Discrete-Time Super Twisting Controller for Networked Control Systems

Jakob Ludwiger * Markus Reichhartinger *
Martin Steinberger * Martin Horn **

* Institute of Automation and Control, Graz University of Technology,
Graz, Austria (e-mail: jakob.ludwiger@tugraz.at)
** Christian Doppler Laboratory for Model Based Control of Complex
Test Bed Systems, Institute of Automation and Control, Graz
University of Technology, Graz, Austria.

Abstract: In this paper, a sliding mode based control concept for networked control systems in the presence of variable time delays and external perturbations is proposed. The control concept consists of a buffering mechanism and a discrete time integral sliding mode based control law. This setting offers the possibility to use discrete-time sliding mode control techniques designed for relative degree one systems. As a consequence, networked control algorithms can be developed based on recent results from this active field of research. Using a discretized version of the super twisting algorithm, which is obtained by the so-called matching approach, increases the accuracy due to the absence of discretization chattering. The effectiveness of the proposed control strategy is demonstrated by means of laboratory experiments.

Keywords: Time-varying delay, Sliding-mode control, Discretization, Closed-loop control

1. INTRODUCTION

The feedback loop of modern control systems is very often closed via a network. This means that a sensor transmits its measurements via a communication network to the controller which computes the actuating signal and sends it via the same or a second network to the actuator. This architecture benefits from increased flexibility and adaptability because it offers the possibility to easily replace components or even add additional ones. Furthermore, large spatial distances can be overcome with very little wiring effort or even without wires using wireless communication technologies. Nevertheless, using those technologies in control engineering goes along with additional challenges in the design of the control algorithms due to network imperfections. One of these imperfections is, that packets could get lost. There are several scientific publications concerning the design of control algorithms considering this type of imperfection (see e.g. Schenato et al. (2007); Xiong and Lam (2007); Azim-Sadjadi (2003)).

The second challenge is to design control algorithms, which are robust with respect to delays induced by the network. There are some approaches, which considers time varying delays and guarantees stability (see Liu and Fridman (2012); Liu et al. (2012)) using Lyapunov-Krasovskii analysis. Other approaches are based on prediction and achieve compensation of communication delays and data losses (see Liu (2010)). Some approaches make use of event-triggered control to reduce the network load, which should indirectly lead to smaller time delays and less packet loss. This idea of using event-triggered control is already combined with sliding mode control and can be found e.g. in Behera and Bandyopadhyay (2016); Incremona et al. (2017). An overview of existing techniques for networked control are given in Zhang et al. (2016); Heemels and van de Wouw (2010).

In Ludwiger et al. (2017) a method was proposed, which considers time varying delays and uses discrete-time first order sliding mode control to alleviate perturbations. An extension of this approach is given in Ludwiger et al. (2018), where two discrete-time sliding mode methods using higher relative degree sliding variables are proposed.

In the present paper a control scheme for networked control systems (NCS) based on integral sliding mode control is presented which offers the opportunity to cast the problem into a form where discrete-time sliding mode control laws designed for relative degree one systems can be applied. As a consequence recently developed algorithms as the discrete-time equivalent super twisting controller can be applied. The properties of the proposed algorithm will be shown by means of laboratory experiments. In the following section the problem statement is explained and the assumptions are pointed out. Afterwards the proposed approach is described in detail starting with the buffering mechanism, followed by the plant modeling and ending with the control design. The effectiveness of the proposed approach is then exemplified by means of laboratory experiments. Final conclusions and an outlook is given in the last section.

2. PROBLEM STATEMENT

In this paper, a linear time-invariant system
\[
\frac{dx}{dt} = A_0x + b_0(u(t) + f(t))
\] (1)
with state vector \( x \in \mathbb{R}^n \), scalar input \( u \in \mathbb{R} \) is considered. Function \( f \in \mathbb{R} \) represents a matched perturbation. Matrix
Due to a time synchronization between the buffer and the sampler, the current time delay $\tau_b$ can be determined. The buffer stores the received packets and forwards them after an additional delay of

$$\tau_b^k = \alpha T - \tau_k$$

(6)

to ensure a constant round trip time. This buffering mechanism is very common in multimedia applications (see e.g. Ramjee et al. (1994); Atzori and Lobina (2006)) but has also been introduced in the control community e.g. in Quevedo and Nesic (2011).

3.2 Modelling of the Plant with Buffered Network

Considering the sampling time $T$, the constant time delay $\alpha T$ achieved by the buffer and plant (1), the discrete-time model of the NCS can be stated as

$$x_{k+1} = Ax_k + b(u_{k-\alpha} + f_k)$$

(7)

with $A = e^{A*T}$ and $b = \int_0^T e^{A*t}b,ds$. Defining the lifted state vector

$$\xi_k = \begin{bmatrix} x_k^T & u_{k-1} & u_{k-2} & \ldots & u_{k-\alpha} \end{bmatrix}^T$$

(8)

results in the lifted model

$$\xi_{k+1} = \begin{bmatrix} A & 0 & \ldots & 0 & b \\ 0 & 0 & \ldots & 0 & 1 \\ 0 & 1 & \ldots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \ldots & 1 & 0 \end{bmatrix} \xi_k + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ b \\ b_f \end{bmatrix} f_k.$$

(9)

Remark 1. In contrast to (1) the perturbation in (9) does not fulfill the matching condition, although it is fulfilled in (7). Nevertheless, it is possible to design a sliding mode control law in order to robustly stabilize the origin of the state vector $x_k$ but not the state vector $\xi_k$, which is common for unmatched uncertainties. However, this is a desired behavior in this NCS applications, because the elements $u_{k-1} u_{k-2} \ldots u_{k-\alpha}$ have to compensate for the matched perturbation.

3.3 Controller Design

The basic concept of integral sliding mode control is to robustify a control loop, which was designed for the nominal case i.e. $f_k = 0, \forall k$. This is achieved by defining the control signal as

$$u_k = u_{N,k} + u_{S,k}$$

(10)

where $u_{N,k}$ denotes a nominal control signal, designed for the nominal case, and $u_{S,k}$ representing the sliding mode based part of the control law. The control component $u_{S,k}$ is designed to compensate for the matched perturbation in order to keep the desired properties, ensured by the nominal control law, also in the perturbed case. The design of these two parts will be explained in more detail in the following sections.

Nominal Control Law

The nominal lifted model

$$\xi_{k+1} = A\xi_k + b u_{N,k}$$

(11)

with the nominal lifted state vector

$$\xi_k = \begin{bmatrix} x_k^T & u_{N,k-1} & u_{N,k-2} & \ldots & u_{N,k-\alpha} \end{bmatrix}^T$$

(12)

results from the lifted model (9) and lifted state vector (8) for $f_k = u_{S,k} = 0, \forall k$. Applying, e.g., classical approaches

\[\text{due to the nature of the content.}\]

3.1 Buffering Mechanism

The sampler attaches a time stamp to each measurement before transmission, which is not altered by the controller.
like assigning $n + \alpha$ eigenvalues by means of a linear state control law

$$u_{N,k} = -k^T \hat{\xi}_k$$  \hspace{1cm} (13)

This control law is designed to achieve stability and desired performance of the unperturbed NCS.

**Sliding Mode Control Law**

In the remainder of this paper, a discrete time equivalent of the super-twisting algorithm based on the so-called matching approach which was recently proposed in Koch and Reichhartinger (2019) is used. The basic idea of this algorithm will be explained in the following paragraph. Consider a continuous time perturbed integrator

$$\frac{\sigma}{dt} = \hat{u}_S + \varphi$$  \hspace{1cm} (14)

$$\frac{\varphi}{dt} = \Delta(t)$$

with $\sup(\Delta(t)) = L_\Delta < \infty$ and applying the super twisting algorithm proposed in Levant (1993) results in the well-known closed loop dynamics

$$\frac{\sigma}{dt} = -\lambda_1 [\sigma]^{1/2} + \sigma_2$$  \hspace{1cm} (15)

$$\frac{\varphi}{dt} = -\lambda_2 [\sigma]^{-1} + \Delta(t)$$

where $[y] = [y]_+ \text{sign}(y)$. As proposed by Reichhartinger and Spurgeon (2018) this closed loop dynamics can be written in the pseudolinear form

$$\frac{d}{dt} \begin{bmatrix} \sigma \\ \sigma_2 \end{bmatrix} = M(\sigma) \begin{bmatrix} \sigma \\ \sigma_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \Delta(t) \end{bmatrix}$$  \hspace{1cm} (16)

with

$$M(\sigma) = \begin{bmatrix} -\lambda_1 |\sigma|^{-1/2} & 1 \\ -\lambda_2 |\sigma|^{-1} & 0 \end{bmatrix}$$

its characteristic polynomial is (almost everywhere)

$$w(s) = s^2 + \lambda_1 |\sigma|^{-1/2} s + \lambda_2 |\sigma|^{-1}$$

and the resulting state dependent eigenvalues are

$$s_1(\sigma) = p_1 |\sigma|^{-1/2} \text{ and } s_2(\sigma) = p_2 |\sigma|^{-1/2}$$

with parameters $p_1, p_2 \in \mathbb{C}$. Such that

$$\lambda_1 = -(p_1 + p_2), \text{ and } \lambda_2 = p_1 p_2.$$  \hspace{1cm} (20)

Performing Euler forward discretization of (14) with sampling time $T$ results in

$$\sigma_{k+1} = \sigma_k + T\hat{u}_{S,k} + T\varphi_k$$  \hspace{1cm} (21a)

$$\varphi_{k+1} = \varphi_k + T\Delta_k.$$  \hspace{1cm} (21b)

The basic idea of the matching algorithm is to design a control law

$$\hat{u}_{S,k} = \frac{1}{T} (u_{1,k} \sigma_k - \sigma_k) + \nu_k$$  \hspace{1cm} (22)

$$\nu_{k+1} = \nu_k + u_{2,k} \sigma_k$$

with $u_{1,k}$ and $u_{2,k}$ such that the state dependent eigenvalues of the discrete-time closed loop system matches the state dependent discretized eigenvalues

$$q_{i,k} = \begin{cases} e^{s_i T} \sigma_k, & s_i \neq 0 \\ 0, & s_i = 0 \end{cases}$$

of the continuous-time closed loop system (15). Applying (22) to (21a) results in the discrete-time closed loop system

$$\begin{bmatrix} \sigma_{k+1} \\ \sigma_{2,k+1} \end{bmatrix} = M_d \begin{bmatrix} \sigma_k \\ \sigma_{2,k} \end{bmatrix} + \begin{bmatrix} 0 \\ \Delta_k \end{bmatrix}$$  \hspace{1cm} (24)

with $\sigma_{2,k} = \nu_k + \varphi_k$ and

$$M_d = \begin{bmatrix} u_{1,k} & T \\ u_{2,k} & 1 \end{bmatrix}.$$  \hspace{1cm} (25)

Computing $\det(zI - M_d)$ results in the characteristic polynomial

$$w(z) = z^2 - (u_{1,k} + 1) z + u_{1,k} - Tu_{2,k}.$$  \hspace{1cm} (26)

Specifying the desired characteristic polynomial

$$z^2 - (q_1 + q_2) z + q_1 q_2$$

and using the desired state dependent eigenvalues (23) results in

$$u_{1,k} = q_1 + q_2 - 1,$$

$$u_{2,k} = \frac{1}{T} (q_1 - q_2)$$

as proposed in Koch and Reichhartinger (2019). This algorithm has some appealing properties. First of all, no discretization chattering appears using this algorithm and in the case $\varphi_k = 0$, the origin of the closed-loop system is asymptotically stable. Secondly, overestimating the desired controller gains has very little negative impact on the accuracy of the closed loop system compared to the explicit Euler discretized version of the super twisting algorithm (see Livne and Levant (2014)). These properties will be demonstrated by means of experiments in the next section.

**Remark 2.** An other possible choice for the desired state dependent eigenvalues would be

$$q_{i,k} = 1 + s_i (\varphi_k) T$$

with $i = 1, 2$ (30) which would lead to the explicit Euler discretized version of the super twisting algorithm. The disadvantage of this algorithm is, that the closed loop accuracy is deteriorated by discretization chattering.

In the following algorithm, the second part of the control law is introduced based on the previously explained eigenvalue assignment based algorithm and the integral sliding mode control approach.

**Algorithm 1.** Considering continuous-time plant (1), the sampling with constant sampling time $T$ and the constant round trip time ensured by the buffer (6) results in the lifted model (9) with state vector $\xi_k$. Define the discrete-time integral sliding variable

$$\sigma_k = m^T \xi_k + w_k$$  \hspace{1cm} (31)

with

$$m^T = \begin{bmatrix} m_1^T & 0 \end{bmatrix}, \text{ and } m_1^T b = 1$$

where $m_1^T \in \mathbb{R}^n$. Let the nominal control law in (10) equal (13) and

$$w_{k+1} = T^T \xi_k,$$

$$T^T = -m^T (\bar{A} - \bar{b} k^T).$$

Design a discrete-time sliding mode control law

$$u_{S,k} = \sigma_k + T\hat{u}_{S,k}$$

with $\hat{u}_{S,k}$ given in (22) and choose

$$\lambda_1 = 1.5 \sqrt{\Lambda}, \text{ and } \lambda_2 = 1.1 \Lambda, \text{ and } \Lambda \geq \frac{L}{T}.$$  \hspace{1cm} (35)

with the change rate $L$ as in (4).

The proposed algorithm ensures that the origin $x_k = 0$ of system (1) is practically stabilized as defined in Edwards and Spurgeon (1998). This can be illustrated by
considering the forward increment of (31) and using (9), (10) and (32) results in
\[
\sigma_{k+1} = m^T \xi_{k+1} + w_{k+1} \\
= m^T A \xi_k + m^T b u_k + m^T b f_k + w_{k+1} \\
= m^T (A \xi_k + b u_{N,k}) + u_{S,k} + f_k + w_{k+1}
\]
Applying (33) and (13) results in
\[
f = m^T \dot{A} \xi_k + m^T \dot{b} u_k + m^T \dot{b} f_k + w_{k+1}
\]
which is equivalent to (21a) using (34) and (35). The parameters \( \lambda_1 \) and \( \lambda_2 \) should be set for the matching algorithm using the very well-established parameter setting
\[
\lambda_1 = 1.5 \sqrt{L} \quad \lambda_2 = 1.1 L \phi 
\]
with
\[
\sup \frac{\varphi_{k+1} - \varphi_k}{T} = L \phi 
\]
which was initially proposed in Levant (1998) and the stability was recently proven in Seeber and Horn (2017). The change rate (38) can easily be computed from (4)
\[
\sup \frac{\varphi_{k+1} - \varphi_k}{T} = \sup \frac{f_{k+1} - f_k}{T^2} = L \phi = \frac{L}{T}. 
\]
Therefore, the gains can be designed using (35).

Remark 3. The sliding variable defined in (31) is the discrete time equivalent to the well-known continuous time sliding variable
\[
\sigma(t) = m^T \xi(t) + \int_0^t L^T \xi(\tau) d\tau. 
\]
see e.g. Utkin et al. (2009).

4. LABORATORY EXPERIMENT

In this section the effectiveness of the previously proposed algorithm will be verified by means of a laboratory experiment. Figure 2 shows a picture as well as the mechanical scheme of the used spring mass laboratory experiment. The setup consists of a mass \( m \) attached to a spring with linear spring characteristic via a pulley using a nylon cord. Friction in the pulley is assumed to be viscous (proportional to the velocity). The other side of the spring is connected to a wheel, which can be actuated using a speed controlled electrical motor. The motor as well as the pulley are equipped with encoders to measure the position \( z(t) \) and the mass position \( y(t) \). Using the state vector
\[
x^T = \begin{bmatrix} y & \frac{dy}{dt} & z \end{bmatrix} = [x_1 \ x_2 \ x_3]
\]
results in the mathematical model
\[
\begin{align*}
\frac{dx}{dt} &= \begin{bmatrix} 0 & 1 & 0 \\ -\frac{c}{m} & -\frac{k}{m} & \frac{c}{m} \\ 0 & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ u \\ f \end{bmatrix} \\
&= A x + B u + F f
\end{align*}
\]
with mass \( m = 0.18 \text{ kg} \), spring constant \( c = 3.840 \text{ N m}^{-1} \), friction coefficient \( v = 0.042 \text{ kg s}^{-1} \) and input gain \( b = 0.086 \text{ m s}^{-1} \text{ V}^{-1} \). In order to verify the performance of the perturbed NCS, a perturbation
\[
f_k = \frac{1}{3} \left[ \sin (kT + 5) + \sin \left( \frac{1}{\pi} (kT + 5) \right) + 1 \right]
\]
consisting of two sinusoidals with different frequency and a constant is applied. The exact change rate can be derived as
\[
L = 0.440 \text{ V s}^{-1}. 
\]

![Fig. 2. Spring mass laboratory experiment (left) and mechanical scheme (right)\( .\]

The state vector \( x_{1,k} = x_1(kT) \) and \( x_{3,k} = x_3(kT) \) is sampled with the constant sampling time
\[
T = 20 \text{ ms}, \quad (44)
\]
the state \( x_{2,k} = x_2(kT) \) is obtained using a differentiating filter. Imperfections of sensors and differentiating filter are neglected in the further investigations. The networked induced delay is implemented using two Simulink delay blocks, one to delay the sensor measurements and the other one to delay the control signal. These blocks are configured such that the worst case round trip time
\[
\tau_k \leq 200 \text{ ms} = 10T \quad (45)
\]
is achieved, which results in \( \alpha = 10 \). The nominal control law (13) was designed by placing the \( n + \alpha = 13 \) poles to \( z_i = e^{-10T}, i = 1, 2, \ldots, 13 \) using Ackermann’s formula. Vector \( m^T \) is designed according to (32). One possible choice is
\[
m^T = [1.143 - 9.157 584.020]. 
\]
Theoretically the choice of \( m^T \) is only restricted by (32) but due to measurement noise, unmodeled dynamics in real world applications it is necessary to tune those parameters. To verify the quality of the current setting, choose \( u_{S,k} = 0, \forall k \) and evaluate the sliding variable \( \sigma_k \). According to (36), the sliding variable should then be equal to the one step delayed perturbation.

The result after this tuning process is depicted in Fig. 3. This figure shows that using the vector \( m^T \) given in (46) is a reasonable choice, because the sliding variable equals the perturbation very well. To design the gains \( \lambda_1 \) and \( \lambda_2 \) of the super twisting algorithm according to (35), the change rate \( L \phi \) of the perturbation \( \varphi_k = \frac{\sigma_k}{T} \) has to be known or estimated. In real world applications usually this change rate is not known exactly and therefore has to be estimated. As a conservative choice could lead to instability, typically the value is estimated very high.

In this paper it is assumed that the estimated change rate \( \Lambda = 132 \) was about six times higher than the actual value...
Fig. 3. Sliding variable $\sigma_k$ for $u_{S,k} = 0$ and perturbation $f_k$.

The evolution of the states during the experiment using the proposed method is shown with blue lines in Fig. 4. In order to show the effectiveness of the sliding mode based part of the control law, the results obtained using only the nominal control law are shown in red. Comparing these two lines shows a significant increase of accuracy. This increased accuracy is also visible in the sliding variable, because for $\sigma_k = 0 \ \forall k$ the perturbation would be compensated exactly, which is not possible for discrete time systems. Therefore, the magnitude of the sliding variable is a measure for the accuracy of the closed loop system.

Figure 5 shows in blue the value of the sliding variable $\sigma_k$ corresponding to the results depicted in Fig. 4 using the proposed approach. Comparing Figs. 3 and 5 exemplifies that the magnitude of the sliding variable using the proposed algorithm is about ten times smaller than when using only the nominal control law. Additionally, Fig. 5 shows in red the evolution of the sliding variable using the explicit Euler discretized version of the super twisting algorithm. One can clearly see that the magnitude of $\sigma_k$ is about three times smaller using the matching algorithm. This is due to rapidly increasing amplitude of discretization chattering for increasing values of the estimated change rate $\Lambda$.

This phenomenon also is illustrated in Fig. 6 where the magnitude of the sliding variable $\sigma_k$ is shown for both algorithms and increasing values of the estimated change rate $\Lambda$. One can clearly see, that the curve representing the explicit Euler discretized scheme ascents much faster than the one representing the matching algorithm. The influence of the parameter $\Lambda$ on the magnitude of the sliding variable using the matching algorithm is very low, which is a huge advantage as the exact value might be unknown.

5. CONCLUSIONS AND OUTLOOK

An integral sliding mode based control strategy for NCS with time varying delays has been proposed in this paper.
Using the integral sliding mode strategy offered the possibility to apply recently developed discrete-time sliding mode control approaches designed for relative degree one systems. Laboratory experiments verified the effectiveness of this approach using the matching discretization technique for the super twisting algorithm. The results of these experiments are also compared to the ones obtained using the explicit Euler discretization technique for the super twisting algorithm. These experiments show clearly the advantages of the matching approach because the accuracy is much less sensitive to overestimating the change rate of the perturbation, whose exact value is usually not known in practical applications. In future research it would be very interesting to extend the proposed approach in order to explicitly consider additional and more complex network effects.

ACKNOWLEDGEMENTS

The financial support by the Christian Doppler Research Association, the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Research, Technology and Development is gratefully acknowledged. The authors appreciate the financial support of the European Union’s Horizon 2020 Research and Innovation Programme (H2020-MSCA-RISE-2016) under the Marie Skłodowska-Curie grant agreement No. 734832. This work was partially supported by the LEAD project “Dependable Internet of Things in Adverse Environments” funded by Graz University of Technology

REFERENCES

Atzori, L. and Lobina, M. (2006). Playout buffering in ip telephony: a survey discussing problems and approaches. IEEE Communications Surveys & Tutorials, 8(3), 36–46.

Azimi-Sadjadi, B. (2003). Stability of networked control systems in the presence of packet losses. In 42nd IEEE International Conference on Decision and Control, volume 1, 676–681.

Behera, A.K. and Bandyopadhyay, B. (2016). Event-triggered sliding mode control for a class of nonlinear systems. International Journal of Control, 89(9), 1916–1931.

Edwards, C. and Spurgeon, S. (1998). Sliding Mode Control: Theory and Applications. CRC Press.

Heemels, W.P.M.H. and van de Wouw, N. (2010). Stability and Stabilization of Networked Control Systems. 203–253. Springer London, London.

Incremona, G.P., Ferrara, A., and Magni, L. (2017). Asynchronous networked MPC with ISM for uncertain nonlinear systems. IEEE Transactions on Automatic Control, 62(9), 4305–4317.

Kalman, R., Ho, B., and Narendra, N. (1963). Controllability of linear dynamical systems. Contributions to Differential Equations, 1, 198–213.

Koch, S. and Reichhartinger, M. (2019). Discrete-time equivalents of the super-twisting algorithm. Automatica, 107, 190–199.

Levant, A. (1993). Sliding order and sliding accuracy in sliding mode control. International Journal of Control, 58(6), 1247–1263.

Levant, A. (1998). Robust exact differentiation via sliding mode technique. Automatica, 34(3), 379–384.

Liu, G.P. (2010). Predictive controller design of networked systems with communication delays and data loss. IEEE Transactions on Circuits and Systems II: Express Briefs, 57(6), 481–485.

Liu, K., Fridman, E., and Hetel, L. (2012). Network-based control via a novel analysis of hybrid systems with time-varying delays. In 2012 IEEE 51st IEEE Conference on Decision and Control (CDC), 3886–3891.

Liu, K. and Fridman, E. (2012). Networked-based stabilization via discontinuous lyapunov functionals. International Journal of Robust and Nonlinear Control, 22(4), 420–436.

Livne, M. and Levant, A. (2014). Proper discretization of homogeneous differentiators. Automatica, 50(8), 2007–2014.

Ludwiger, J., Steinberger, M., Horn, M., Kubin, G., and Ferrara, A. (2018). Discrete time sliding mode control strategies for bufferless networked systems. In 2018 IEEE 57th Annual Conference on Decision and Control (CDC), 6735–6740. IEEE.

Ludwiger, J., Steinberger, M., Rotulo, M., Horn, M., Luppi, A., Kubin, G., and Ferrara, A. (2017). Towards networked sliding mode control. In 2017 IEEE 56th Annual Conference on Decision and Control (CDC), 6021–6026. IEEE.

Quevedo, D.E. and Nesci, D. (2011). Input-to-state stability of packetized predictive control over unreliable networks affected by packet-dropouts. IEEE Transactions on Automatic Control, 56(2), 370–375.

Ramjee, R., Kurose, J., Towsley, D., and Schulzrinne, H. (1994). Adaptive playout mechanisms for packetized audio applications in wide-area networks. In Proc. INFOCOM ’94 Conf. Computer Communications, 680–688 vol.2.

Reichhartinger, M. and Spurgeon, S. (2018). An arbitrary-order differentiator design paradigm with adaptive gains. International Journal of Control, 91(9), 2028–2042.

Schenato, L., Sinopoli, B., Franceschetti, M., Poolla, K., and Sastry, S.S. (2007). Foundations of control and estimation over lossy networks. Proceedings of the IEEE, 95(1), 163–187.

Seeber, R. and Horn, M. (2017). Stability proof for a well-established super-twisting parameter setting. Automatica, 84, 241–243.

Utkin, V., Guldner, J., and Shi, J. (2009). Sliding Mode Control in Electro-Mechanical Systems. CRC Press.

Xiong, J. and Lam, J. (2007). Stabilization of linear systems over networks with bounded packet loss. Automatica, 43(1), 80–87.

Zhang, X., Han, Q., and Yu, X. (2016). Survey on recent advances in networked control systems. IEEE Transactions on Industrial Informatics, 12(5), 1740–1752.