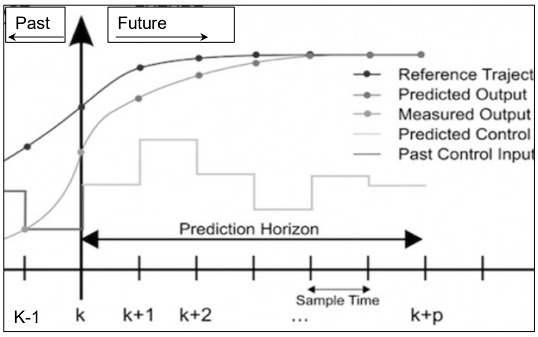
6.7 Networked Learning Predictive Control

■ Introduction

History of predictive control

- ✓ Smith predictor control (1959)
- ✓ Model predictive control
  - Model algorithmic control (1970s)
  - Dynamic matrix control (1976)
  - Generalised predictive control (1987)
  - Stable predictive control (1990s)
- ✓ Networked predictive control (2004)[1]



Predictive control

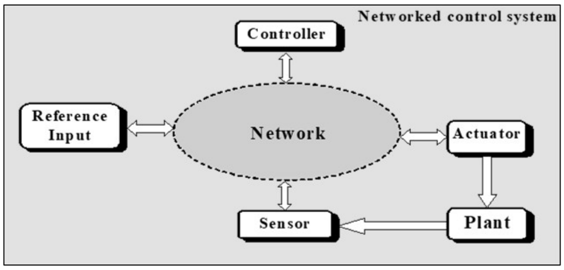
[1] G.P. Liu, J. Mu and D. Rees, Networked predictive control of systems with random communication delay, *Proceedings of the UKACC Control '04*, Bath, ID-015, 2004.

■ Networked Control Systems

A networked control system (NCS) is a system whose control loop is closed through networks.

♦ Design problem of NCS

- ✓ Compensate for random network delay
- ✓ Achieve desired control performance
- ✓ Guarantee closed-loop stability

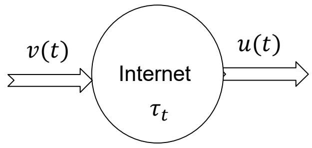


♦ Assumptions on NCS

- ✓ There are networks in both forward and feedback channels
- ✓ The network delay is bounded
- ✓ The number of consecutive data package drops is bounded
- ✓ Transmitted data with time stamps

♦ **Methods of Dealing with Data Loss or Attacks**

- ✓ Zero value method
- ✓ Zero order holder method
- ✓ **Predication method**



$$u(t) = \begin{cases} 0 & \text{Zero value} \\ u(t-1) & \text{Previous value} \\ \hat{v}(t|t-\tau_t) & \text{Predication value} \end{cases}$$

♦ **Methods of Dealing with Network Delays**

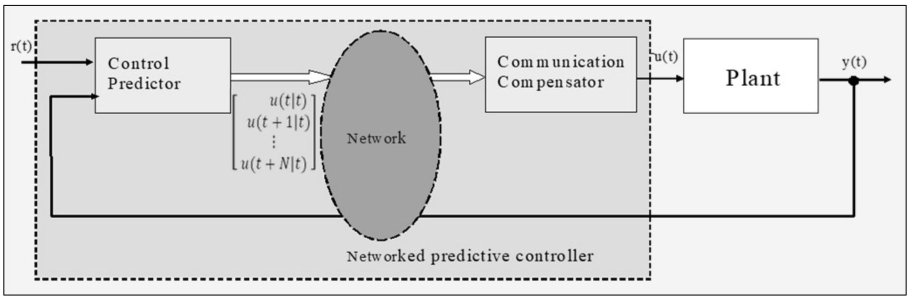
- ✓ Passive compensation method
- ✓ **Active compensation method**

$$u(t) = \begin{cases} v(t-\tau_t), & (passive) \\ \hat{v}(t|t-\tau_t) & (active) \end{cases}$$

■ Networked Predictive Control

♦ **Networked Predictive Control Scheme**

- ✓ **The control predictor** generates a set of control predictions which achieve the required control performance.
- ✓ **The communication compensator** compensates for the unknown random communication delay and data loss.
- ✓ The control data are transmitted **in package** via networks.



♦ **Networked predictive control**

➢ **The plant**

$$x_{t+1} = Ax_t + Bu_t$$
$$y_t = Cx_t$$

where (A,B) is controllable and (A,C) is observable.

➢ **The state observer**

$$\hat{x}_{t+1|t} = A\hat{x}_{t|t-1} + Bu_t + L(y_t - C\hat{x}_{t|t-1})$$

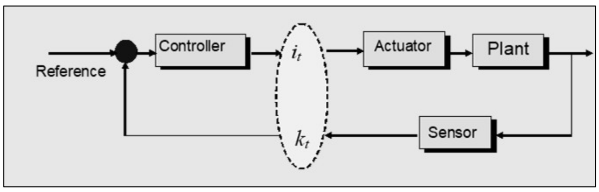
where matrix *L* can be obtained using observer design approaches.

➢ **The multi-step state predictor**

It is assumed that the network delays in the feedback and forward channels are k_t and i_t, respectively.

Based on the output data up to t-k_t, the state predictions from time t-k_t to t+i_t are constructed by

$$\hat{x}_{t-k_t+1|t-k_t} = A\hat{x}_{t-k_t|t-k_t-1} + Bu_{t-k_t} + L(y_{t-k_t} - C\hat{x}_{t-k_t|t-k_t-1})$$
$$\hat{x}_{t-k_t+2|t-k_t} = A\hat{x}_{t-k_t+1|t-k_t} + B\hat{u}_{t-k_t+1|t-k_t}$$
$$\vdots$$
$$\hat{x}_{t+i_t|t-k_t} = A\hat{x}_{t+i_t-1|t-k_t} + B\hat{u}_{t+i_t-1|t-k_t}$$



The control predictor

- **Method 1**

$\hat{u}_{t+i|t-k_t} = K\hat{x}_{t+i|t-k_t}$, for $i = -k_t + 1, -k_t + 2, \cdots, i_t$

where K can be designed as the system does not have communication delays.

- **Method 2**

$U^*_{t+i_t|t-k_t} = \arg\ \min\ J(t, \hat{u}_{t-k_t+1|t-k_t}, \hat{u}_{t-k_t+2|t-k_t}, \ldots, \hat{u}_{t+i_t|t-k_t})$

where J(.) is a cost function.

Communication compensator

Choose the latest control action for time t, *e.g.,*

$$u(t) = \hat{u}(t|t - \min\{ i_1 + k_1,\ i_2 + k_2,\ \cdots,\ i_t + k_t\})$$

which is the latest predictive control value at time t if the following predictive control sequences are available on the plant side:

$$\{\hat{u}(t|t - i_1 - k_1) \quad \hat{u}(t|t - i_2 - k_2) \quad \cdots \quad \hat{u}(t|t - i_t - k_t)\}$$

- **Stability of the closed-loop system**

The closed-loop networked predictive control system

$$Z_{t+1} = \Lambda(i_t,\ k_t)Z_t$$

where Z_t is the augmented system state vector and $\Lambda(i_t,\ k_t)$ the system matrix.

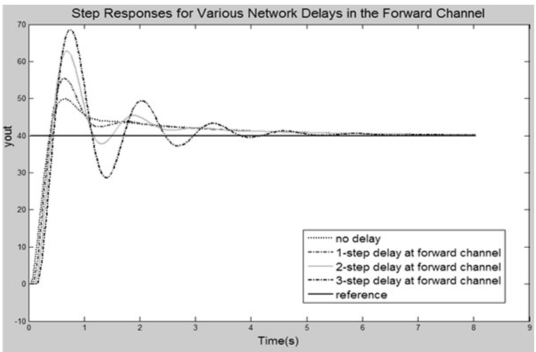
Case 1: Fixed communication delays

The system is stable if and only if $\Lambda(i_t,\ k_t)$ is Schur stable.

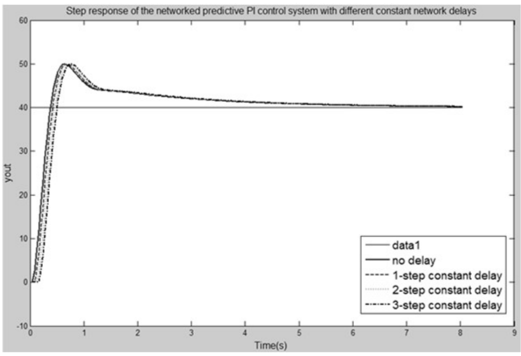
Case 2: Time-varying communication delays

The system stability can be analysed using the switching control theory or time-varying control theory.

- **Step responses of a system without or with delay compensation** (an example)
  - ✓ No network delay
  - ✓ Various network delays (*e.g.*, τ =1, 2, 3)



Without delay compensation



With delay compensation (NPC)

■ Networked learning predictive control

If the plant is unknown or slowly time-varying, recursive learning methods (e.g., neural network learning methods) can be employed.

The networked learning predictive control algorithm is constructed below.

♦ **Algorithm** 6.7.1 (Learning NPC)

Step 1: Set up the initialization of the parameter identification

Step 2: Sample the current actual output and the reference input.

Step 3: Construct a data-driven model of the controlled plant using a recursive learning algorithm online.

Step 4: Calculate the state predictions using the multi-step state predictor based on the data-driven model.

Step 5: Implement the predictive controller via networks

Step 6: Return to Step 2 and continue the loop.

■ Various networked predictive control methods

✓ **Artificial intelligent NPC**	(G.P. Liu, ***IEEE-TCNS***, 9(4): 1975-1986, 2022)
✓ **Blockchain NPC**	(Y. Yu, G.P. Liu, et al, ***IEEE-TIE***, 70(1):783-792, 2023)
✓ **Cloud NPC**	(G.P. Liu, ***IEEE-TC***, 47(8):1852-1859, 2017)
✓ **Digital twin NPC**	(G.P. Liu, ***IEEE/CAA-JAS***, 11(1):1-11, 2024)
Data-driven NPC	(G.P. Liu, ***IEEE-TSMCA***, 50(11):4447-4457, 2020)
	(G.P. Liu, ***IEEE/CAA-JAS***, 11(1):1-11, 2024)
⋮	
✓ **High-order fully actuated NPC**	(G.P. Liu, ***IEEE/CAA-JAS***, 9(4):615-623, 2022)
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? **Metaverse NPC**	
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✓ **PID NPC**	(G.P. Liu, ***IEEE/CAA-JAS***, 10(1):216-225, 2023)