Reconstructibility and Controllability Analysis in Bandwidth Limited Industrial Networked Control Systems

Mohammad Mahdi Share Pasand[1*]

Abstract – This paper studies structural properties of bandwidth limited Industrial Networked Control Systems in which the number of simultaneous network accesses is limited. Conventional control theory assumes that the measured output is available as a vector at each time instant and the input vector can be applied simultaneously to the actuator. However, when the system is bandwidth limited, it is not possible to instantly read all of the sensors and nor it is possible to apply the whole input (control) vector to the actuator. Therefore, the plant may lose its controllability (reconstructibility), after adding a bandwidth limited network as the communication media. The communication medium therefore changes the overall system structural properties. This is of utmost importance since existing control and estimation algorithms are based on the assumptions that the whole output vector (input vector) is read from sensors (applied to actuators) instantly. We assume that communication medium is shared among both sensors and actuators. It is shown that controllability and reconstructibility analysis could not be performed independently (as inherently assumed or ignored by previous works in this field).For the special case of equidistant sequences with separate read/write cycles, we prove that controllability and reconstructibility analysis's can be done independently if a specific procedure is followed. Examples are included to clarify the results.

Keywords: Networked control and estimation, Communication sequence, Controllability, Reconstructibility

1. Introduction

Networked Control Systems (NCS) has attracted significant attention due to inevitable use of a shared network in many control applications[1].Insertion of a shared network into the control loop may affect structural and stability properties [2-4]. A restrictive networked induced constraints bandwidth limitation which requires allocation of (limited) communication capacity to sensors and actuators (i.e. a schedule for medium access). A policy to grant access to communication medium for each node in a time tick (i.e. communication sequence)is required in an NCS with access constraints. It is assumed that the network uses a shared bandwidth for sensors and actuators while performing read/computation and write actions is separate sub-cycles. It is also assumed that the arbitration of network access is performed centrally by a master node. Since multi-rate sampled data systems are shown to be a special class of bandwidth limited NCS [5], the scope of this paper covers those systems as well. Reconstructibility and Controllability are two important concepts [2] in systems and control theory. Reconstructibility of a networked system guarantees that the system whole state vector can be reconstructed from the measured signals (known as the process outputs). Controllability ensures that the system state can be steered to the origin via appropriate selection of the control input signal. Both concepts are vital in state feedback control, while the first is of more importance since it may be required in model based fault detection schemes [17]. It is worth noting that the inclusion of an industrial network which inevitably incur bandwidth limitation issues, will adversely affect reconstructibility and controllability of the underlying system. Therefore, it is important to study the effect of bandwidth limited communications on the system reconstructibility and controllability. This paper provides sufficient conditions assuring reconstructibility and controllability of a networked control system. We assume bandwidth limitations as the main communication restriction present in industrial networks [8]. In order to mathematically model the bandwidth limitation phenomenon, we will use the

1* **Corresponding Author :**
Department of Electrical Engineering, Standard Research Institute, Tehran, Iran. Email: sharepasand@standard.ac.ir
Received:2021.02.08 ; Accepted: 2021.05.24

concept of periodic communication sequence introduced in [6]. The communication sequence is a sequence according to which access to network is granted to different nodes [6]. Almost all industrial networks including Profibus, Flex Ray and Modbus [9] use a predefined medium access policy which could be modeled as a periodic communication sequence. Therefore, the model used in this paper which is the same as that of [6-11] covers those industrial networks as well as many others.

In [6] conditions for existence of a periodic communication sequence to preserve stabilizability are given. In [7] the provided conditions are improved to reduce the upper bound of the communication sequence period. Results of [8, 9] further reduced the upper bound of the period, assuming additional conditions on the system eigenvalues. In [10], the concept of communication sequence characteristic polynomial is introduced and utilized to determine which sequence preserves controllability and reconstructibility of the plant. Reference [11] enhances the result of [9] by eliminating extra conditions on the system eigenvalues but results in a slightly greater communication period compared to [8, 9]. In [12] constant delays are added to the bandwidth limited model to provide a more realistic one. Sufficient conditions are then given for the controllability and reconstructibility as well as stabilizability and detectability of the NCS. References [13-16] are dedicated to the optimal scheduling problem in which optimization procedures are examined to find the most suitable communication sequence to apply optimal filtering [13], model predictive control [14], linear quadratic regulation [15] or linear quadratic Gaussian control and estimation [16] as well as unknown input observation schemes [17, 18] which too rely on variations of the notion of observability. Networked control systems structural properties is still an active area of research [19, 20].

Previous works did not address structural properties when the communication medium is shared for both sensor and actuator accesses. Since most of industrial control systems use the same network for both sensor and actuator communications, it is inevitable to have sensor scheduling in mind, when designing an actuator communication sequence. References [14, 15] considered only actuator scheduling while [13] considered only sensor scheduling and [8-12, 16] analyzed both of the two problems independent of each other. However as shown in this paper, when the communication medium is shared among sensors and actuators, actuator communication sequence cannot be chosen regardless of sensor scheduling. This motivated the present paper.

The paper is organized as follows: The second section introduces a generic model, some preliminary notions, definitions and theorems. In the third section, structural properties of NCS are reviewed and main results are proposed. In the fourth section, results are generalized to capture situations in which both sensors and actuators use the shared communication medium. An example is first presented to show that separate design of sensor and actuator communication sequences may impact system controllability (and not reconstructibility). It is then shown that implementing read and write actions in separate sub-cycles simplifies this problem. The final section concludes the paper.

2. Modeling NCS with bandwidth limitations

Suppose a networked control system subject to bandwidth limitations. State equations are given in(1).Sensor and actuator signals are sent via a shared medium with a limited bandwidth. Access constraints are modeled as (2) and (3).

$$x(k+1) = Ax(k) + Bu(k)\,, \qquad y(k) = Cx(k) \tag{1}$$

$$u(k) = S_A(k)\hat{u}(k) + \bar{S}_A(k)u(k-1) \tag{2}$$

$$\hat{y}(k) = S_S(k)y(k) + \bar{S}_S(k)\hat{y}(k-1) \tag{3}$$

The vector $\hat{y}(k)$ is theheld output and $\hat{u}(k)$ is the updated input, sent from controller to the plant. Matrices $A_{n\times n}, B_{n\times n_u}, C_{n_y\times n}$ are the state, input distribution and output matrices of the state space description (1). Matrix $A_{n\times n}$ is assumed invertible. Matrices $S_A(k), S_S(k), \bar{S}_A(k), \bar{S}_S(k)$ in (3)represent access of sensor/actuator to network for sending/receiving updated data and defined as follows;

$$S_A(k) = \left[s_{Aij}(k)\right]_{n_u\times n_u};\ S_S(k) = \left[s_{Sij}(k)\right]_{n_y\times n_y}$$

In which $s_{Aij}(k)$ and $s_{Sij}(k)$ are unity if the corresponding node has access to the communication medium and are zero otherwise. Note that;

$$\mathrm{rank}(S_A(k)) \le b_A < n_u \tag{4}$$

$$\mathrm{rank}(S_S(k)) \le b_S < n_y \tag{5}$$

Scalar b_A (b_S) is the maximum number of actuators (sensors) which can simultaneously access the network. The scheduling matrices specify those nodes which are granted access at time k. A combined scheduling matrix may be defined as;

$$S(k) = \begin{bmatrix} S_A(k) & 0 \\ 0 & S_S(k) \end{bmatrix} \tag{6}$$

Throughout this paper, symbols$S(k)$, $S_A(k)$, $S_S(k)$, σ_p, σ_{pa} and $\sigma_{ps}$are called "scheduling matrix", "actuator scheduling matrix", "sensor scheduling matrix", "communication sequence", "actuator communication sequence" and "sensor communication sequence" respectively. This paper considers p- periodic communication sequences. i.e.:

$$S(k) = S(k+p) \quad k = 1,2,\dots \tag{7}$$

A communication sequence is called equidistant p-periodic if it is p-periodic and the time interval between two consecutive accesses of a single node is constant. It is called admissible if all nodes are granted (one or more) access, during each period. i.e.:

$$\mathrm{rank}(\sum_{j=0}^{p-1} S(j)) = n_u + n_y \tag{8}$$

Defining$n^{(i)}$as the number of accesses granted to node i, during each period. For an equidistant p-periodic communication sequence, pshould be a common multiple of all $n^{(i)}$'s.

Definition 1. A read/write sub-cycles is a group of consecutive communication slots dedicated respectively to reading a number of sensors or writing control data into actuators.

For the purpose of the following lemma, consider a time varying linear periodic system described as:

$$x(k+1) = A_p(k)x(k) + B_p(k)u(k)y(k) = C_p(k)x(k) \tag{9}$$

$$A_p(k) = A_p(k-p), B_p(k) = B_p(k-p), C_p(k) = C_p(k-p) \quad k = 0,1,\dots \tag{10}$$

Lemma 1. [10] A time varying periodic system described by (10) is controllable if and only if (11) is fulfilled for all eigenvectors, corresponding to nonzero eigenvalues of the matrix,$\varphi_p(k, k-p)$, where $\varphi_p(k,j)$ is the state transition matrix.

$$v[B_p(k-1)\varphi_p(k,k-1)B_p(k-1) \dots \varphi_p(k,k-p+1)B_p(k-p)] \ne 0 \tag{11}$$

3. Structural Properties of NCS

Lemma 2 **.**[9] An admissible, p-periodic actuator communication sequence preserves controllability of system (1)-(3) if (12) and (13) hold:

$$\frac{\lambda_a}{\lambda_b} \ne \exp\left(\frac{2\pi l\sqrt{-1}}{p}\right) \tag{12}$$

$$\lambda \ne \exp\left(\frac{2\pi l\sqrt{-1}}{p - k_f^{(i)} + \hat{q}^{(i)}(k_f^{(i)})}\right), \quad i = 1,\dots n_u, \quad l = 1,\dots p - k_f^{(i)} + \hat{q}^{(i)}(k_f^{(i)}) - 1 \tag{13}$$

$$\hat{q}^{(i)}(k) \triangleq \min\left\{\bar{q}^{(i)} - 1, k\right\} \bar{q}^{(i)} \triangleq \min l: \prod_{k=0}^{l-1} \bar{Z}^{(i)}(k) = 0$$

In which λ , λ_a, λ_b arearbitrary eigenvalues of A and $k_f^{(i)}$ is the last time in a period, in which actuator i is granted access. The integer$\bar{q}^{(i)} - 1$, represents the first time in a period, in which actuator iis granted access.

Theorem 1. For an equidistant p-periodic schedule, the following properties hold:

$$1 \le \bar{q}^{(i)} \le \frac{p}{n^{(i)}} \tag{14}$$

$$p - \frac{p}{n^{(i)}} \le k_f^{(i)} \le p - 1 \tag{15}$$

$$\bar{q}^{(i)} - 1 \le k_f^{(i)} \tag{16}$$

$$k_f^{(i)} - \bar{q}^{(i)} + 1 = p - \frac{p}{n^{(i)}} \tag{17}$$

Proof: In an equidistant p-periodic schedule, an actuator is granted access each $\frac{p}{n^{(i)}}$ steps. Therefore if the first access is granted later than $\frac{p}{n^{(i)}}$ steps after $k = 0$, the sequence will not be equidistant. Also from (13) it could be inferred that $\bar{q}^{(i)}$ is at least one. This proves (14).

Based on definition of $k_f^{(i)}$, if the last access is granted earlier than step $p - 1 - \frac{p}{n^{(i)}}$, then the sequence will not be equidistant as the next access will not be granted earlier than the next period. Therefore, $k_f^{(i)}$ is always greater than $p - 1 - \frac{p}{n^{(i)}}$. Also, $k_f^{(i)} \leq p - 1$ by its definition. This completes the proof of (15).

Property (16) is trivially derived assuming (14) and (15). To prove (17), Note that individual scheduling matrices of equidistant sequences has the following form:

$$Z_A^{(i)}(k) = \begin{bmatrix} 0 & \dots & 0 \\ \vdots & z_A(i,i)(k) & \vdots \\ 0 & \dots & 0 \end{bmatrix} \; ; \; z_A(i,i) \tag{18}$$

$$= \begin{cases} 1 & k = \bar{q}^{(i)} + \dfrac{lp}{n^{(i)}} \quad l = 0,1,..,n^{(i)} - 1 \\ 0 & otherwise \end{cases}$$

As a result:

$$k_f{}^{(i)} = \bar{q}^{(i)} + \frac{(n^{(i)} - 1)p}{n^{(i)}} \tag{19}$$

Subtracting $\bar{q}^{(i)}$ from (19) yields (17). The proof is complete. ■

Lemma 3. [5] An admissible, equidistant p-periodic actuator communication sequence with $n^{(i)}$ accesses for actuator i, preserves controllability of system (1)-(3) if;

$$\frac{\lambda_a}{\lambda_b} \neq \exp\left(\frac{2\pi l\sqrt{-1}}{p}\right) \tag{20}$$

$$\lambda \neq exp\left(\frac{2\pi l\sqrt{-1}}{p} n^{(i)}\right) \tag{21}$$

$$i = 1,..n_u \qquad l = 1, \dots \frac{p - n^{(i)}}{n^{(i)}}$$

Proof: (20) is identical to (12), substituting (17) into (13) will result in(21). ■

Theorem 2. The following properties hold:

1. $\sum_{j=0}^{p-1} n_j^{(i)} = p$

2. Number of nonzero coefficients of $g_{Ai}(\mu)$ is equal to the maximum distant between two consecutive accesses granted to actuator i.

3. For all i, $n_j^{(i)} \geq n_{j+1}^{(i)} \geq 0$

Proof:

1. First notice that $n_j^{(i)}$ counts the number of slots in a period, located j steps later than a slot dedicated to actuator i, (e.g. $n_1^{(i)}$ counts the number of slots located immediately after those dedicated to actuator i). Therefore by adding each $n_j^{(i)}$ to the summation, one counts number of slots not dedicated to node i, $n_0^{(i)}$ which is the same as $n^{(i)}$ counts the number of slots dedicated to actuator i , as a result, the summation is equal to the total number of slots in a period, which is p.

2. If $d^{(i)}$ represents maximum distance between two consecutive slots dedicated to actuator i, $n_j^{(i)}$ will be zero for $j > d^{(i)}$.

3. Notice that if $j > d^{(i)}$,then $j + 1 > d^{(i)}$ as well. As a result, $n_j^{(i)}$ is always greater than or equal to $n_{j+1}^{(i)}$. Also, each $n_j^{(i)}$ is trivially non-negative. ■

4. Simultaneous scheduling of sensors and actuators

In this section, the interaction of sensor and actuator scheduling is considered when both communications take place within the same bandwidth limited communication medium. Many NCSs utilize a single bus to schedule all communications including sensors and actuators. Therefore, it is not realistic to analyze actuator and sensor scheduling independent of each other. Independent structural analysis of controllability and reconstructibility, performed in most of previously published papers in this field[8-12]may be misleading because if a networked control system is controllable using scheduling sequence $\{S_A(0), S_A(1), \dots S_A(p_A)\}$ and observable by $\{S_S(0), S_S(1), \dots S_S(p_S)\}$, it is not necessarily controllable using arbitrary combinations of these two sequences. This is shown by the following example.

Example 1: Consider the following system, connected to a channel with bandwidth limitation.

$$A=\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix},\quad B=\begin{bmatrix}1\\ 0\end{bmatrix},\quad C=[1\ \ 1]$$

The plant is controllable and observable. When there are separate channels for sensors and actuators, controllability will be preserved using any admissible communication sequence for sensor / actuator. Now consider that communication bandwidth is equal to unity. Then scheduling sequence may be $\{\text{actuator}, \text{sensor}\}$. In the following, it is shown that system loses its controllability with this sequence. Form an augmented system by defining:

$$x_{aug}(k)=[x^T(k)\quad y(k-1)\quad u(k-1)]^T$$

The augmented system is described as:

$$A_p(k)=\begin{bmatrix}0 & -1 & 0 & s\\ 1 & 0 & 0 & 0\\ s & s & 1-s & 0\\ 0 & 0 & 0 & s\end{bmatrix},B_p(k)=\begin{bmatrix}1-s\\ 0\\ 0\\ 1-s\end{bmatrix},C_p(k)=[s\quad s\quad 0\quad 1-s]$$

In which:

$$s=\begin{cases}0 & k=2l\\ 1 & k=2l+1\end{cases}$$

The state transition matrix $\varphi_p(k,k-2)$ is:

$$\varphi_p(k,k-2)=A_p(k)A_p(k-1)=\begin{bmatrix}0 & -1 & 0 & 0\\ 0 & -1 & 0 & 1-s\\ 1 & (-1)^s & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$

Non-zero eigenvalues of the above matrix are $\lambda=1$. Define v_{11}, v_{12} and v_{21}, v_{22} as eigenvectors corresponding to nonzero eigenvalues of $\varphi_p(k,k-2)$ for even and odd k respectively;

$$-v_{11}=\varphi_p(k,k-2)v_{12}\ ,\quad -v_{12}=\varphi_p(k,k-2)v_{12}\ ;\ k=2l$$

$$-v_{21}=\varphi_p(k,k-2)v_{21}\ ,-v_{22}=\varphi_p(k,k-2)v_{22}\ ;\ k=2l+1$$

After simple manipulations, one obtains;

$$v_{22}\left[B_p(k-1)\varphi_p(k,k-1)B_p(k-1)\right]=0\qquad k=2l+1$$

$$v_{12}\left[B_p(k-1)\varphi_p(k,k-1)B_p(k-1)\right]=0\qquad k=2l$$

Therefore system lost its controllability after using shared medium for both sensor and actuator. ■

Example 2: Suppose that an actuator communication sequence with periodicity of p_a is designed for a network with a bandwidth of unity, to preserve controllability of plant with n_u actuators and $n_y=2$ sensors. It is desired to use the same network with the same time slot, to schedule sensors as well. If a round robin schedule is used for sensors in the beginning of each period, then:

$$\sigma_p=\{S(k)\}_p=\left\{\begin{bmatrix}0 & 0\\ 0 & S_S(0)\end{bmatrix},\begin{bmatrix}0 & 0\\ 0 & S_S(1)\end{bmatrix},\begin{bmatrix}S_A(0) & 0\\ 0 & 0\end{bmatrix},\ldots\begin{bmatrix}S_A(p_a-1) & 0\\ 0 & 0\end{bmatrix}\right\}$$

Which implies:

$$S(k)=\begin{cases}\begin{bmatrix}0 & 0\\ 0 & S_S(k)\end{bmatrix} & k=0,1\\ \begin{bmatrix}S_A(k-2) & 0\\ 0 & 0\end{bmatrix} & 1<k<p-1\end{cases},\ S(k)=S(k+p)$$

The shortest possible period p as well as all $\bar{q}^{(i)}(k)$ and $k_f^{(i)}$ are incremented by 2. Therefore, it is essential to amend these parameters when examining the controllability property.■

Corollary 1. System (1)-(3) with an admissible periodic equidistant communication sequence, and separate read/computation/write cycles, is controllable if:

$$\frac{\lambda_a}{\lambda_b}\neq\exp\left(\frac{2\pi l\sqrt{-1}}{p_T}\right)\tag{22}$$

$$\lambda\neq exp\left(\frac{2\pi l\sqrt{-1}}{p_T}{n_a}^{(i)}\right)\tag{23}$$

$$i=1,..n_u\qquad l=1,\ldots\frac{p_T-n^{(i)}}{n^{(i)}}$$

In which $n_a^{(i)}$ is the number of accesses granted to actuator i, during each communication period and p_T is the total communication sequence period including both sensors and actuators scheduling.

Corollary 1 presents an important advantage of implementing communications in separate read/write sub-cycles. Controllability analysis could be done only by knowing the number of sensors and without being concerned about sensor communication sequence. This is not the case for non-equidistant periodic sequences neither for generic communication sequences (other than separate read-write cycles) as shown in the examples. As an instance, consider the following example;

Example 3: Consider the system described in Example1. Assuming equal times for sensor and actuator communications, (23) results in a period of 2, which violates (20). Therefore a period of 3 should be considered. A slot for the sensor, an empty slot and the third slot for the actuator. If non-equidistant periodic sequences are allowed, a 3-periodic sequence including two sensor accesses and one actuator access or vice versa may be considered. ■

Note that based on [9, 11], the system described by(1)-(3) is reconstructible (observable) if (1) is reconstructible (observable) and the sensor communication sequence is admissible. While sharing the communication medium affects controllability by inserting zero actuator scheduling matrices in the sequence, the situation is not the same for sensors (i.e. inclusion of actuator scheduling does not affect reconstructibility as long as sensor communication sequence is admissible).

5. Conclusion

In this paper, sufficient conditions for controllability and reconstructibility of bandwidth limited networked control systems with periodic equidistant communication sequences is derived. To make the model more realistic, a shared bus is assumed for sensors and actuators and separate read and write sub-cycles are considered. An example is included to show how using a shared bus may cause interdependency between controllability and reconstructibility. Using the previously established results, it is shown that the reconstructibility analysis may be performed independent of controllability when the sensor communication sequence is admissible with respect to sensors. However, controllability analysis can't be done independent of the sensor communication sequence. It is shown that using separate read/write sub-cycles and equidistant sequences makes the analysis significantly easier.

References

[1] Panos Antsaklis, and John Baillieul, "Special issue on technology of networked control systems",Proceedings of the IEEE, Vol.95, No.1: 5-8, 2007.

[2] Linda Bushnell, "Networked control systems: architecture and stability issues", Encyclopedia of Systems and Control, 2014.

[3] Lixian Zhang, Huijun Gao, and Okyay Kaynak, "Network-induced constraints in networked control systems - a survey", IEEE Transactions on Industrial Informatics, Vo. 9, No.1: 403-416, 2013.

[4] Rachana AshokGupta, and Mo-Yuen Chow, "Networked control system: overview and research trends",IEEE Transactions on Industrial Electronics,Vol. 57, No.7: 2527-2535, 2010.

[5] Mohammad Mahdi SharePasand, and Mohsen Montazeri, "Controllability and stabilizability of multi-rate sampled data systems",Systems & Control Letters, Vol. 113, No.1: 27-30, 2018.

[6] Lei Zhang and Dimitrios Hristu-Varsakelis, "Stabilization of Networked Control Systems: designing effective communication sequences", ISR technical report, 2004.

[7] Dimitrios Hristu-Varsakelis, "Short-period communication and the role of zero-order holding in networked control systems", IEEE Transactions on Automatic Control, Vol.53, No.5: 1285-1290, 2008.

[8] Stefano Longo, Guido Herrmann, and Phil Barber, "Controllability, observability in networked control" Robust Control Design,Vol.6, No.1: 438-446,2009.

[9] Stefano Longo, et al. Optimal and robust scheduling for networked control systems. CRC Press, 2013.

[10] Tatsuo Suzuki, et al. "Controllability and stabilizability of a networked control system with periodic communication constraints", Systems & Control Letters, Vol. 60, No.12: 977-984, 2011.

[11] Mohammad Mahdi Share Pasand, and Mosen Montazeri, "l□Step Reachability and Observability of Networked Control Systems with Bandwidth Limitations: Feasible Lower Bounds on Communication Periods",Asian Journal of Control, Vol. 19, No.4:1620-1629, 2017.

[12] Mohammad Mahdi Share Pasand, and Mohsen Montazeri, "Structural Properties of Networked Control Systems with Bandwidth Limitations and Delays",Asian Journal of Control, Vol. 19, No.3: 1228-1238, 2017.

[13] Mohammad Mahdi Share Pasand, and Mohsen Montazeri, "Kalman Filtering with Optimally Scheduled Measurements in Bandwidth Limited Communication Media", ETRI Journal, Vol.39, No.1: 13-20, 2017.

[14] ME Mongi BenGaid, Arben Cela, and Yskandar Hamam, "Optimal integrated control and scheduling of networked control systems with communication constraints:

application to a car suspension system",IEEE Transactions on Control Systems Technology, Vol. 14, No.4: 776-787, 2006..

[15] Henrik Rehbinder and Martin Sanfridson, “Scheduling of a limited communication channel for optimal control”, Automatica, Vol. 40, No.3:491-500, 2004.

[16] Mohammad Mahdi SharePasand, and Mohsen Montazeri, "Structural properties, LQG control and scheduling of a networked control system with bandwidth limitations and transmission delays",IEEE/CAA Journal of Automatica Sinica, Vol. 4, No.4:817-829, 2017.

[17] Mohammad MahdiShare Pasand, and Mohsen Montazeri, "Observer design for descriptor networked control systems with unknown and partially known inputs", Journal of Control and Decision, Vol. 5, No.4: 346-362, 2018.

[18] Yue Wu, and Jiuxiang Dong, "Cyber-Physical Attacks against State Estimators Based on a Finite Frequency Approach", IEEE Transactions on Systems, Man, and Cybernetics: Systems, Vol. 51, No.2:864 - 874, 2021.

[19] Erick J. Rodríguez-Seda, "Self-triggered reduced-attention output feedback control for linear networked control systems",IEEE Transactions on Industrial Informatics, Vol. 15, No.1: 348-356, 2019.

[20] Héctor Benítez-Pérezet et al. "Design of Networked Control System",Control Strategies and Co-Design of Networked Control Systems, Springer, 2019: 83-103.