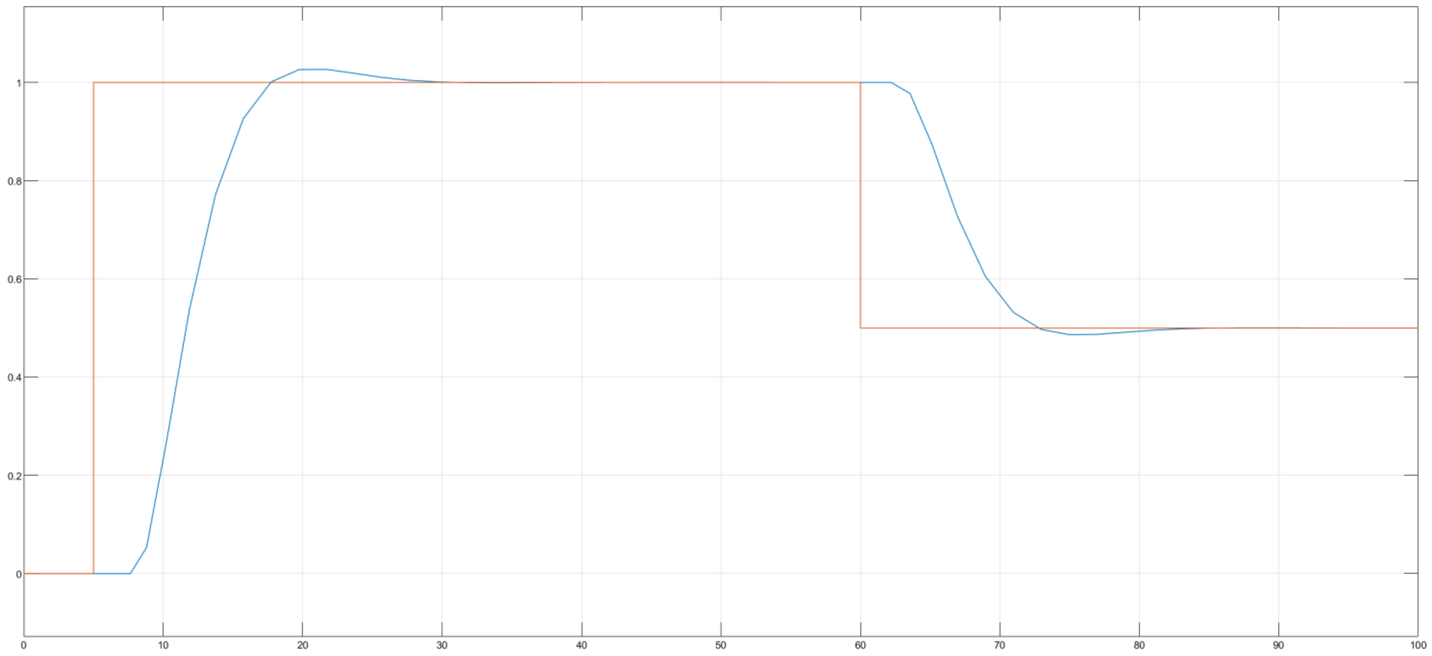
- SMC against Dead-time



Output

Case Study

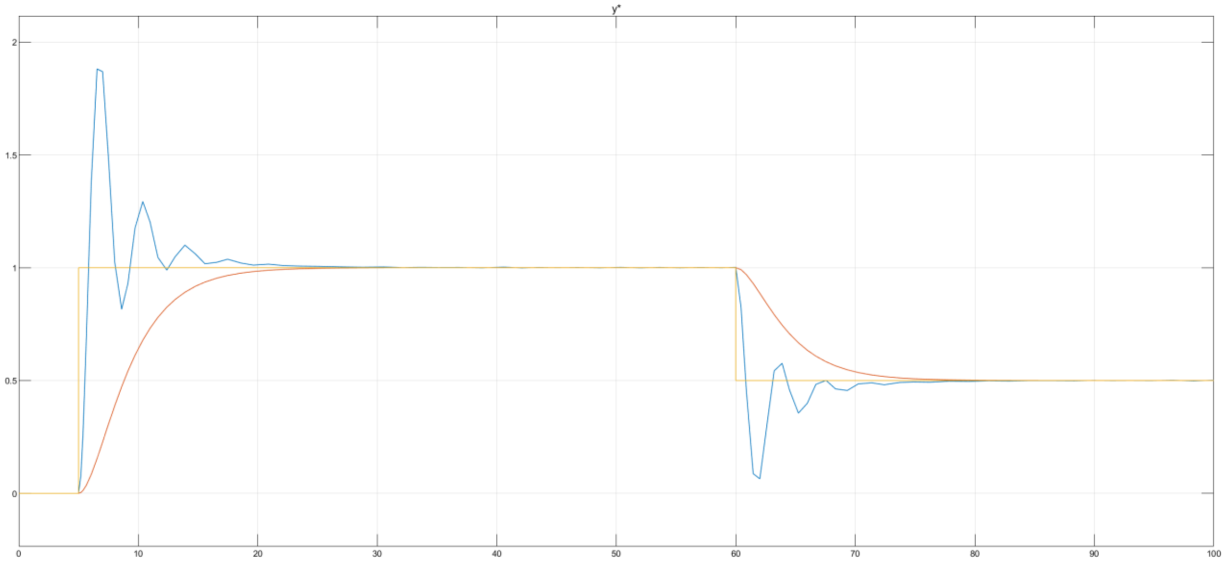
- DSMC against Dead-time

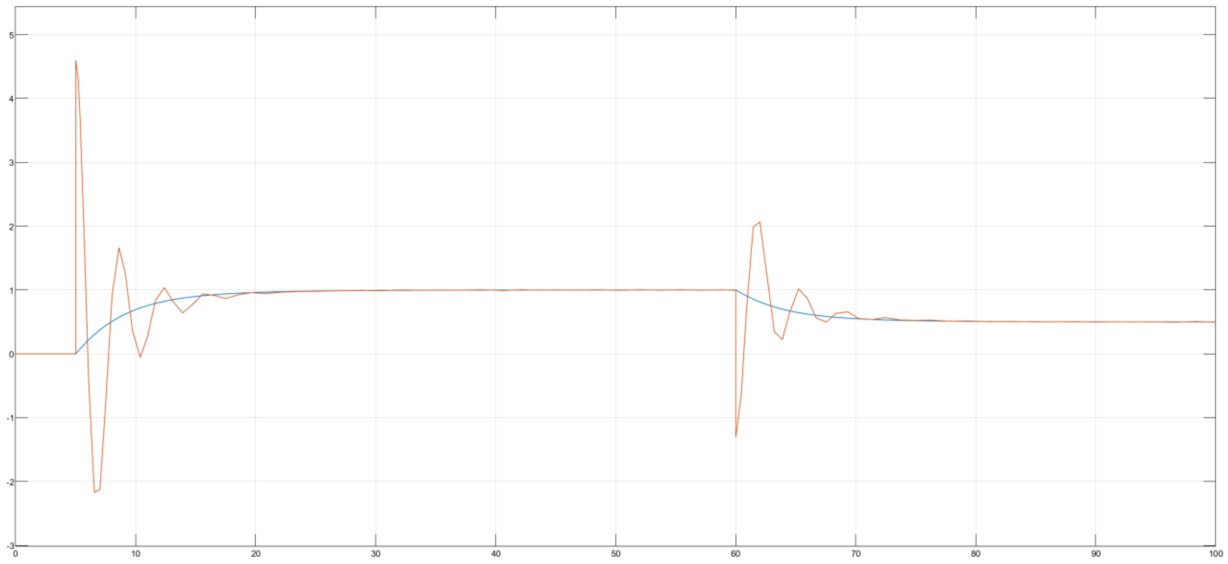


Output

Case Study

- Final Comparison





Output

Control Effort

Nonlinear Control

Chapter 05: Conclusion

Summarize the main points covered in this Presentation.

Conclusion

- ✓ DSMC has been applied to a wide range of control problems in various fields, including robotics, aerospace, automotive, and power electronics.

- ✓ Overall, DSMC offers improved performance over traditional SMC by **reducing Chattering** and providing robustness in the face of uncertainties and disturbances. However, DSMC can be more complex to design and implement compared to traditional sliding mode control, which may **require more computational resources and expertise.**

Conclusion

- Future Direction

  ✓ There are several future directions and potential areas for improvement in DSMC. Some of these areas include:

  ❖ **ML and Intelligent Control:** Integrating machine learning techniques into DSMC can enhance its performance and robustness, especially in cases where the system dynamics are highly nonlinear or Poorly Understood.

Conclusion

- **Improved sliding surfaces and observers**: Developing more efficient sliding surfaces and observers can improve the accuracy and speed of DSMC. Researchers are exploring various techniques such as **Adaptive Sliding Mode Control**, **Higher-Order Sliding Mode Control, and Fractional-Order Sliding Mode Control.**

- **Impact on energy consumption**: DSMC has the potential to impact energy consumption in systems that rely on power management. Researchers are exploring ways to minimize the energy consumption of DSMC while maintaining its robustness and stability.

Conclusion

- ❖ **Real-time implementation**: Efficient implementation of DSMC in real-time systems is critical for its successful application. Researchers are developing hardware and software solutions to improve the speed and accuracy of DSMC implementation.

- ✓ Future research in DSMC is focused on enhancing its performance, robustness, and energy efficiency, as well as improving its implementation in real-time systems. These advancements will enable DSMC to be applied to an even wider range of systems and applications.

Seminar - Control

Chapter 06: References

Introducing The References used in This Presentation.

References

[01] G. Ruskell, “The Human Eye, Structure and Function Clyde W. Oyster; Sinauer Associates, Sunderland, MA, 1999, 766 pages, hardback, ISBN 0-87893-645-9, £49.95,” Ophthalmic Physiol. Opt., vol. 20, no. 4, pp. 349–350, 2000.

[02] H. (thijs) Meenink, “Vitreo-retinal eye surgery robot:sustainable precision.” Technische Universiteit Eindhoven, 2011.

[03] M. M. S. Tosunoglu, “Robotic Ocular Surgery.”

[04] V. Vitiello, S.-L. Lee, T. P. Cundy, and G.-Z. Yang, “Emerging robotic platforms for minimally invasive surgery,” IEEE Rev. Biomed. Eng., vol. 6, pp. 111–126, 2013.

[05] I. Tsui, A. Tsirbas, C. W., S. D., and J.-P. Hubschm, “Robotic surgery in ophthalmology,” in Robot Surgery, InTech, 2010.

[06] A. S. Jagtap and C. N. Riviere, “Applied force during vitreoretinal microsurgery with handheld instruments,” Conf. Proc. IEEE Eng. Med. Biol. Soc., vol. 2004, pp. 2771–2773, 2004.

[07] P. K. Gupta, P. S. Jensen, and E. de Juan Jr, “Surgical forces and tactile perception during retinal microsurgery,” in Medical Image Computing and Computer-Assisted Intervention – MICCAI’99, Berlin, Heidelberg: Springer Berlin Heidelberg, 1999, pp. 1218–1225.

[08] M. Taefi, “Optimal Design and Implementation of Master-Slave Mechanism for Intravitreal Injection,” Amirkabir University of Technology (Tehran Polytechnic), Tehran, 2020.

[09] H. Hayati, “Analysis, design and implementation in visual servoing of robotic platform for intra-ocular injection,” Amirkabir University of Technology (Tehran Polytechnic), Tehran, 2019.

[10] M. K. Tameesh et al., “Retinal vein cannulation with prolonged infusion of tissue plasminogen activator (t-PA) for the treatment of experimental retinal vein occlusion in dogs,” Am. J. Ophthalmol., vol. 138, no. 5, pp. 829–839, 2004.

Thanks for Your Attention