Stabilization of Networked Systems under Information Structure Constraints

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Abstract: The objective of this paper is to propose a systematic approach to decentralized stabilization with sampled-data delayed feedback for basic models of networked continuous-time complex systems. Single-packet transmissions and multiple-packet transmissions are considered for the I/O-oriented systems as well as the interconnected systems with disjoint structure of subsystems and their interconnections. The Liapunov-Razumikhin based method is used. An attention is focused on the effect of data-packet dropout and communication delays between the plant and the controller to design stabilizing decentralized controllers. It is shown how this methodology can lead to a decentralized control design with time-varying delays in the input. For such a purpose, a delay-dependent approach is considered in order to obtain decentralized controllers asymptotically stabilizing closed-loop networked control systems.

Keywords: Decentralization, large scale systems, complex systems, continuous-time systems, networked control systems

INTRODUCTION

Networked control systems (NCS) are spatially distributed dynamic systems in which communication between plants, sensors, actuators, and controllers is performed through a shared band-limited digital network. Networks are used as a medium to connect elements of the systems. Such a medium brings new functionalities that were not available in the past such as essential reduction of wiring costs and maintenance. The traditional point-to-point architectures are being replaced by those based on serial communication channels and a low price microprocessors which are used as controllers. Due to permanently increasing complexity of recent large scale systems, there has been recognized growing importance of the interconnections and a renewed emphasis on distributed/decentralized control architectures considered within the communication issues. A variety of models, structures, and feedback control architectures have been analyzed and synthesized in this framework. The most important issues in NCS such as delay and packet dropouts have been incorporated in the centralized NCS design by several approaches.

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Decentralized design schemes result from a division of the overall design problem into subproblems that can be solved independently so that the solution of subsystem problems satisfactorily solves the overall system problem. Decentralized NCS (DNCS) are the control systems with multiple control stations while transmitting control signals through a network, i.e. date signals are transmitted to multiple local controllers in the feedback loop. DNCS combine the advantages of the centralized NCS and the decentralized control systems. Such a combination enables to cut unnecessary wiring, reduce the complexity and the overall system cost when designing and implementing control systems. The most important issues in DNCS are closely related to stability criteria for delayed differential or difference equations with multiple time-varying delays and multiple-packet transmissions.

However, it has been recognized that a deep gap still remains between the areas of decentralized control and control over networks.

Prior Work

There is not available a unified theory of the NCSs up to now. Recent surveys on this topic can be found in Hristu-Varsakelis and Levine [2005], Antsaklis and Tabuada [2006], and Matveev and Savkin [2009]. Decentralized control is recently surveyed in the reference Bakule [2008].

Reference Yan et al. [2008] deals with the robust stability for a class of MIMO continuous-time NCSs with uncertainties and multiple time-varying delays. Reference Gupta and Martins [2008] is focused on the determination of necessary and sufficient conditions for the stabilizability of an unstable time-invariant NCSs in discrete-time setting without availability of acknowledgements. References Li [2005] and Li et al. [2008] deal with delay-dependent asymptotic LMI-based criteria for nominally linear continuous-time systems with nonlinear and norm-bounded perturbations and multiple time-varying delays.

Stabilization of NCS with multiple-packet transmission is considered in Yu et al. [2004]. Both continuous-time and discrete-time cases are included for the centralized state feedback controller design by using LMIs. References Wen and Yang [2009] and Zhu and Yang [2008] are focused on the state feedback controller design for continuous-time NCS with multiple-packet transmission. A numerical procedure to design output feedback NCS is proposed in Naghshtabrizi and Hespanha [2005], while the reference Lian et al. [2001] considers the controller design for the NCS MIMO systems with multiple-time delays. Reference Wu and Chen [2007] deals with both single- and multiple-packet transmissions within the notion of stochastic stability, while the reference Chen et al. [2009] presents the LMI type sufficient condition for the mean square asymptotic stability within multi-packet transmissions.

Recently, the results dealing with the DNCS design methods are rare. Relevant problems are introduced in Bakule [2008], Xu and Hespanha [2004]. Decentralized stabilization of NCS using periodically time-varying local controller is presented in Jiang et al. [2008]. References Matveev and Savkin [2009], Nair et al. [2004],Yüksel and Başar [2007] consider the DNCS under date rate constraints. Reference Wei [2008] presents necessary and sufficient conditions for stability of the two control stations considered within the DNCS architecture. Reference Bakule and de la Sen [2009] deals with continuous-time DNCS for a class of complex composite systems, while the reference Bakule and de la Sen [2010] extends these results to the resilient setting. Reference Alessio and Bemporad [2008] presents a sufficient condition for the closed-loop system asymptotic stability with decentralized model predictive controller under packet dropout.

To the authors best knowledge, the problem of decentralized sampled-data feedback for continuous-time linear complex networked control systems including packet dropouts and communication delays in the feedback loops has not been solved up to now.

Outline of the Paper

Sufficient conditions for the DNCS design with a state stabilizing controller are presented for basic structures of large scale complex systems. The plant and the controller are connected through a network channel. A network channel is modelled using bounded packet dropouts and communication delays in the decentralized setting. Therefore, each local loop is modelled by a local feedback gain and a local communication channel with a particular time-varying delay. Information structure constraints is modelled for continuous-time systems with sampled-data feedback for the I/O-oriented models and the interaction-oriented models when considering the disjoint structure of subsystems and interconnections. It is shown how the results for centralized multiple-packet transmission and centralized multiple time-varying delays appearing in the NCSs can be extended for the DNCSs design.

The paper extends the results from Yu et al. [2004], Yu et al. [2005], and Zhu and Yang [2008] into the DNCS setting when considering the delay-dependent LMI based approach.

1. PROBLEM FORMULATION

2.1 System Description

Consider a continuous-time LTI system described as follows

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad x(0) = x_o \tag{1}$$

where $x(t)$ and $u(t)$ are n-, m-dimensional vectors of the system states and control inputs, respectively.

Assumption 1. The pair (A, B) is stabilizable. A and B are constant matrices of appropriate dimensions.

Assumption 2. The matrix B has a full column rank.

The goal is to find a stabilizing piecewise constant controller for the system (1) in the form

$$u(t) = K\underline{x}(t_k) \qquad t \in [t_k, t_{k+1}) \qquad k = 1, 2, ... \tag{2}$$

where K is a constant gain matrix to be selected, while t_k is a sampling instant. Suppose that $t_k = k\Delta$ with k being any positive integer, a sampler with the uniform sampling period Δ, and a standard zero order hold in the feedback loop. The basic structure of the closed-loop system considers the continuous-time system with a sampled feedback. Such a structure enables to interpret the connection of the controller with the system via a communication channel. The sampled value $\underline{x}(t_k)$ is transmitted through a network channel and, if transmitted correctly, it is registered in a buffer. $\underline{x}(t_k)$ denotes the output from the buffer. This value is the input to the controller. It generates the proper control action.

Since a NCS operates over a network, data transfer between the controller and the remote plant induce network delays as well as the controller processing delay. Therefore, the basic properties of a network channel must be respected when transmitting the signal. In this paper, two essential phenomena appearing in network communication channels are modelled: Data packet dropout and time-varying input delays.

Data packet dropout is a well-known essential feature of network in the feedback loop. The quantity of dropped packets is cumulated from the last update at the time t_k. Denoting some sampling interval-dependent integer $d_k \geq 1$ at time t_k, then the output from the buffer yields $\underline{x}(t_k) = x(t_k - d_k\Delta)$.

Suppose that the resulting input time-varying delay consists of the constant communication delay denoted as d_c and the delay caused by data packet dropout $d_k\Delta$. The input of the controller is $\underline{x}(t_k) = x(t_k - d_k\Delta - d_c)$. K is the controller matrix to be determined.

Denote the time-varying delay $d(t) = t - t_k - d_k\Delta - d_c$, where $1 \leq d_k \leq (t_{k-1} - d_c)/\Delta$.

Assumption 3. The number of packet dropouts is bounded so that it satisfies the constraint

$$0 < d(t) \leq \overline{d} \tag{3}$$

where $\overline{d}$ is a given positive constant.

Assumption 4. Acknowledgment ACK about data losses is always available to the sender of the system.

Consider now the closed-loop overall system (1)–(2) satisfying Assumptions 1-4 as follows

$$\begin{aligned} &\dot{x}(t) = Ax(t) + BKx(t - d(t)) \\ &\qquad x(t_o) = \overline{\Phi}_k(t_o) \qquad t_o \in [-\overline{d}, 0] \end{aligned} \tag{4}$$

where $\overline{\Phi}_k(t_o)$ denotes the function of initial condition for the corresponding time instant.

2.2 The Problem

Consider the system (1) and the controller (2) satisfying Assumptions 1-4. The goal is to design the gain matrix K of the state controller (2) being globally asymptotically stabilizing the closed-loop system (4) when considering a decentralized setting of the DNCS design. Consider the following particular cases:

- DNCS design within a single-packet transmission

- DNCS design for the I/O-oriented systems within a multiple-packet transmission

- DNCS design for the interconnected systems within a multiple-packet transmission

Solve the problem by using the linear matrix inequalities (LMI) approach.

Remark 1. The control design for the system (1) with the controller (2) leads to the system (4) with a time-varying delay. Such a controller design requires delay-dependent approach. In principle, the Liapunov-Krasovski and the Liapunov-Razumikhin methods can be used. We select the Liapunov-Razumikhin approach which does not require any restriction on the time derivative. The paper is focused on a systematic presentation of the DNCS design for large scale systems.

2. MAIN RESULTS

Consider the information structure constraints on only two local controllers. An extension to more local controllers is straightforward for all included cases.

3.1 Stabilization of DNCSs with Single-Packet Transmission

There are available various scenarios when dealing with DNCSs. The most simple case is to consider only block diagonal controller in the closed-loop control system with a single packet transmission. It means that every control station receives only one packet through the network in each transmission. An equivalent understanding is to consider such transmission as multiple data packets transmission from sensors to control stations through parallel network channels simultaneously, where each channel corresponds with a local feedback loop in the DNCS. In general, it leads to individual time-varying delays in each channel caused by individual data packet dropouts. In this paper, the availability of Acknowledgement (ACK) about data losses to the sender is supposed at each local channel as well as the communication of ACK among all local channel Kurose and Rose [2005]. Suppose also implemented communication logics realizing packet dropouts to all local channels simultaneously when a data packet dropout appears in any local channel. Then, only a single identical time-varying delay can be applied for any channel. It can be considered as a single communication channel with data packet dropouts and communication delays connected within a block diagonal structure of the gain matrix, i.e. the sensor-actuator pair structure in the NCS.

Theorem 1. Given the system (1) satisfying Assumptions 1-4 and an integer $\overline{d}$. Suppose that there exist symmetric positive definite diagonal matrices $M, R1, R2$ with $(n_i \times n_i)-$dimensional diagonal blocks, a symmetric positive definite diagonal matrix Q with $(m_i \times m_i)-$dimensional diagonal blocks, and a diagonal matrix N with $(m_i \times n_i)-$diagonal blocks, $i = 1, 2$ satisfying the following relations

$$\begin{aligned} S1(A) &< 0 \\ S2(A) &\leq 0 \\ S3(A) &\leq 0 \\ S4(A) &\leq 0 \\ S5(A) &\leq 0 \end{aligned} \tag{5}$$

where

$$\begin{aligned} S1(A) &= \begin{pmatrix} \frac{1}{\overline{d}}(MA^T + AM + N^TB^T + BN) & BQ \\ \bullet & -Q \end{pmatrix} \\ S2(A) &= \begin{pmatrix} -M & N^TB^T \\ \bullet & -R2 \end{pmatrix} \\ S3(A) &= \begin{pmatrix} -M & N^TA^T \\ \bullet & -R1 \end{pmatrix} \\ S4(A) &= \begin{pmatrix} -Q & N \\ \bullet & -M \end{pmatrix} \\ S5(A) &= R1 + R2 - M \end{aligned} \tag{6}$$

Then, the system (1) is asymptotically stabilized by the controller (2), where the gain matrix is given as

$$K = NM^{-1} \tag{7}$$

for the packet dropout $d(k)$ satisfying the interval bounds $0 \leq d(k) \leq \frac{\overline{d}}{\Delta} - 1$.

3.2 Stabilization of DNCSs with I/O-oriented System

A single channel transmission of data in the feedback loop of DNCSs is evidently restrictive. Decentralized controller operates locally, i.e. individual local controllers have local inputs and they enter to the systems also locally. It means that when considering communication in the feedback loop within decentralized structure of controllers, it is desirable to communicate also locally. It corresponds with a set of local communications channels operating in parallel. Supposing that the control in feedback loop at each local channel is realized by a sampled data approach, then there exist local dropouts and transmission delays at each channel. It finally results in the closed-loop system with multiple delays. The DNCS controller design is considered by using this approach for unstructured systems in this subsection.

Instead of the system (1), the I/O-oriented model with two channels is used in the form

$$\dot{x}_s(t) = Ax_s(t) + \sum_{i=1}^{2} B_{si}u_{si}(t) \qquad x(0) = x_o \tag{8}$$

where $B = (B_{s1}\ B_{s2})$. Note that the notions of the I/O-oriented model or the multi-channel system are equivalent. The controller (2) is considered in a decentralized setting with two local controllers, i.e. for $i = 1,\ 2$, as follows

$$u_{si}(t) = K_{si}\underline{x}_{si}(t_k) \qquad t \in [t_k, t_{k+1}) \qquad k = 1, 2, ... \tag{9}$$

where $\underline{x}_s(t) = (\underline{x}_{s1}^T(t)\ \underline{x}_{s2}^T(t))^T$ and $u(t) = (u_{s1}^T(t)\ u_{s2}^T(t))^T$ consist of n_i- and m_i-dimensional vectors $\underline{x}_{si}(t_k)$ and $u_{si}(t)$, respectively. The gain matrix has the form $K_s = \mathrm{diag}(K_{s1}\ K_{s2})$.

$x_{s1}(t_k)$ and $x_{s2}(t_k)$ are transmitted over different channels. Each channel produces its own data packet dropouts and delays. Thus, the multiple-channel network is modelled as a switch. Analogously to the single-packet transmission, the resulting input time-varying delays consist of the constant communication delays denoted as d_{ci} and the delays caused by data packet dropout $d_{ki}\Delta$. The input of the controllers is $\underline{x}_{si}(t_k) = x_{si}(t_k - d_{ki}\Delta - d_{ci})$.

Denote the time-varying delays $d_i(t) = t - t_k - d_{ki}\Delta - d_{ci}$, where $1 \le d_{ki} \le (t_{k-1} - d_{ci})/\Delta$.

Assumption 5. The number of packet dropouts is bounded so that it satisfies the constraints

$$0 < d_i(t) \le \overline{d} \tag{10}$$

for $i = 1, 2$, where $\overline{d}$ is a given positive constant.

Remark 2. The relation (10) supposes that both channels have the same upper bound $\overline{d}$. Such a simplification does not restrict the control design.

Therefore, the input to the controller includes two different delays has the form

$$\underline{x}_s(t_k) = \begin{pmatrix} \underline{x}_{s1}(t_k) \\ \underline{x}_{s2}(t_k) \end{pmatrix} = \begin{pmatrix} x_{s1}(t - d_1(t)) \\ x_{s2}(t - d_2(t)) \end{pmatrix} \qquad t \in [t_k, t_{k+1}) \quad k = 1, 2, ... \tag{11}$$

Consider now the closed-loop overall system (8)–(11) as follows

$$\begin{aligned} \dot{x}_s(t) &= Ax_s(t) + BK_s\underline{x}_s(t_k) \\ &= Ax_s(t) + BK_sC_1x_s(t - d_1(t)) \\ &\quad + BK_sC_2x_s(t - d_2(t)) \\ x_s(t_o) &= \overline{\Phi}_k(t_o) \qquad t_o \in [-\overline{d}, 0] \end{aligned} \tag{12}$$

where

$$C_1 = \begin{pmatrix} I_{n_1} & 0 \\ 0 & 0 \end{pmatrix} \qquad C_2 = \begin{pmatrix} 0 & 0 \\ 0 & I_{n_2} \end{pmatrix} \tag{13}$$

with the block diagonal gain matrix K_s. $\overline{\Phi}_k(t_o)$ denotes the function of initial condition of the corresponding time instant t_o.

Assumption 6. Acknowledgment ACK about data losses is always available to the sender at each local channel of the system (12).

Theorem 2. Given the system (8) satisfying Assumptions 1, 2, 5, 6, and an integer $\overline{d}$. Suppose that there exist symmetric positive definite diagonal matrices $P_s, T_1, T_2, T_3, T_4, T_5,\ T_6$ with $(n_i \times n_i)-$dimensional diagonal blocks, a symmetric positive definite diagonal matrix X with $(m_i \times m_i)-$dimensional diagonal blocks, and a diagonal matrix Y with $(m_i \times n_i)-$diagonal blocks, $i = 1, 2$, satisfying the following relations

$$\begin{aligned} M1(A) &= 0 \\ M2(A) &\le 0 \\ M3(A) &\le 0 \\ M4(A) &\le 0 \\ M5(A) &\le 0 \\ M6(A) &\le 0 \\ M7(A) &\le 0 \\ M8(A) &\ge 0 \\ M9(A) &\ge 0 \\ M10(A) &\le 0 \end{aligned} \tag{14}$$

where

$$\begin{aligned} &M1(A) = P_sB - BX \\ &M2(A) = A^TT_1A - P_s \qquad M3(A) = A^TT_4A - P_s \\ &M4(A) = T_2 - P_s \qquad M5(A) = T_3 - P_s \\ &M6(A) = T_5 - P_s \qquad M7(A) = T_6 - P_s \\ &M8(A) = \begin{pmatrix} P_s & C_1^TY^TB^T \\ \bullet & P_s \end{pmatrix} \quad M9(A) = \begin{pmatrix} P_s & C_2^TY^TB^T \\ \bullet & P_s \end{pmatrix} \\ &M10(A) = \begin{pmatrix} W & W1 & W1 & W1 & W2 & W2 & W2 \\ \bullet & -D1 & 0 & 0 & 0 & 0 & 0 \\ \bullet & \bullet & -D2 & 0 & 0 & 0 & 0 \\ \bullet & \bullet & \bullet & -D3 & 0 & 0 & 0 \\ \bullet & \bullet & \bullet & \bullet & -D4 & 0 & 0 \\ \bullet & \bullet & \bullet & \bullet & \bullet & -D5 & 0 \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & -D6 \end{pmatrix} \end{aligned} \tag{15}$$

and $W = P_sA + A^TP_s + BYC_1 + BYC_2 + C_1^TY^TB^T + C_2Y^TB^T + 6\overline{d})P_s, W1 = \overline{d}BYC_1, W2 = \overline{d}BYC_2,\ D1 = \overline{d}T_1, D2 = \overline{d}T_2, D3 = \overline{d}T_3, D4 = \overline{d}T_4, D5 = \overline{d}T_5, D6 = \overline{d}T_6$. Then, the system (8) is asymptotically stabilized by the controller (9), where the gain matrix has the form

$$K_s = YX^{-1} \tag{16}$$

for the packet dropouts satisfying the interval bounds $0 \le d_1(k) \le \frac{\overline{d}}{\Delta} - 1$ and $0 \le d_2(k) \le \frac{\overline{d}}{\Delta} - 1$.

3.2 Stabilization of DNCSs with Disjoint Subsystems

The I/O-oriented model (8) considers the systems as one whole. It can be further structured into the subsystems and the interconnections. Therefore, the interconnection-oriented model has the form

$$\dot{x}_{ci}(t) = A_i x_{ci}(t) + B_i u_{ci}(t) + A_{ij} x_{cj}(t) \qquad x_i(0) = x_{oi} \quad i,j = 1,2 \tag{17}$$

The relation between the compacted description by (1) and the system (17) is given as

$$A = \begin{pmatrix} A_1 & A_{12} \\ A_{21} & A_2 \end{pmatrix} = A_D + A_C \tag{18}$$

where $A_D = \text{diag}(A_1 \; A_2)$ and $B = \text{diag}(B_1 \; B_2)$.

Consider the controller (2) in a decentralized setting as

$$u_{ci}(t) = K_{ci} \underline{x}_{ci}(t_k) \qquad t \in [t_k, t_{k+1}) \qquad k = 1, 2, ... \tag{19}$$

where

$$\underline{x}_c(t_k) = \begin{pmatrix} \underline{x}_{c1}(t_k) \\ \underline{x}_{c2}(t_k) \end{pmatrix} = \begin{pmatrix} x_{c1}(t - d_1(t)) \\ x_{c2}(t - d_2(t)) \end{pmatrix} \qquad t \in [t_k, t_{k+1}) \quad k = 1, 2, ... \tag{20}$$

Then, the closed-loop overall system (17)–(20) has the form

$$\begin{aligned} \dot{x}_c(t) &= Ax_c(t) + BK_c \underline{x}_c(t_k) \\ &= Ax_c(t) + BK_c C_1 x_c(t - d_1(t)) \\ &+ BK_c C_2 x_c(t - d_2(t)) \\ & x_c(t_o) = \overline{\Phi}_k(t_o) \qquad t_o \in [-\overline{d}, 0] \end{aligned} \tag{21}$$

where

$$C_1 = \begin{pmatrix} I_{n_1} & 0 \\ 0 & 0 \end{pmatrix} \qquad C_2 = \begin{pmatrix} 0 & 0 \\ 0 & I_{n_2} \end{pmatrix} \tag{22}$$

with the block diagonal gain matrix K_c. $\overline{\Phi}_k(t_o)$ denotes the function of initial condition of the corresponding time instant t_o.

The structure of a sampled-data feedback of the system (17)–(19) remains identical with the structure of feedback of the I/O-oriented system (8), (9). Therefore, we can apply directly Assumptions 5 and 6 on the system (21). It leads to the following theorem.

Theorem 3. Given the system (17) satisfying Assumptions 1, 2, 5, 6, and an integer $\overline{d}$. Suppose that there exist symmetric positive definite diagonal matrices $P_c, Z_1, Z_2, Z_3, Z_4, Z_5, Z_6$ with $(n_i \times n_i)-$dimensional diagonal blocks, a symmetric positive definite diagonal matrix U with $m_i \times m_i-$dimensional diagonal blocks, and a diagonal matrix V with $(m_i \times n_i)-$diagonal blocks, $i = 1, 2$, satisfying the following relations

$$\begin{aligned} O1(A) &= 0 \\ O2(A) &\le 0 \\ O3(A) &\le 0 \\ O4(A) &\le 0 \\ O5(A) &\le 0 \\ O6(A) &\le 0 \\ O7(A) &\le 0 \\ O8(A) &\ge 0 \\ O9(A) &\ge 0 \\ O10(A) &\le 0 \end{aligned} \tag{23}$$

where

$O1(A) = P_c B - BU$

$O2(A) = A_D^T T_1 A_D - P_s \qquad O3(A) = A_D^T T_4 A_D - P_s$

$O4(A) = T_2 - P_s \qquad O5(A) = T_3 - P_s$

$O6(A) = T_5 - P_s \qquad O7(A) = T_6 - P_s$

$O8(A) = \begin{pmatrix} P_s & C_1^T Y^T B^T \\ \bullet & P_s \end{pmatrix} \qquad M9(A) = \begin{pmatrix} P_s & C_2^T Y^T B^T \\ \bullet & P_s \end{pmatrix}$

$$O10(A) = \begin{pmatrix} F & F1 & F1 & F1 & F2 & F2 & F2 & F3 \\ \bullet & -E1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \bullet & \bullet & -E2 & 0 & 0 & 0 & 0 & 0 \\ \bullet & \bullet & \bullet & -E3 & 0 & 0 & 0 & 0 \\ \bullet & \bullet & \bullet & \bullet & -E4 & 0 & 0 & 0 \\ \bullet & \bullet & \bullet & \bullet & \bullet & -E5 & 0 & 0 \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & -E6 & 0 \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & -I_n \end{pmatrix} \tag{24}$$

and $F = P_c A_D + A_D^T P_s + BVC_1 + BVC_2 + C_1^T V^T B^T + C_2 V^T B^T + 6\overline{d}) P_s, F1 = \overline{d} BVC_1, F2 = \overline{d} BVC_2, F3 = P_c A_C$, $E1 = \overline{d} Z_1, E2 = \overline{d} Z_2, E3 = \overline{d} Z_3, E4 = \overline{d} Z_4, E5 = \overline{d} Z_5, E6 = \overline{d} Z_6$. Then, the system (17) is asymptotically stabilized by the controller (19), where the gain matrix has the form

$$K_c = VU^{-1} \tag{25}$$

for the packet dropouts satisfying the interval bounds $0 \le d_1(k) \le \frac{\overline{d}}{\Delta} - 1$ and $0 \le d_2(k) \le \frac{\overline{d}}{\Delta} - 1$. It means that the maximum allowed delay is not larger than the sampling period.

Remark 3. Theorems 1-3 show how to adapt the results for single- and multiple-packet transmissions in the decentralized control design setting. Proofs of Theorems 1-3 are omitted. The results for the centralized continuous-time NCS design with sampled-data feedback using the Liapunov-Razumikhin method are available in Yu et al. [2005]. The presented Theorems 1-3 can be proved by using Theorems 1 and 2 in Yu et al. [2005].

Remark 4. Theorems 1-3 are sufficient conditions for the design of a decentralized state feedback DNCS controller. A simple extension can be performed for a static output feedback DNCS controller design when considering any left upper block of the matrix C_1 and any right lower block of the matrix C_2 in (13) or (22).

3. CONCLUSION

In the paper, we have proposed a systematic approach to decentralized stabilization with a sampled-data delayed feedback for basic models of networked continuous-time large scale linear dynamic systems. Three different architectures of the DNCS design are presented. A single-packet channel with a block diagonal controller as well as multi-packet transmission approaches are applied on the I/O-oriented systems and the interconnected systems with disjoint structure of subsystems and interconnections. The Liapunov-Razumikhin method is used as a method which requires no restriction on delay derivatives. The effect of data-packet dropout and communication delays between the plant and the controller within multiple-packet transmission methods are considered and directly included into the controller design. Sufficient conditions for the asymptotic stabilization of the closed-loop systems by the proposed decentralized networked controllers are given. For such a purpose, delay-dependent procedures have been selected for the design of gain matrices by using the linear matrix inequalities.

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