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Simplified Algorithm and Framework for Networked Predictive Control Systems

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Abstract: The packet-based control approach has proven to be a promising method to deal with the communication constraints in networked control systems. Within this framework, model predictive control is often used to design the packet-based controller due to its favored control structure. In this work we discover an implicit relationship of the feedback gains obtained using the model predictive control method between networked predictive control systems and conventional control systems. This relationship is shown to be effective in simplifying the algorithm as well as the framework of the original networked predictive control system structure, and thus is of importance in the implementation of networked predictive control systems.

Key Words: Networked predictive control systems, Packet-based control, Model predictive control, Simplification

1 Introduction

The rapid developments of the communication technologies and the embedded devices in recent years have enabled their vast applications in control systems, thus forming a novel class of control systems termed as "networked control systems (NCSs)". In NCSs, data is typically exchanged through communication networks, including, for example, the control-oriented networks such as Control Area Network, DeviceNet, etc. and also the increasing use of the data networks such as the Internet. The introduction of the data networks in NCSs distinguishes NCSs from conventional control systems since practical communication channels inevitably produce delay, dropout, disorder, etc. (usually termed as the "communication constraint") for the transmitted data packets, a feature rarely seen in conventional control systems [1, 2].

The existence of the communication constraints in NCSs fails a large number of conventional control approaches. In order to deal with these emerged difficulties, both the control and communication communities have done considerable works. Roughly speaking, the control community tends to simplify the communication channels as some constrained, negative parameters to the control systems–delay, absence of control signal (dropout), etc. This effort can enable NCSs to be modeled in a familiar fashion to the control community and conventional control methods can then play their roles [3–7]. On the contrary, the communication community has its own perspectives and objectives, achieved usually by improving the reliability and efficiency of the communities channels through particularly designed communication protocols for the control purpose [8–10]. In recent years, the convergence of these two communities are also often seen–works in this line are usually labeled as "co-design" for NCSs [11, 12].

Within the co-design framework, a packet-based control approach is recently proposed [13–16]. This approach takes advantage of the packet-based data transmission in NCSs to actively compensate for the communication constraints in NCSs. Specifically, in packet-based networked control systems (PB-NCSs), at each time instant, the packet-based controller produces a sequence of forward control signals and sends them together in one data packet to the actuator side. The smart actuator then selects the appropriate control action from this sequence according to the current network condition and applies it to the plant. This control framework is simple to implement and yet efficient in compensating for the communication constraints in NCSs. Its effectiveness has been verified successfully both numerically and experimentally [16].

PB-NCSs with the packet-based controller being designed using the model predictive control (MPC) method is also termed as networked predictive control systems (NPCSs). MPC is a favored control method in designing the packet-based controller due to its particular control structure, and has been applied successfully in existing works [15]. In this work, for NPCSs with linear plant, we discover an implicit relationship of the feedback gains in terms of different delays, which leads to a close connection between MPC-based NPCSs and conventional control systems. This relationship is then shown to be able to simplify the algorithm as well as the overall framework of NPCSs dramatically, making it important in practical implementation of NPCSs.

The remainder of the paper is organized as follows. For completeness Section 2 briefly covers the design considerations of NPCSs. The main results are then presented in Section 3, including the implicit relationship discovered and its application of simplifying the algorithm and framework of NPCSs. The paper is concluded in Section 4. Note that no numerical examples are included in the paper since the main results of this work are simplifications of original networked predictive control design, but not improvements in terms of the control performance. The reader of interest in the applications of NPCSs are referred to [15], where both numerical and experimental examples of NPCSs can be found.

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2 Networked Predictive Control Systems

The following multi-input multi-output linear time-invariant system S is considered,

$$S : \begin{cases} x(k+1) = Ax(k) + Bu(k) & \text{(1a)} \\ y(k) = Cx(k) & \text{(1b)} \end{cases}$$

where $x(k) \in \mathbb{R}^n$, $u(k) \in \mathbb{R}^m$, $y(k) \in \mathbb{R}^r$, $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$ and $C \in \mathbb{R}^{r\times n}$. This plant is controlled remotely over the communication network, as illustrated in Fig. 1.

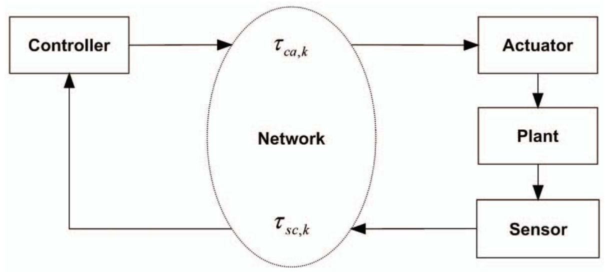

Fig. 1: The block diagram of a networked control system.

As mentioned earlier, NPCSs are PB-NCSs with the use of MPC. For completeness in what follows we will briefly present the underlying idea of PB-NCSs and the design of the packet-based controller using MPC. However, before preceding with this, it is necessary first to present the following two assumptions required for the successful implementation of general PB-NCSs, the rationalities and implications of which can be referred to [15–17].

Assumption 1 (Delay bound) *The sum of the network-induced delay and consecutive data packet dropout in both the sensor-to-controller and the controller-to-actuator channels are upper bounded, i.e.,*

$$\bar{\tau}_{sc} \triangleq \max_{k\geq 1}\{\tau_{sc,k} + \bar{\chi}_{sc}\} < \infty \tag{2a}$$

$$\bar{\tau}_{ca} \triangleq \max_{k\geq 1}\{\tau_{ca,k} + \bar{\chi}_{ca}\} < \infty \tag{2b}$$

where $\bar{\tau}_{sc}$ and $\bar{\tau}_{ca}$ are the upper bounds, $\tau_{sc,k}$, $\bar{\chi}_{sc}$ and $\tau_{ca,k}$, $\bar{\chi}_{ca}$ represent the network-induced delay and the upper bound of consecutive data packet dropout, in the sensor-to-controller and the controller-to-actuator channels, respectively.

Assumption 2 (Time stamp) *The control components in NCSs including the sensor, the controller and the actuator are time synchronized and data packets are sent with time stamps to notify when they were sent.*

2.1 Packet-Based Control Framework for NCSs

The essential idea of the packet-based control approach is to notice the fact that the number of control signals that one data packet can contain is usually relatively large, especially in the use of data networks. Indeed, denoting the effective load of the data packet being used by B_p and the data size required for encoding a single step of the control signal by B_c, the following relationship typically holds for data networks,

$$\lfloor \frac{B_p}{B_c} \rfloor > \bar{\tau}_{ca} \tag{3}$$

where $\lfloor \frac{B_p}{B_c} \rfloor = \max\{\varsigma | \varsigma \in \mathbb{N}, \varsigma \leq \frac{B_p}{B_c}\}$, and $\mathbb{N}$ is the set of natural numbers.

The relationship in (3) allows us to pack a sequence of forward control signals with the length of $\bar{\tau}_{ca} + 1$ (so-called "forward control sequence" (FCS)) into one data packet and send it through the network simultaneously. That is, in PB-NCSs, instead of calculating and sending only current control signal $u(k)$ at time k, the following FCS $U(k|k - \tau_{sc,k})$ is packed into one data packet and sent to the actuator,

$$\begin{aligned} & U(k|k - \tau_{sc,k}) \\ = \; & [u(k|k - \tau_{sc,k}) \; \ldots \; u(k + \bar{\tau}_{ca}|k - \tau_{sc,k})] \end{aligned} \tag{4}$$

where $u(k+i|k-\tau_{sc,k}), i = 0, 1, \ldots, \bar{\tau}_{ca}$ are the control predictions based on the sensing information at time $k - \tau_{sc,k}$.

Upon receiving $U(k|k - \tau_{sc,k})$, the actuator then selects from it the appropriate control signal to actively compensate for current communication constraints in NCSs, using a specially designed module named "control action selector" (CAS). The general structure of this framework is illustrated in Fig. 2. This packet-based control approach, as shown in [15–17], generally leads to a better performance of NCSs than that using conventional control approaches, since more dynamics of the control system and properties of communication network in NCSs have been considered. The reader is referred to [15–17] for further details of this approach.

2.2 Packet-Based Controller Design Using MPC

The packet-based control approach itself provides us with only the control framework to actively compensate for the communication constraints, while the design of the packet-based controller can be varied. It is not surprising why the use of MPC is dominant in the early development of PB-NCSs: Unlike other controller design methods, MPC can naturally produce a sequence of forward predictions at each step, a perfect choice of the FCS in PB-NCSs.

The implementation of MPC is based on a step by step finite-horizon optimization. Distinct from conventional MPC methods, the performance index for NPCSs is defined by taking the communication constraints into account [15], as follows,

$$\begin{aligned} J_{k,\tau_{sc,k}} \triangleq & Y^T(k|k - \tau_{sc,k})QY(k|k - \tau_{sc,k}) \\ & + \Delta U^T(k|k - \tau_{sc,k})R_{\tau_{sc,k}}\Delta U(k|k - \tau_{sc,k}) \end{aligned} \tag{5}$$

where $J_{k,\tau_{sc,k}}$ is the performance index at time k, $\Delta U(k|k-\tau_{sc,k}) = [\Delta u^T(k-\tau_{sc,k}|k-\tau_{sc,k}) \cdots \Delta u^T(k+N_u-1|k-\tau_{sc,k})]^T$ is the forward control increment sequence, $Y(k|k-\tau_{sc,k}) = [y^T(k+1|k-\tau_{sc,k}) \cdots y^T(k+N_p|k-\tau_{sc,k})]^T$ is the predictive output trajectory, $Q > 0$ and $R_{\tau_{sc,k}} > 0$ are diagonal weighting matrices with appropriate dimensions and N_p and N_u are the prediction horizon and the control horizon, respectively. Notice here that the dimension of $R_{\tau_{sc,k}}$ is time varying, dependent on the sensor-to-controller delay, $\tau_{sc,k}$.

In order to optimize the performance index, system S is rewritten as follows by letting $\bar{x}(k) \triangleq [x(k) \; u(k-1)]^T$,

$$S' : \begin{cases} \bar{x}(k+1) = \bar{A}\bar{x}(k) + \bar{B}\Delta u(k) & \text{(6a)} \\ y(k) = \bar{C}\bar{x}(k) & \text{(6b)} \end{cases}$$

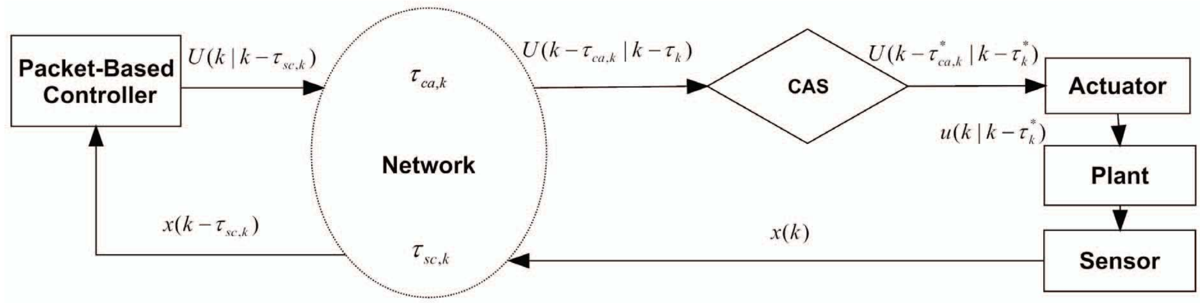

Fig. 2: The general framework of packet-based networked control systems.

where $\bar{A} = \begin{pmatrix} A & B \\ 0 & I \end{pmatrix}$, $\bar{B} = \begin{pmatrix} B \\ I \end{pmatrix}$, $\bar{C} = \begin{pmatrix} C & 0 \end{pmatrix}$ and $\Delta u(k) = u(k) - u(k-1)$.

The optimal forward control incremental sequence at time k, i.e., $\Delta U^*(k|k-\tau_{sc,k}) = [\Delta u^{*T}(k|k-\tau_{sc,k}) \cdots \Delta u^{*T}(k+N_u-1|k-\tau_{sc,k})]^T$, obtained by minimizing (5), turns out to be state feedback control, as follows [15],

$$\Delta U^*(k|k-\tau_{sc,k}) = K_{\tau_{sc,k}} \bar{x}(k-\tau_{sc,k}) \tag{7}$$

with

$$K_{\tau_{sc,k}} = -M_{\tau_{sc,k}}(F^T_{\tau_{sc,k}} Q F_{\tau_{sc,k}} + R)^{-1} F^T_{\tau_{sc,k}} Q E_{\tau_{sc,k}} \tag{8}$$

where $M_{\tau_{sc,k}} = [0_{mN_u \times m\tau_{sc,k}} \; I_{mN_u \times mN_u}]$, $F_{\tau_{sc,k}}$ is a block lower triangular matrix with its non-null elements defined by $(F_{\tau_{sc,k}})_{ij} = \bar{C}\bar{A}^{\tau_{sc,k}+i-j}\bar{B}, j-i \leq \tau_{sc,k}$ and $E_{\tau_{sc,k}} = [(\bar{C}\bar{A}^{\tau_{sc,k}+1})^T \cdots (\bar{C}\bar{A}^{\tau_{sc,k}+N_p})^T]^T$.

After the operation of CAS in Fig. 2, the control incremental signal actually adopted at time k (time at the actuator side) is

$$\Delta u(k) = u(k|k-\tau^*_k) = d^T_{\tau^*_{ca,k}} \Delta U^*(k-\tau^*_{ca,k}|k-\tau^*_k) \tag{9}$$

where $\tau^*_k = \tau^*_{sc,k} + \tau^*_{ca,k}$ is the round trip delay of $\Delta U^*(k-\tau^*_{ca,k}|k-\tau^*_k)$, and $d_{\tau^*_{ca,k}}$ is a $N_u \times m$ matrix with all entries 0 except the $(\tau^*_{ca,k}+1)$th row being 1.

3 Simplified Algorithm and Framework for NPCSS

In this section we will discover an implicit relationship of the feedback gains $K_{\tau_{sc,k}}$ in (8) in terms of different sensor-to-controller delays, and then use this observation to simplify the original NPCSs control algorithm and framework. For simplicity of notations in what follows we let $i \triangleq \tau_{sc,k}$.

3.1 Rediscovering the Feedback Gains

The following theorem discovers a fact regarding he feedback gains K_i in (8), showing that the variation of these feedback gains in terms of different sensor-to-controller delays is closely related to the weighting matrix Q in (5).

Theorem 1 *The feedback gains K_i in* (8) *can be constructed as follows,*

$$K_i = \Omega_0(Q_i)\bar{A}^i, \; i \geq 0 \tag{10}$$

where $Q_i = Q + \sum_{j=0}^{i} \Delta Q_j, i \geq 0$,

$$\Delta Q_i = \begin{cases} 0 & i = 0 \quad (11a) \\ -Qf_i(f_i^T Q f_i + r_i)^{-1} f_i^T Q & i \geq 1 \quad (11b) \end{cases}$$

$$f_i = \begin{pmatrix} \bar{C}\bar{A}^i\bar{B} \\ \bar{C}\bar{A}^{i+1}\bar{B} \\ \vdots \\ \bar{C}\bar{A}^{i+N_p-1}\bar{B} \end{pmatrix}, \; i \geq 1 \tag{12}$$

r_i is the upper right block of R_i with dimension $m \times m$, i.e.,

$$R_i = \begin{pmatrix} (r_i)_{m\times m} & 0 \\ 0 & (R_{i-1})_{m(N_u+i-1)\times m(N_u+i-1)} \end{pmatrix} \tag{13}$$

and matrix-valued function $\Omega_0(x)$ is defined as follows,

$$\Omega_0(x) = -(F_0^T x F_0 + R_0)^{-1} F_0^T x E_0 \tag{14}$$

Before preceding with the proof of Theorem 1, we recall the following well-known fact.

Lemma 1 *The inverse of a 2-dimensional block matrix can be calculated as follows,*

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix}^{-1} = \begin{pmatrix} \star & \star \\ -(d-ca^{-1}b)^{-1}ca^{-1} & (d-ca^{-1}b)^{-1} \end{pmatrix}$$

where a, b, c, d are matrices with appropriate dimensions, $\star$ represents those items of no interest, and all the matrices are invertible where necessary.

Proof of Theorem 1: Firstly, by the definition of E_i in (8), the following relationship holds

$$E_i = E_{i-1}\bar{A}, \; i \geq 1 \tag{15}$$

In addition, we can also obtain the following relationship in light of the definitions of F_i in (8) and f_i in (12),

$$F_i = [f_i \; F_{i-1}], \; i \geq 1 \tag{16}$$

Define $P_j = [0_{m(N_u+j)\times m} \; I_{m(N_u+j)\times m(N_u+j)}], j \geq 0$, we then have

$$M_i = \prod_{j=0}^{i-1} P_j, \; \forall i \geq 1 \tag{17}$$

where $M_i = [0_{mN_u \times mi}\ I_{mN_u \times mN_u}]$.

Now consider

$$K_i = -M_i(F_i^T Q F_i + R_i)^{-1} F_i^T Q E_i,\ i \geq 1$$

We first calculate $(F_i^T Q F_i + R_i)^{-1}$ by the use of (16), (13) and Lemma 1, as follows.

$$\begin{aligned}
&(F_i^T Q F_i + R_i)^{-1} \\
=&(\begin{pmatrix} f_i^T \\ F_{i-1}^T \end{pmatrix} Q[f_i\ F_{i-1}] + R_i)^{-1} \\
=&\begin{pmatrix} f_i^T Q f_i + r_i & f_i^T Q F_{i-1} \\ F_{i-1}^T Q f_i & F_{i-1}^T Q F_{i-1} + R_{i-1} \end{pmatrix}^{-1} \\
=&\begin{pmatrix} \star & \star \\ -W_i F_{i-1}^T Q f_i (f_i^T Q f_i + r_i)^{-1} & W_i \end{pmatrix}
\end{aligned}$$

where

$$\begin{aligned}
W_i =&(F_{i-1}^T Q F_{i-1} + R_{i-1} - F_{i-1}^T Q f_i \\
&\times (f_i^T Q f_i + r_i)^{-1} f_i^T Q F_{i-1})^{-1} \\
=&(F_{i-1}^T (Q + \Delta Q_i) F_{i-1} + R_{i-1})^{-1}
\end{aligned}$$

by the use of (11).

Using above result and noticing (15), we then obtain

$$\begin{aligned}
&P_{i-1}(F_i^T Q F_i + R_i)^{-1} F_i^T Q E_i \\
=&\begin{pmatrix} -W_i F_{i-1}^T Q f_i (f_i^T Q f_i + r_i)^{-1} & W_i \end{pmatrix} \\
&\times \begin{pmatrix} f_i^T \\ F_{i-1}^T \end{pmatrix} Q E_i \\
=&W_i F_{i-1}^T (Q + \Delta Q_i) E_i \\
=&(F_{i-1}^T (Q + \Delta Q_i) F_{i-1} + R_{i-1})^{-1} \\
&\times F_{i-1}^T (Q + \Delta Q_i) E_{i-1} \bar{A}
\end{aligned} \tag{18}$$

Define matrix-valued function $\Omega_i(x), i \geq 0$ as follows,

$$\Omega_i(x) = -(F_i^T x F_i + R_i)^{-1} F_i^T x E_i,\ i \geq 0 \tag{19}$$

Notice that this definition is consistent with the definition in (14) when $i = 0$.

Using (19) we can rewrite (18) as follows,

$$P_{i-1}\Omega_i(Q) = \Omega_{i-1}(Q + \Delta Q_i)\bar{A}, \forall i \geq 1 \tag{20}$$

The fact that (20) is held for all $i \geq 1$ actually implies (noticing (17))

$$\begin{aligned}
K_i =& - M_i(F_i^T Q F_i + R_i)^{-1} F_i^T Q E_i \\
=&\prod_{j=0}^{i-1} P_j \Omega_i(Q) \\
=&\prod_{j=0}^{i-2} P_j \Omega_{i-1}(Q + \Delta Q_i)\bar{A} \\
=&\ldots \\
=&\Omega_0(Q + \sum_{j=1}^{i} \Delta Q_j)\bar{A}^i \\
=&\Omega_0(Q_i)\bar{A}^i,\ i \geq 1
\end{aligned} \tag{21}$$

Notice that $M_0 = I_{mNu \times mNu}$, $\bar{A}^0 = I_{n \times n}$ and $Q_0 = Q$, we thus have

$$\begin{aligned}
K_0 =& - M_0(F_0^T Q F_0 + R_0)^{-1} F_0^T Q E_0 \\
=&\Omega_0(Q_0)\bar{A}^0
\end{aligned} \tag{22}$$

This together with (21) completes the proof. ■

Theorem 1 builds the relationship between the MPC method used in NPCSs and conventional MPC methods, which is stated in the following Corollary.

Corollary 1 *Given the sensor-to-controller delay $i \triangleq \tau_{sc,k}$, the FCSs generated in NPCSs using the delayed performance index in* (5) *is equivalent to the following control strategy:*

1) *Keep the plant open loop for i time steps;*
2) *Design the FCS using MPC based on the following non-delayed performance index with delay-dependent weighting matrix Q_i:*

$$J_{k;Q_i} \triangleq Y^T(k|k) Q_i Y(k|k) + \Delta U^T(k|k) R \Delta U(k|k) \tag{23}$$

Proof. The proof is straightforward by looking into (10) in Theorem 1. ■

Remark 1 *In PB-NCSs, before selecting the appropriate control action from the FCS, CAS is required first to compare the newly arrived FCS and the one already stored and only the one containing the latest information is stored. This mechanism is designed to deal with data packet disorder in NCSs. The rationality of introducing such a functionality can be justified by Theorem 1. In fact,* (20) *tells us that (by left-multiplying M_{i-1})*

$$K_i = M_i\Omega_i(Q) = M_{i-1}\Omega_{i-1}(Q + \Delta Q_i)\bar{A} \tag{24}$$

and in addition,

$$K_{i-1} = M_{i-1}\Omega_{i-1}(Q) \tag{25}$$

Comparing these two feedback gains, it is seen that K_i is obtained by keeping the plant open loop for one time step and then modifying the gain by adding some correction factor ΔQ_i. Nevertheless no closed-loop information at this time step is involved in K_i and, therefore, K_{i-1} should contain more precise control information than K_i does. This is why such a comparison process is introduced in CAS.

3.2 Simplified Algorithm and Framework for NPCSs

Corollary 1 provides us with the possibility of simplifying the original NPCSs design. This is discussed as follows, firstly a simplified controller design method for the general framework of NPCSs and then a simplified control framework for some particular cases.

3.2.1 Simplified controller design

Corollary 1 implies that the optimization problem of MPC in (5) is no longer necessary to be solved at each step. Indeed, the equivalence between the delayed and non-delayed optimization problems stated in Corollary 1 renders us the privilege of calculating only the non-delayed conventional optimization problem offline and making modifications when the system is up and running. This results in the following simplified algorithm for NPCSs, where the general framework is unchanged as in Fig. 2.

Algorithm 1 (Simplified algorithm for NPCSs)
S1. Solve the non-delayed optimization problem using the performance index in (23) *and store the related parameters: Function* $\Omega_0(x)$*, delay-dependent weighting matrices* $Q_i, i \geq 0$ *and extended system matrix* $\bar{A}$.
S2. Whenever a sampled system state, $x(k-\tau_{sc,k})$ *arrives at the controller side, then:*

1) *Measure the sensor-to-actuator delay:* $\tau_{sc,k}$;
2) *Construct the extended state:* $\bar{x}(k-\tau_{sc,k}) = [x(k-\tau_{sc,k})\ u(k-\tau_{sc,k}-1)]^T$;
3) *Calculate the open-loop current extended state:* $\bar{x}(k) = \bar{A}^{\tau_{sc,k}}\bar{x}(k-\tau_{sc,k})$;
4) *Produce the FCS:* $U(k|k-\tau_{sc,k}) = \Omega_0(Q_{\tau_{sc,k}})\bar{x}(k)$.

S3. The CAS selects the appropriate control action from the latest FCS and applies it to the plant.

3.2.2 Simplified control framework for particular cases

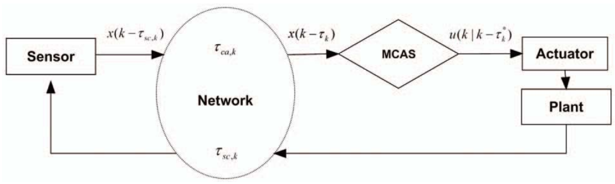

Fig. 3: Simplified framework of networked predictive control systems.

Corollary 1 can be more important in a networked control structure where the sensor is remotely placed away from the plant, and the data exchange between the sensor and the plant is through the communication network. Thanks to the dramatically simplified controller design process, this simplified packet-based controller can be embedded into the CAS without using the complicated controller at all. In this case, the parameters that are computed offline in Algorithm 1 will be stored in the modified CAS (MCAS) and control signal will be directly calculated in CAS and applied to the plant, as illustrated in Fig. 3. The algorithm in this case is organized as follows.

Algorithm 2 (Simplified framework for NPCSs)
S1. Solve the non-delayed optimization problem using the performance index in (23) *and store the related parameters in the MCAS: Function* $\Omega_0(x)$*, delay-dependent weighting matrices* $Q_i, i \geq 0$ *and extended system matrix* $\bar{A}$.
S2. Whenever a sampled system state, $x(k-\tau_k)$ *arrives at the MCAS, then:*

1) *Determine the latest system state* $x(k-\tau_k^*)$ *available as well as the round trip delay* τ_k^*;
2) *Construct the extended state:* $\bar{x}(k-\tau_k^*) = [x(k-\tau_k^*)\ u(k-\tau_k^*-1)]^T$;
3) *Calculate the open-loop current extended state:* $\bar{x}(k) = \bar{A}^{\tau_k^*}\bar{x}(k-\tau_k^*)$;
4) *Calculate the appropriate control action:* $\Delta u(k) = d^T_{\tau^*_{ca,k}}\Omega_0(Q_{\tau_k^*})\bar{x}(k)$ *and applies it to the plant.*

Notice that in this case there will be no FCSs calculated and transmitted.

For comparisons of these simplified algorithm and framework with typical NPCSs, the reader is referred to [15, 16, 18].

4 Conclusions

An implicit relationship of the feedback gains is discovered between the model predictive controllers in networked predictive control systems and conventional control systems. This relationship is shown to contribute to simplify the algorithm of networked predictive control systems and, in particular cases, can simplify the whole control framework. This result eases the implementation of networked predictive control systems in practice. Future work may focus on the simplification of the general packet-based control framework.

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1. Simplified algorithm and framework for networked predictive control systems

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