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Discrete-Time Sliding Mode Control for Networked Control System

Springer

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To our Parents, Teachers, Family and Friends.

Preface

Networked Control Systems (NCSs) are traditional feedback control loops closed through a real-time communication network. In other words, the exchange of information such as reference input or set point, plant output or sensor data and controller output between control system components (sensors, controllers, actuators) is carried out via a communication network. NCS has become popular in the field of control due to its distinct advantages such as low cost, reduced weight, simple installation and maintenance, resource sharing and high reliability. Moreover, NCS has got wide industrial applications such as in manufacturing plants, smart grid, haptic collaboration, vehicles, aircraft, robotics, spacecraft. NCS generally possesses a dynamic nature, which results in various challenges for researchers such as network-induced time delay, packet loss, packet disordering, resource allocation and bandwidth sharing. It is well known that the performance of NCS is significantly deteriorated due to these communication irregularities if these challenges are not handled properly. Among all these issues, network-induced time delay and packet loss are considered to be crucial issues in NCS that deteriorate the stability and performance of closed-loop control systems significantly.

The network-induced delays may be constant, time-varying and, in most cases, random. The nature of network-induced delay mainly depends on the configuration of the communication medium. If the communication medium is configured using leased lines concept, then the delays are always deterministic in nature. And whenever the communication medium is shared by a large number of devices, then the delays are random in nature. It is worth to mention here that the amount of time required for the data packets to travel from sensor to controller and controller to actuator is defined as total network delay. The controller mainly suffers from sensor to controller delay. When such network-induced delays are transformed into discrete-time domain, it mostly possesses non-integer type of values. Such network-induced delays in discrete-time domain are referred to fractional delays, which may be either deterministic or random in nature. So, it is important to compensate the effect of deterministic as well as random fractional delays in discrete-time domain at each sampling instant.

Further, as mentioned above, there are also possibilities of packet loss/information loss during the transmission of data packets from sensor to controller as well as controller to actuator. The packet loss usually takes place due to heavy network load, network congestion and node competition. In discrete-time domain, the network-induced delay greater than one sampling time is also considered as packet loss. The nature of network-induced delay and single packet loss as well as multiple packet loss is mainly dependent on the configuration of network medium.

In recent years, many algorithms have been studied for the stability analysis and controller design for NCS that include PI controller, state feedback controller, H_∞ controller, model predictive controller, sliding mode controller. Among them, sliding mode controller (SMC) is one of the robust control algorithms due to its invariance properties to parameter variation and uncertainties.

This monograph presents some novel algorithms for designing discrete-time sliding mode controller (DSMC) for NCS having both types of fractional delays, i.e. deterministic and random, along with different packet loss conditions, i.e. single packet loss and multiple packet loss. The efficacy of the proposed control algorithm is tested with real-time networks such as CAN and Switched Ethernet medium and experimentally verified by DC servomotor. The robustness of the proposed discrete-time sliding mode controller is improved through disturbance estimator in the presence of multiple packet transmission policy and matched uncertainty.

This monograph contributes mainly the following:

- In Chap. 1, the introduction of Networked Control System in continuous- and discrete-time domains that include time delay compensation methods and design of controllers with single packet loss and multiple packet loss is briefly discussed.
- In Chap. 2, preliminaries and literature survey of NCS and SMC technique in continuous- and discrete-time domains are presented.
- In Chap. 3 and Chap. 4, a modified discrete-time sliding surface and discrete-time sliding mode controller are proposed using the compensated state information that encompasses deterministic type fractional delay and single packet loss. The proposed algorithms are also compared with conventional sliding mode controller using CAN and Switched Ethernet as network medium.
- In Chap. 5, the multirate output feedback approach for the state estimation in the closed loop is incorporated. The main advantage of using multirate output feedback approach is that the system states are computed based on the output information available and the error between computed and estimated state variables goes to zero exactly after one sampling instant even in the presence of networked delay.
- In Chap. 6, discrete-time sliding surface is designed for random fractional delay and single packet loss that occur within the sampling period. The random delay is compensated using Thiran's approximation technique in the presence of packet loss situation. The efficacy of proposed non-switching type of DSMC is endowed by simulation results and also experimentally validated on servo system.

- Further in Chap. 7, the proposed algorithm is extended for random fractional delay with multiple packet loss situation. The disturbance estimator is designed that estimates the disturbance signal and improves the performance of the system. The efficacy of the algorithm is endowed by the simulations under various fractional delays and matched uncertainties.
- In Chap. 8, concluding remarks, future scope and challenges in NCSs are presented.

Keywords Networked control system, Discrete-time sliding mode control, Fractional delay, Packet loss, Multirate output feedback, Disturbance estimator.

Ahmedabad, India
September 2017

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Contents

About the Authors

Dipesh H. Shah was born in Vadodara, Gujarat, India, in 1985. He completed his B.E. (Instrumentation and Control), M.E. (Applied Instrumentation) and Ph.D. (Networked Control System) in 2007, 2010 and 2018 from Gujarat University and Gujarat Technological University, Ahmedabad respectively. He is currently working as an Assistant Professor in Instrumentation and Control Department at Sardar Vallabhbhai Patel Institute of Technology, Vasad, Gujarat, India. He is also serving as an Faculty Advisor at Institute level for ISA student' chapter. He has published various research papers in peer-reviewed journals and presented several papers in national and international conferences. His research interest includes discrete-time sliding mode control, networked control system and communication protocols.

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Acronyms

Abbreviations

CAN	Controller area network
CSMA/CD	Carrier sense multiple access collision detection
DNSMC	Discrete-time networked sliding mode control
DSMC	Discrete-time sliding mode control
FIFO	First-in, first-out
GSM	Gain schedule middleware
LAN	Local area network
LQG	Linear–quadratic–Gaussian
LQR	Linear–quadratic regulator
LTI	Linear time-invariant
MAN	Metropolitan area network
MROF	Multirate output feedback
NCS	Networked Control System
PAN	Personal area network
RMPC	Robust model predictive control
RTT	Round-trip time
SISO	Single input, single output
SMC	Sliding mode control
TOD	Try-one-discard
VSC	Variable structure control
WAN	Wide area network
WSN	Wireless sensor networks
ZOH	Zero-order hold

Symbols

$x(t)$	Plant state vector in continuous-time domain
$u(t)$	Control input signal in continuous-time domain
$d(t)$	Slow time-varying disturbance signal in continuous-time domain

$y(t)$	Output signal in continuous-time domain
$x(k)$	Plant state vector in discrete-time domain
$u(k)$	Control input signal in discrete-time domain
$d(k)$	Disturbance signal in discrete-time domain
$y(k)$	Output signal in discrete-time domain
A	System matrix in continuous-time domain
B	Control input matrix in continuous-time domain
C	Output matrix
F	System matrix in discrete-time domain
G	Input matrix in discrete-time domain
a_1, a_2, M_s, c	Constants
$s(t)$	Sliding surface in continuous-time domain
$s_d(k)$	Priori function
$k_s, \imath, \psi$	User-defined constant
δ_0	Positive offset
p_s, k'	Positive integer
k_t	User-defined gain
k_t^+, k_t^-	Lower and upper bounds coefficients
$\hat{S}$	Model uncertainty
S_1, S_2	Mean and deviated value of $\hat{S}$
S_u, S_l	Upper and lower bounds of $\hat{S}$
λ_s	Switching gain
τ_t	Total delay which includes system- and network-induced delay in continuous-time domain
τ	Total network-induced delay (feedback and forward channel delay) in continuous-time domain
τ_{sc}	Sensor to controller delay in continuous-time domain
τ_{ca}	Controller to actuator in continuous-time domain
h	Sampling interval
τ'	Deterministic total network-induced fractional delay
τ'_{sc}	Sensor to controller deterministic type fractional delay
τ'_{ca}	Controller to actuator deterministic type fractional delay
τ_r	Total random network delay in continuous-time domain
$\hat{\tau}$	Total random network fractional delay in discrete-time domain
τ_{rsc}	Random sensor to controller delay in continuous-time domain
τ_{rca}	Random controller to actuator delay in continuous-time domain
$\hat{\tau}_{sc}$	Random sensor to controller fractional delay in discrete-time domain
$\hat{\tau}_{ca}$	Random controller to actuator fractional delay in discrete-time domain
$\hat{\tau}_l$	Lower bound of random fractional delay
$\hat{\tau}_u$	Upper bound of random fractional delay
d_l	Lower bound of disturbance
d_u	Upper bound of disturbance

τ_p	Total processing delay in continuous-time domain
τ_{sp}	Sensor processing delay in continuous-time domain
τ_{cp}	Controller computational delay in continuous-time domain
τ_{ap}	Actuator processing delay in continuous-time domain
v	Fractional part of delay
l	Order of approximation
δ	Signal transmission delay
$s(k)$	Sliding variable in discrete-time domain
C_s	Sliding gain
α	Parameter calculated using Thiran's approximation
$Q,\ R$	Matrices of appropriate dimensions in LQR
$\varepsilon,\ q$	User-defined constants of Gao's law
sgn	Signum function
d_1	Mean value of disturbance
d_2	Deviated value of disturbance
d_s	Compensated disturbance signal
$\eta, \beta, \rho, \gamma$	Smallest parameter constant obtained using Lyapunov stability analysis
V_s	Lyapunov function
Φ, κ	Stability parameters
α'	Parameter computed based on actuator to controller fractional delay
u_a	Compensated control signal at actuator side
T_s	Settling time
τ_{CAN}	Amount of network delay in CAN medium
τ_{ETHER}	Amount network delay in Switched Ethernet medium
$\theta(s)$	Output of the system (position)
V_m	Input to the system
J_m	Rotor inertia
R_m	Terminal resistance
K_m	Motor back emf constant
$\bar{\alpha}, \bar{\beta}$	Probability of state and control data packet loss
$x'_c(k)$	Communicated state variable over the network
$\{d_1, d_2, .., d_q\}$	Values in a finite set
β_v	Positive scalar quantity
$\alpha(k), d_v$	Stochastic variables
$E\{d_v\}$	Expectation of stochastic variable d_v
w	Number of trials
λ	Average number of events per interval
e	Euler's constant
ς, γ'	Random parameter generated using Thiran's approximation
$E\{\alpha(k)\}$	Expectation of stochastic variable $\alpha(k)$
$u_c(k)$	Communicated control signal over the network

Γ	Stability parameter computed using packet loss and random fractional delay
τ_c	Sampling rate of control input signal
ζ	Sampling rate of output signal
F_ϕ	System matrix sampled at ϕ sampling interval
G_ϕ	Control input matrix sampled at ϕ sampling interval
Λ	Positive integer
F_ζ	System matrix sampled at ζ sampling interval
G_ζ	Control input matrix sampled at ζ sampling interval
$\hat{x}$	Estimated state variable computed using multirate output feedback approach
y_k	Output stack
$\hat{\tau}_{sc_{max}}$	Max delay experienced by the packet as the sensor to controller delay
$\hat{\tau}_{sc_i}$	Sensor to controller fractional delay generated from i^{th} sensor
$\rho_1 .., \rho_n$	Random variables uniformly distributed over the interval [0,1]
$P_{loss1}, .., P_{lossn}$	Probability of multiple state packet loss over the network
ζ_{max}	Parameter designed using Thiran's approximation for max delay experienced by the packet
$\hat{d}_s(k)$	Compensated estimated disturbance applied to the network
$\hat{d}(k)$	Output of disturbance estimator

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