Networked Control Systems with Application to Industrial Processes

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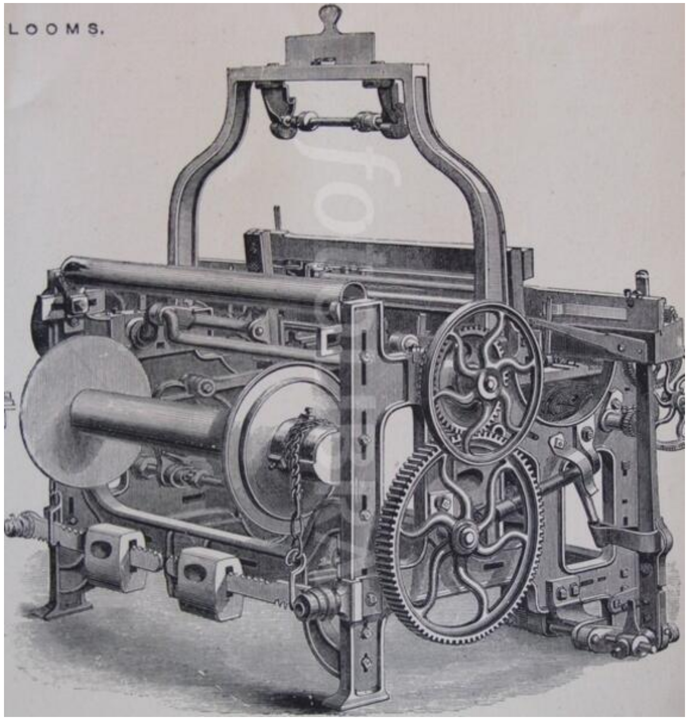
Outline

- Background
- Networked Control and Estimation
- Networked Process Control
- Future Work

Background

Industrial Revolution: From Industry 1.0 to Industry 4.0

1st industrial revolution



Mechanical waving loom (1784)

egree of complexity

1st industrial revolution

Through introduction of mechanical production facilities with the help of water and steam power

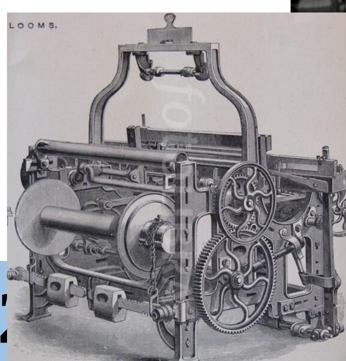
1790s

Background

Industrial Revolution: From Industry 1.0 to Industry 4.0

Assembly line (1870)

1st industria
revolution



gree of complexity

ial revolution

Through introduction of mass production with the help of electrical energy

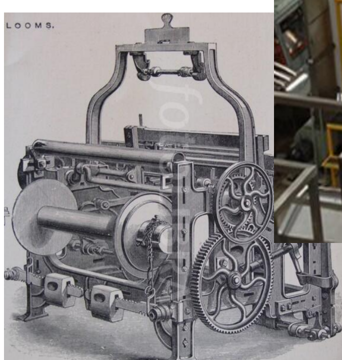
1790s 1870s

Industrial Revolution: From Industry 1.0 to Industry 4.0

Programmable logic control system (1969)

1st industria

revolution



ndustrial revolution

Mechan

waving

(1784)

Through application of electronics and IT to further automate production

Degree of complexity

1790s

1870s

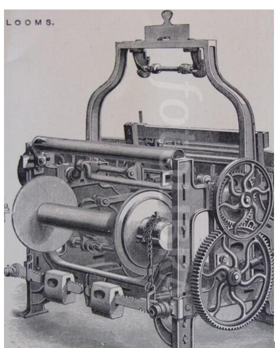
1970s

Background

Industrial Revolution: From Industry 1.0 to Industry 4.0

4th industrial …ion

1st industria… revolution



Cyber-physical systems

(CPS)

…ial 3.0

…ial 2.0

Degree of complexity

4th industrial revolution

On the basis of cyber-physical systems (CPS), merging of real and virtual world

1790s … 1870s … 1970s … Today

Background

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- **Current Stage:**
  - Industry 3.0 (Most)
  - Industry 4.0 (Part): *Trumpf, SAP, Bosch, Wittenstein, Festo, Boeing…*
- **Objectives:**
  - Smart logistics
  - Smart manufacturing
  - Smart factory

Germany Industry 4.0

- **Current Stage:**
  - Industry 3.0 (Most)
  - Industry 4.0 (Part): *LIFT, Power America, AIM Photonics, Flexible hybrid electronics…*
- **Objectives:**
  - Technological transformation
  - Sustainable development

U.S.A. NNMI

- **Current Stage:**
  - Industry 2.0 (Most)
  - Industry 3.0 (Part): *Haier, Huawei, Lenovo, Baosteel…*
- **Objectives:**
  - Upgrade industrial structure
  - Moderate power
  - Leading power

Made In China 2025

Background

Core of industry 4.0: Cyber-physical system (CPS)

Computation

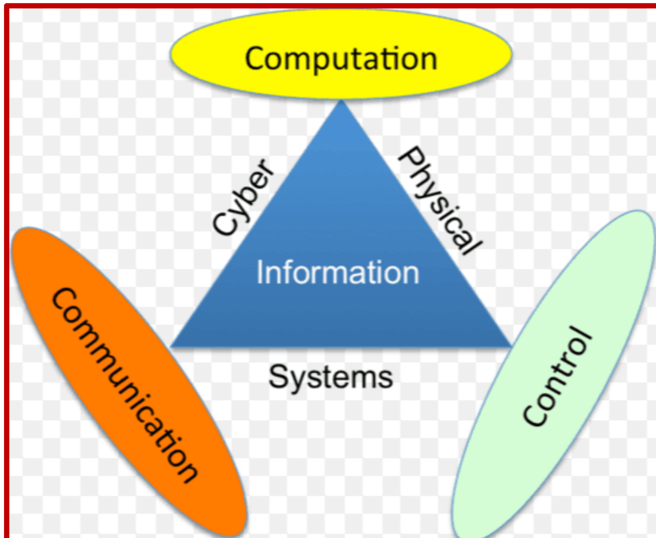
- Advanced computing
- Intelligent computing
- Online computing
- Smart protocol

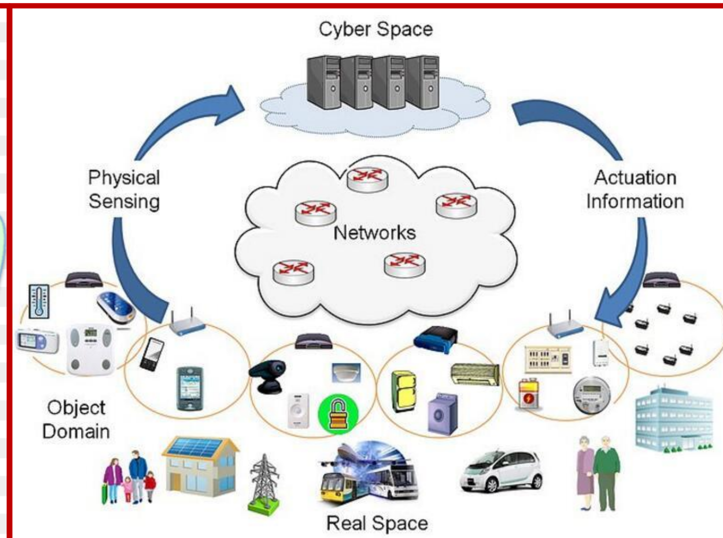
Communication

- Smart sensors
- Smart networks
- Ubiquitous connectivity
- Pervasive sensing

Control

- Large-scale physical plants
- Embedded processers
- Secure-control





Background

Industrial Process Automation Technology

Integration of Information Technology and Industrialization → Industrial Process Automation Technology

- Information Technology
- Knowledge of the Industrial Process
- Intelligence and Integrated Optimization

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Production Index Optimal Control

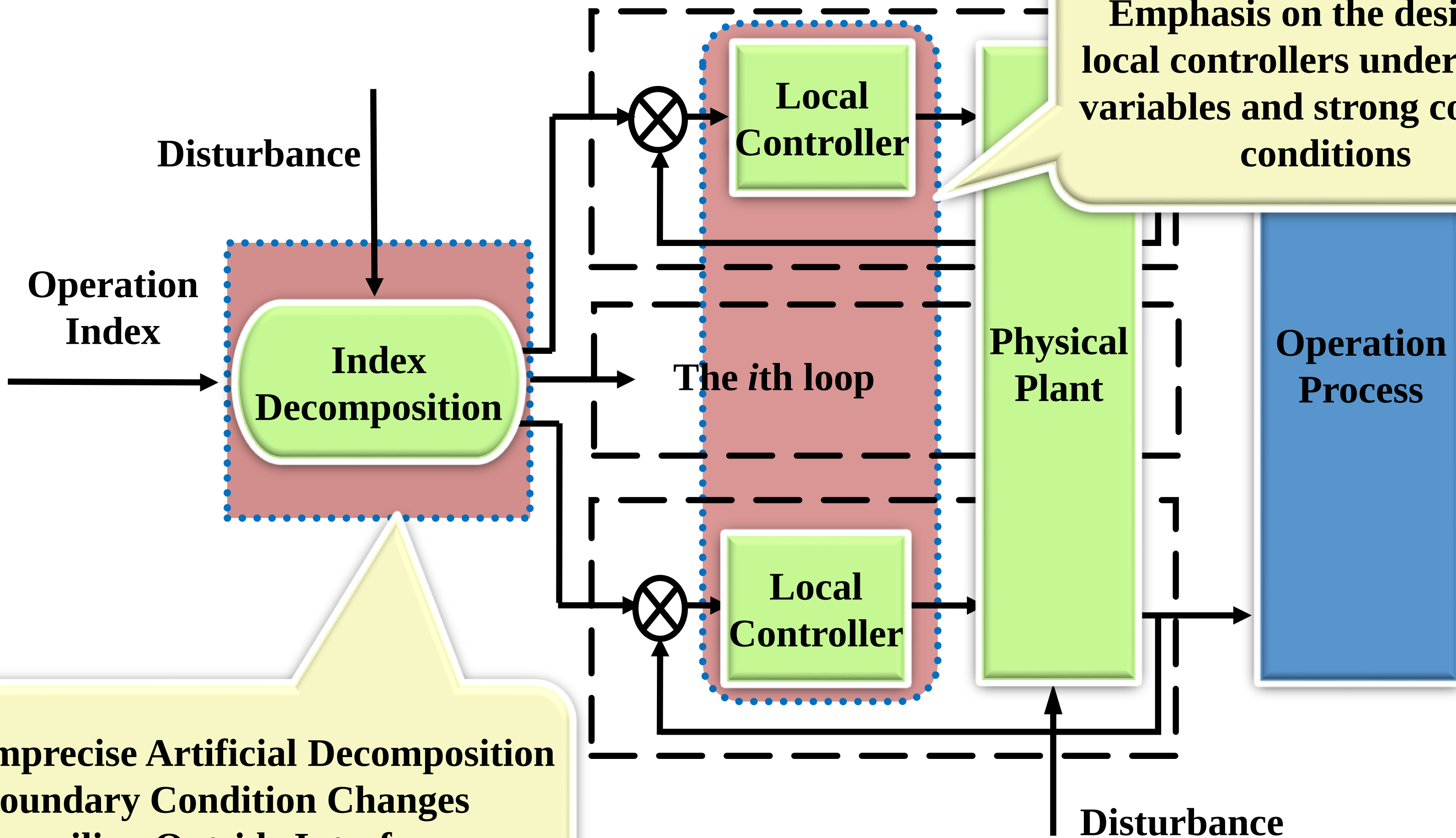
Enterprise Knowledge Productivity

Background

Stage I

Traditional Artificial Decomposition of Performance Index (Open-loop Control)

Emphasis on the design of local controllers under multi-variables and strong coupling conditions

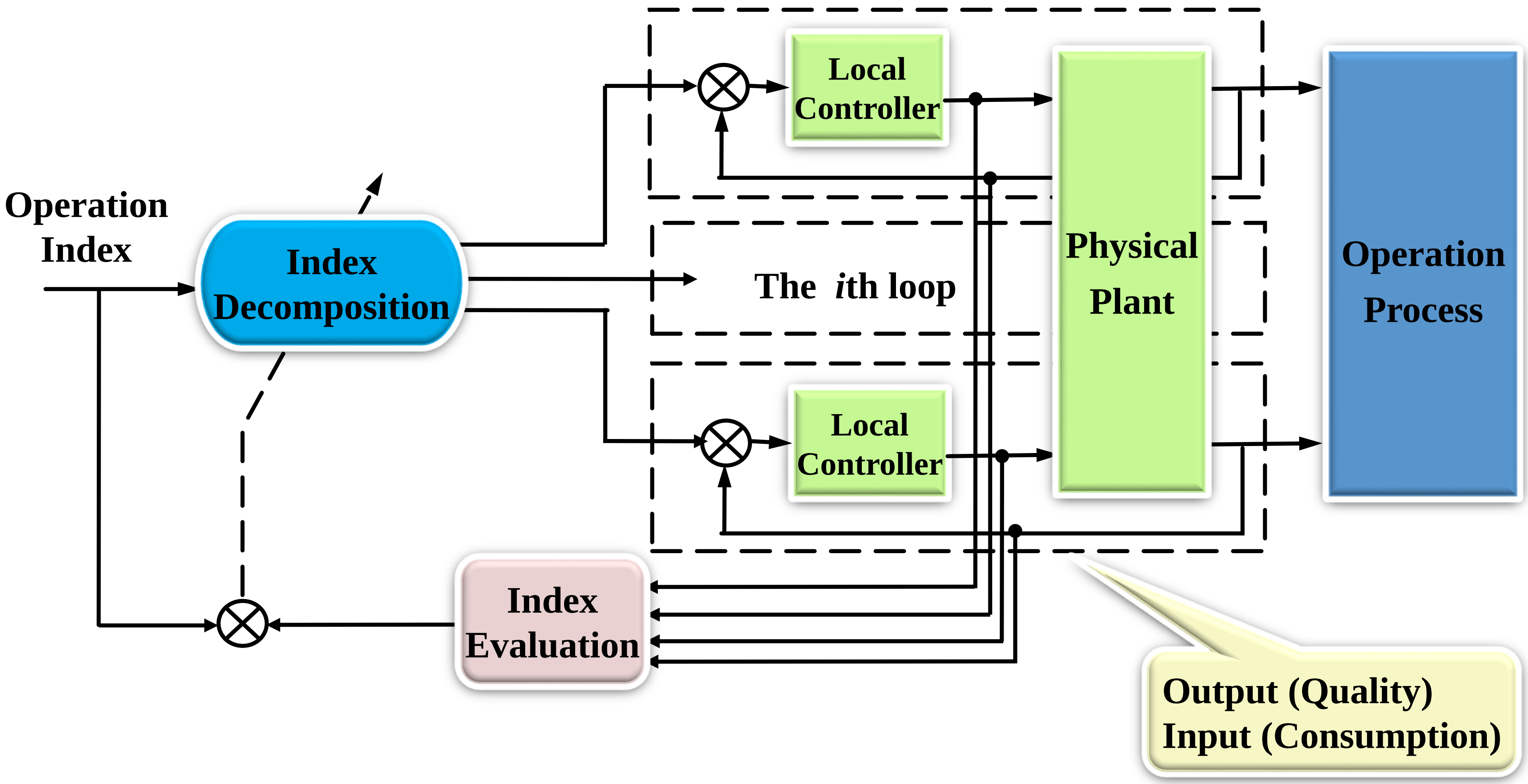


- Imprecise Artificial Decomposition
- Boundary Condition Changes
- Prevailing Outside Interference

Background

Stage II

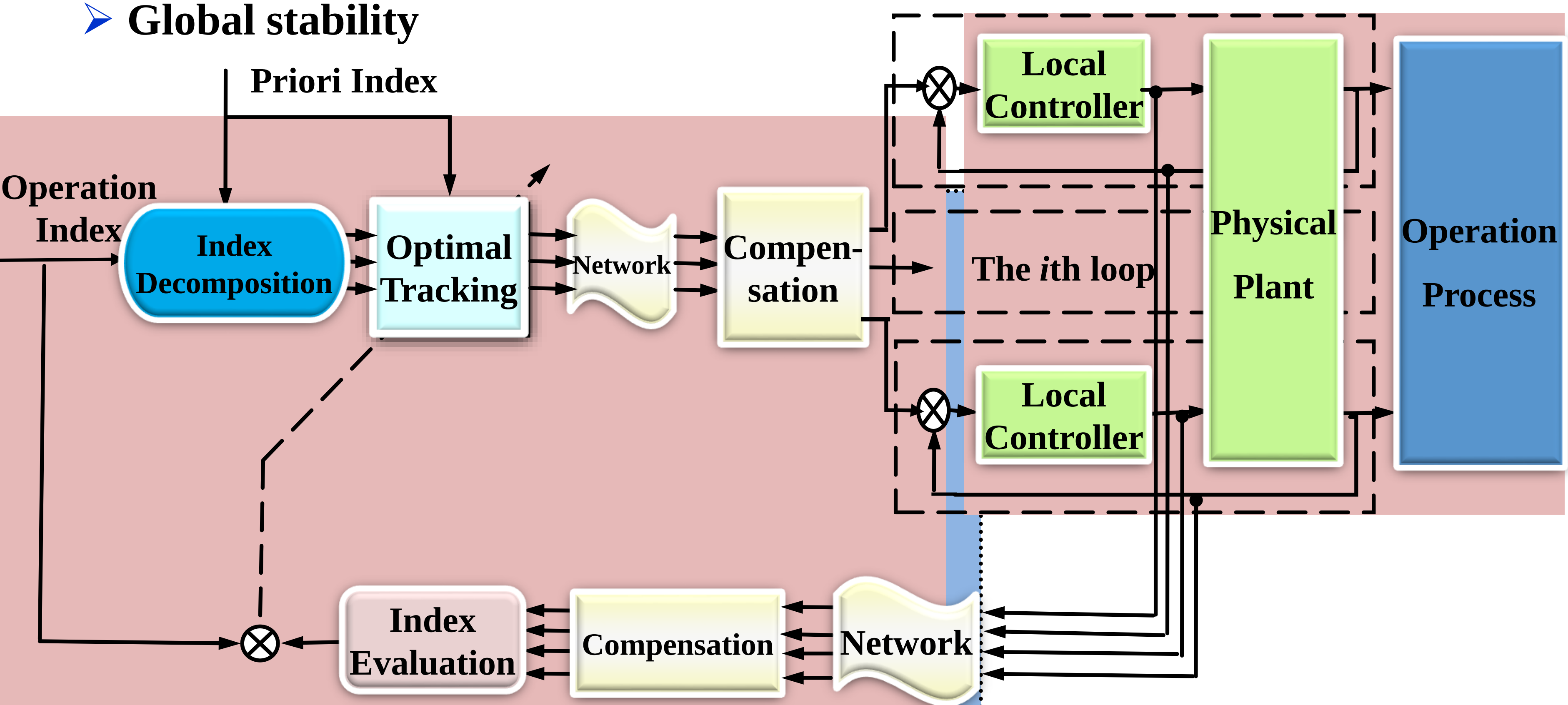
Integrated Operation Control



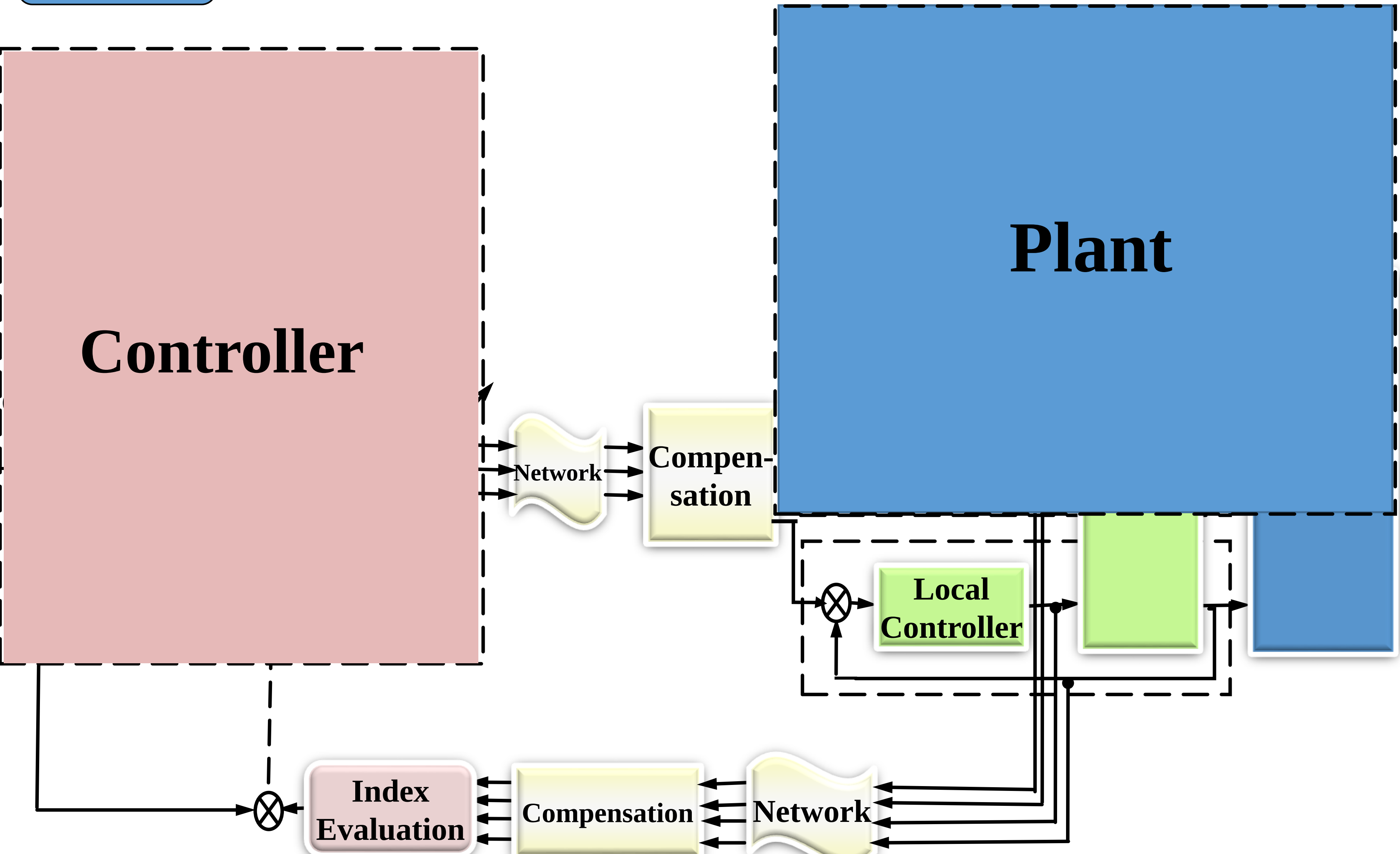
Stage III

Network-Based Integrated Operation Control

- Asynchronous networks
- Multirate sampling
- Data packet dropouts, time-delay & disorder
- Index evaluation
- Global stability



Stage III Network-Based Integrated Operation Control



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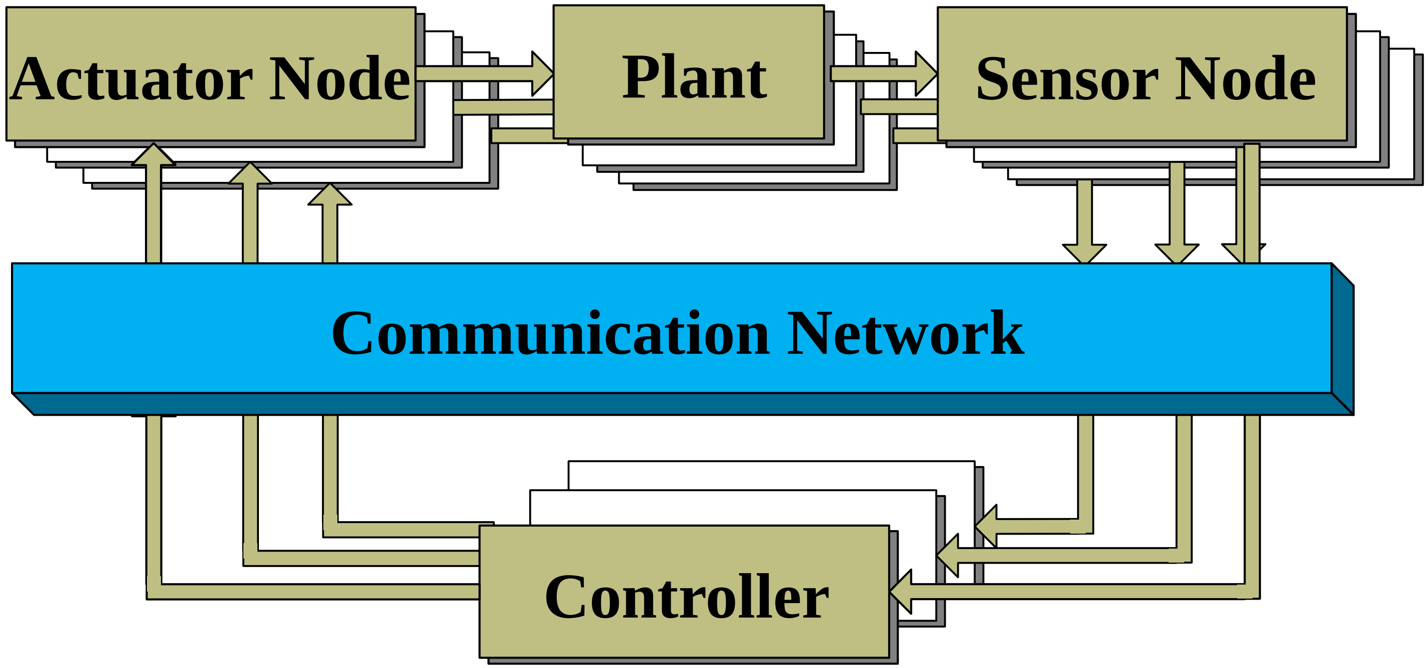
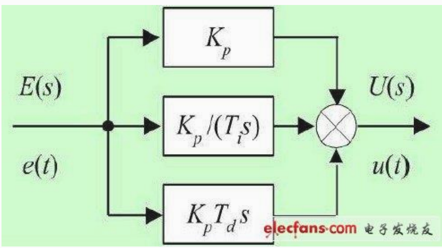
Traditional Control Systems

Networked Control Systems (NCSs)

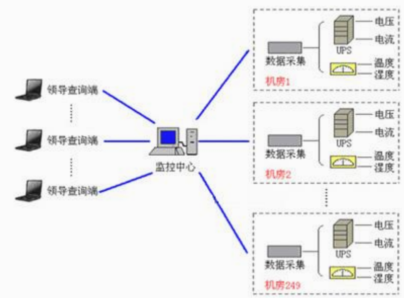


NCS Advantages	Resource sharing	Lower cost	Flexibility
	Independent node	Module design	… …

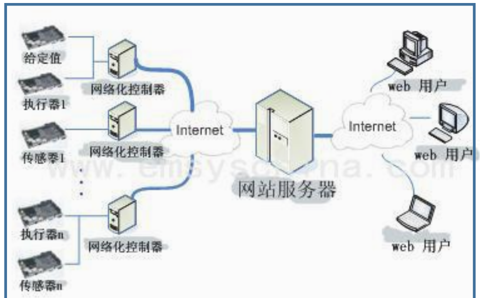
Control methods progress:



Centralized Control



Decentralized Control



Networked Control

Networked control is the significant revolution in industry processes after centralized control and decentralized control methods.

J. Baillieul, P. Antsaklis. *Proceedings of the IEEE*, 2007.

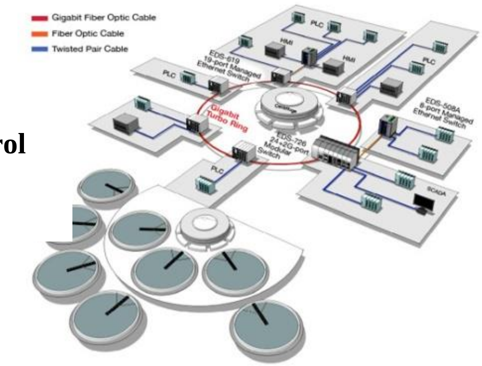
NCS applications:

➢ Automobile

Typically electronic control units are networked together on one or more buses based on the Controller Ares Network (CAN) standard.

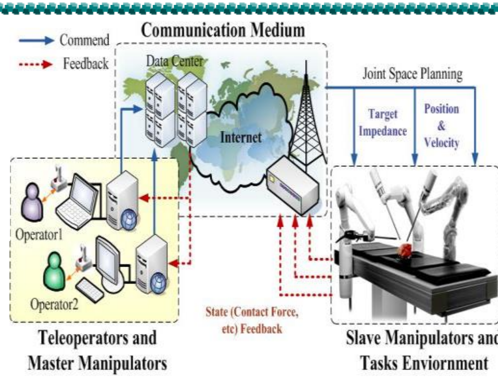
➢ Process Control

Industrial process control under networked environment



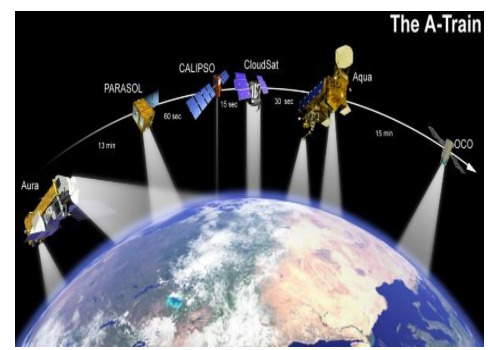
➢ Remote Operation

Remote operation based on network

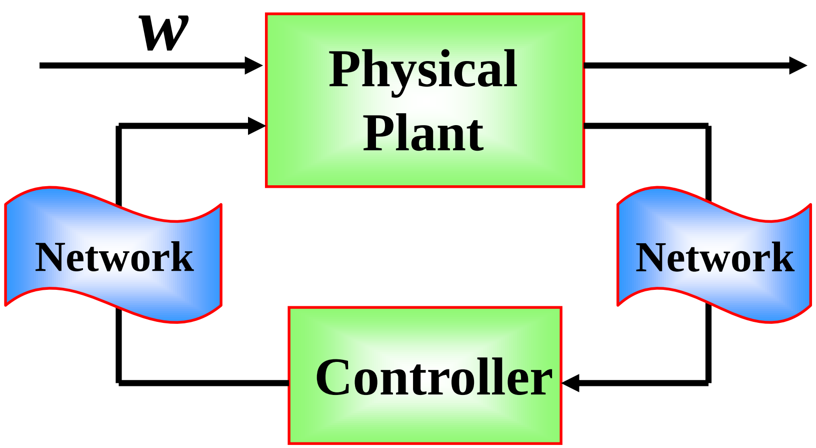


➢ Cooperative Formation

Cooperative formation for multi-agent systems based on network



Networked Control and Estimation



1. Time Delay
2. Packet Disorder
3. Packet Dropouts
4. Quantization
5. Network Security
6. Non-uniform Sampling

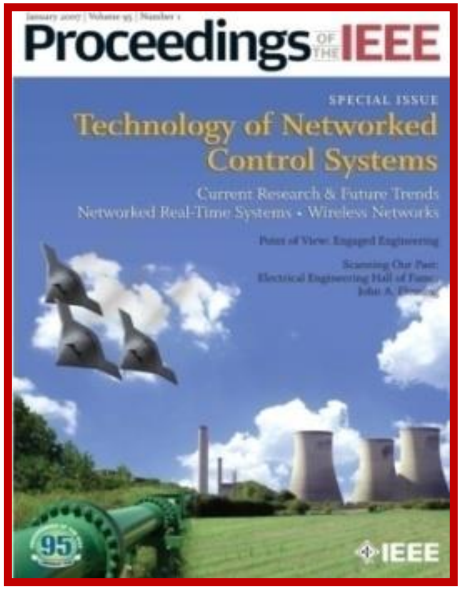
… …

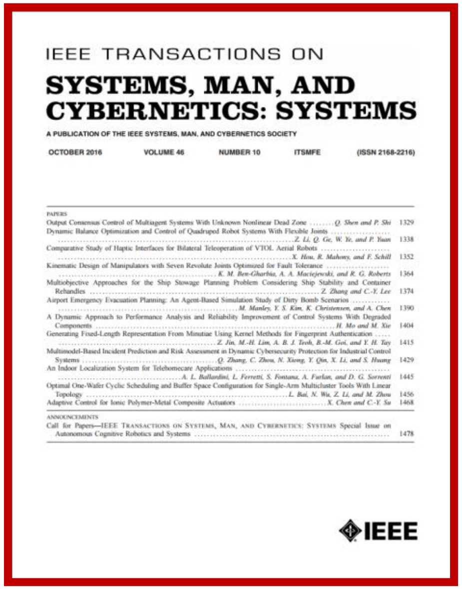
Nonlinear Physical Plants

Challenges to Classical Control Theory

Recent Special Issues:

- Proceedings of the IEEE
- IEEE Trans. System, Man, Cybernetics: Systems
- IEEE Trans. Automatic Control
- IEEE Trans. Industrial Electronics
- IEEE Control Systems Magazine
- ……

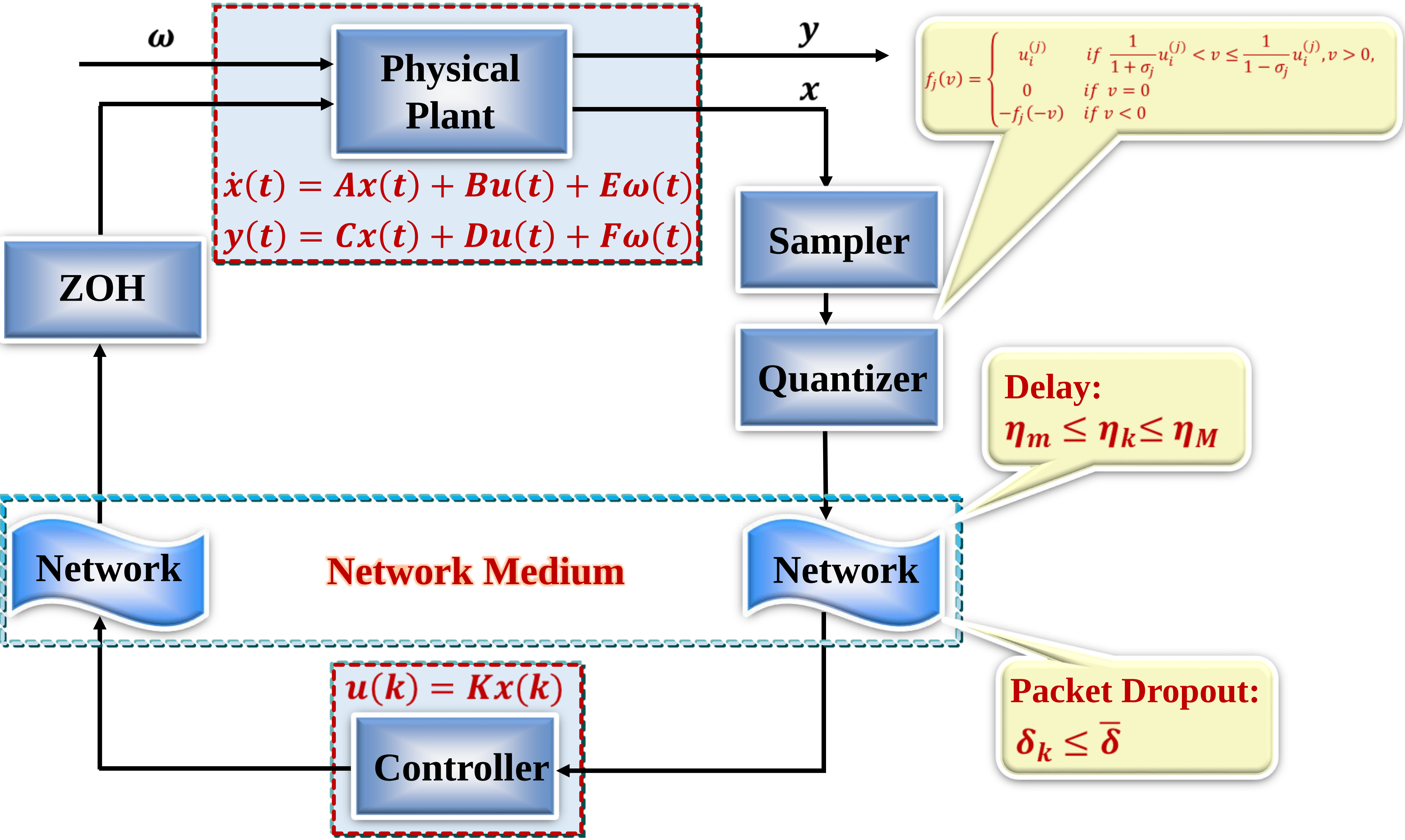




Problems

- ***Controller Design over Communication Networks***
- ***State Estimation over Communication Networks***

State Feedback Control Problem:



Network-based Control

Networked closed-loop system:

$$\dot{x}(t) = Ax(t) + BKf\big(x(t_k - \eta_k)\big) + E\omega(t)$$
$$y(t) = Cx(t) + DKf\big(x(t_k - \eta_k)\big) + F\omega(t)$$

Transformation

$$t_k - \eta_k = t - \eta_k - \eta(t)$$
$$\eta(t) = t - t_k + \eta_k - \eta_m$$

Closed-loop system with two successive delays:

$$\dot{x}(t) = Ax(t) + BKf\big(x(t - \eta_m - \eta(t))\big) + E\omega(t)$$
$$y(t) = Cx(t) + DKf\big(x(t - \eta_m - \eta(t))\big) + F\omega(t)$$

General model

$$\dot{x}(t) = Ax(t) + A_d x(t - d_1(t) - d_2(t))$$

PERFORMANCE FOR DIFFE

Prescribed $\mathcal{H}_\infty$ performance γ	0.2			0.3		
$\bar{a}$	0.1	0.13	0.4	0.1	0.21	0.4
Minimum β by Theorem 1	0.0346	0.0350	0.0392	0.0021	0.0028	0.0041
Minimum β by [17]	0.0705	infeasible	infeasible	0.0244	infeasible	infeasible

less conservative

CALCULATED DELAY BOUNDS FO

	Delay bound d_2 for given d_1			Delay bound d_1 for given d_2		
	$\bar{d}_1 = 1$	$\bar{d}_1 = 1.2$	$\bar{d}_1 = 1.5$	$\bar{d}_2 = 0.1$	$\bar{d}_2 = 0.2$	$\bar{d}_2 = 0.3$
Theorem 1	0.512	0.406	0.283	2.300	1.779	1.453
Lam et al. (2007)	0.415	0.376	0.248	2.263	1.696	1.324
Wu et al. (2004), Jing et al. (2004), Fridman and Shaked (2003)	0.180	0.080	Infeasible	1.080	0.980	0.880
Lee et al. (2001)	Infeasible	Infeasible	Infeasible	0.098	Infeasible	Infeasible
Kim (2001)	Infeasible	Infeasible	Infeasible	0.074	Infeasible	Infeasible

less conservative

Lyapunov-Krasovskii Functional

$$V(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t),$$

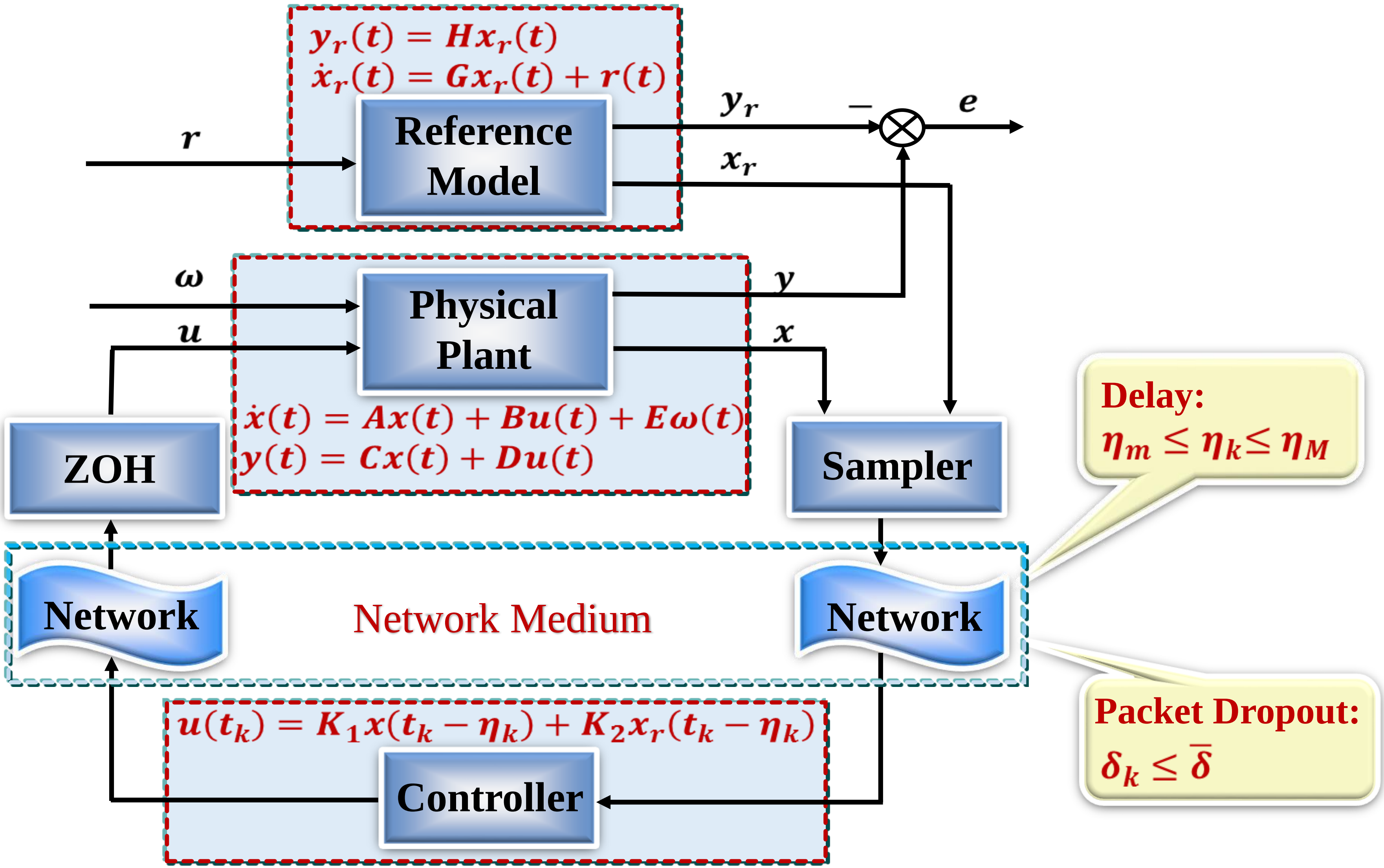
$$V_1(t) = x^{\mathrm{T}}(t)Px(t),$$

$$V_2(t) = \int_{t-d_1(t)}^{t} x^{\mathrm{T}}(s)Q_1x(s)\,\mathrm{d}s + \int_{t-d(t)}^{t-d_1(t)} x^{\mathrm{T}}(s)Q_2x(s)\,\mathrm{d}s,$$

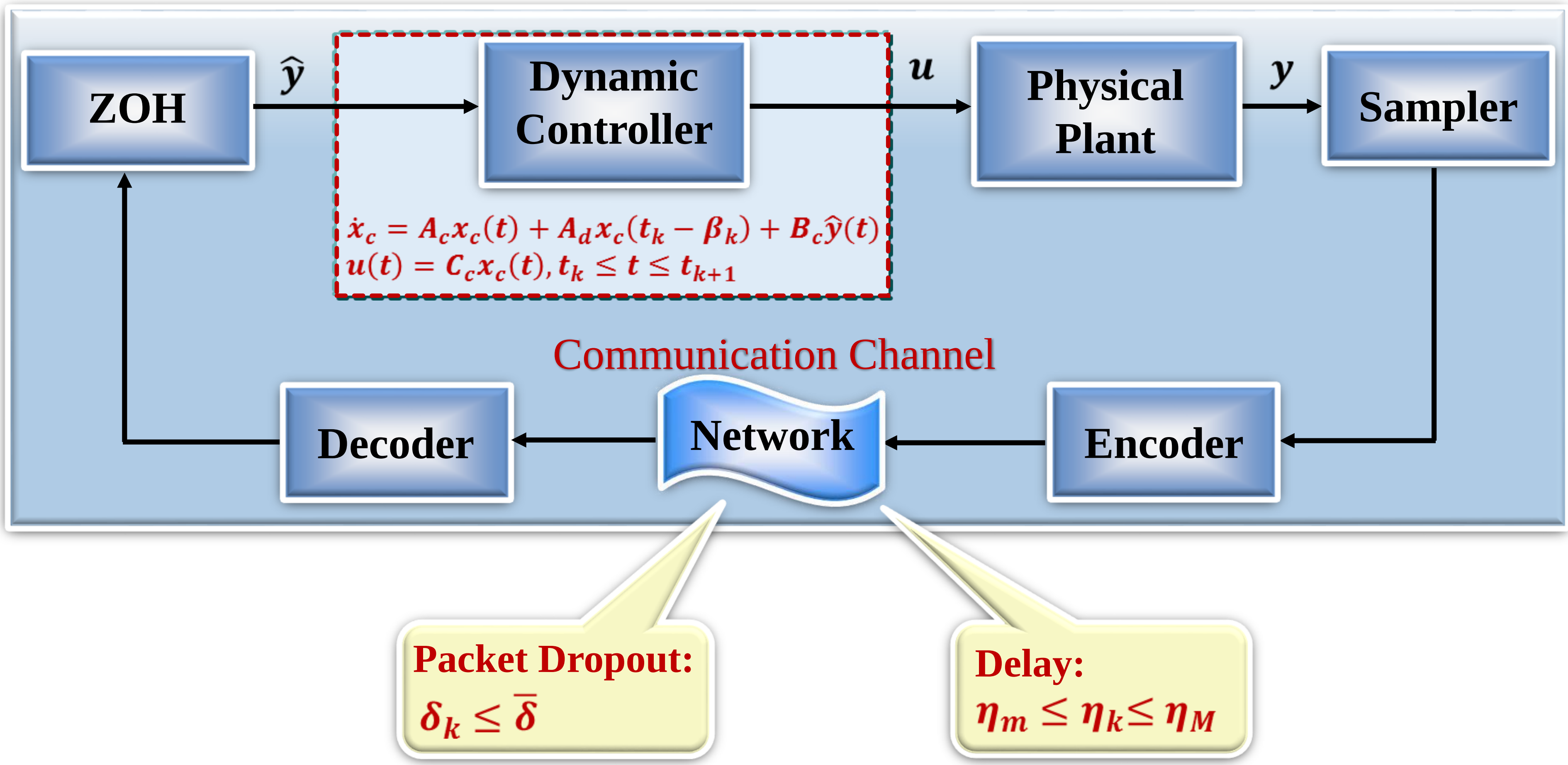
$$V_3(t) = \int_{t-\bar{d}}^{t} x^{\mathrm{T}}(s)Rx(s)\,\mathrm{d}s,$$

$$V_4(t) = \int_{-\bar{d}_1}^{0}\int_{\beta}^{0} \dot{x}^{\mathrm{T}}(t+\alpha)Z_1\dot{x}(t+\alpha)\,\mathrm{d}\alpha\,\mathrm{d}\beta + \int_{-\bar{d}}^{-\bar{d}_1}\int_{\beta}^{0} \dot{x}^{\mathrm{T}}(t+\alpha)Z_2\dot{x}(t+\alpha)\,\mathrm{d}\alpha\,\mathrm{d}\beta + \int_{-\bar{d}}^{0}\int_{\beta}^{0} \dot{x}^{\mathrm{T}}(t+\alpha)M\dot{x}(t+\alpha)\,\mathrm{d}\alpha\,\mathrm{d}\beta,$$

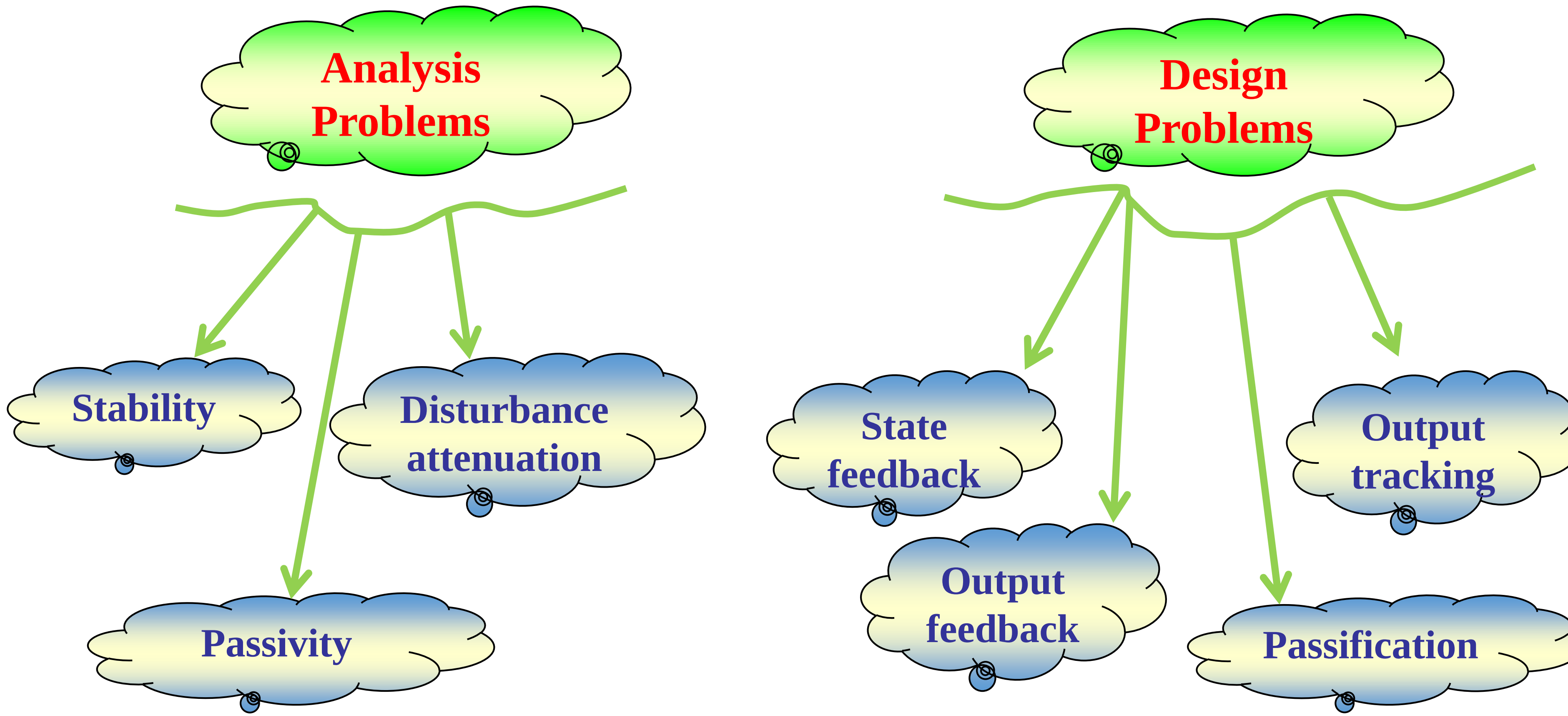
Output Tracking Problem:



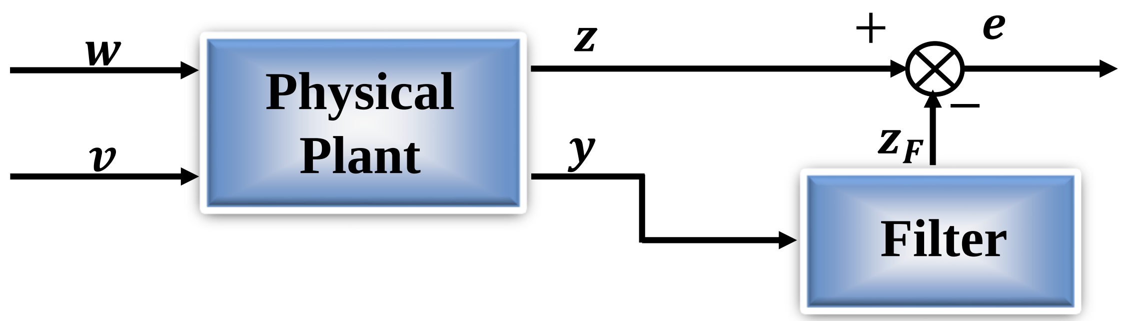
Output Feedback Control Problem:



Problems solved in this framework:



Traditional filter design



Filtering design problems:

Kalman Filtering

- Most commonly used optimal recursive data processing algorithm

Robust Filtering

- Without knowing the exact statistics knowledge of noise/disturbance
- Parameter uncertainty

Adaptive Filtering

- Suitable for parameter/ structure adjustable filter design problem

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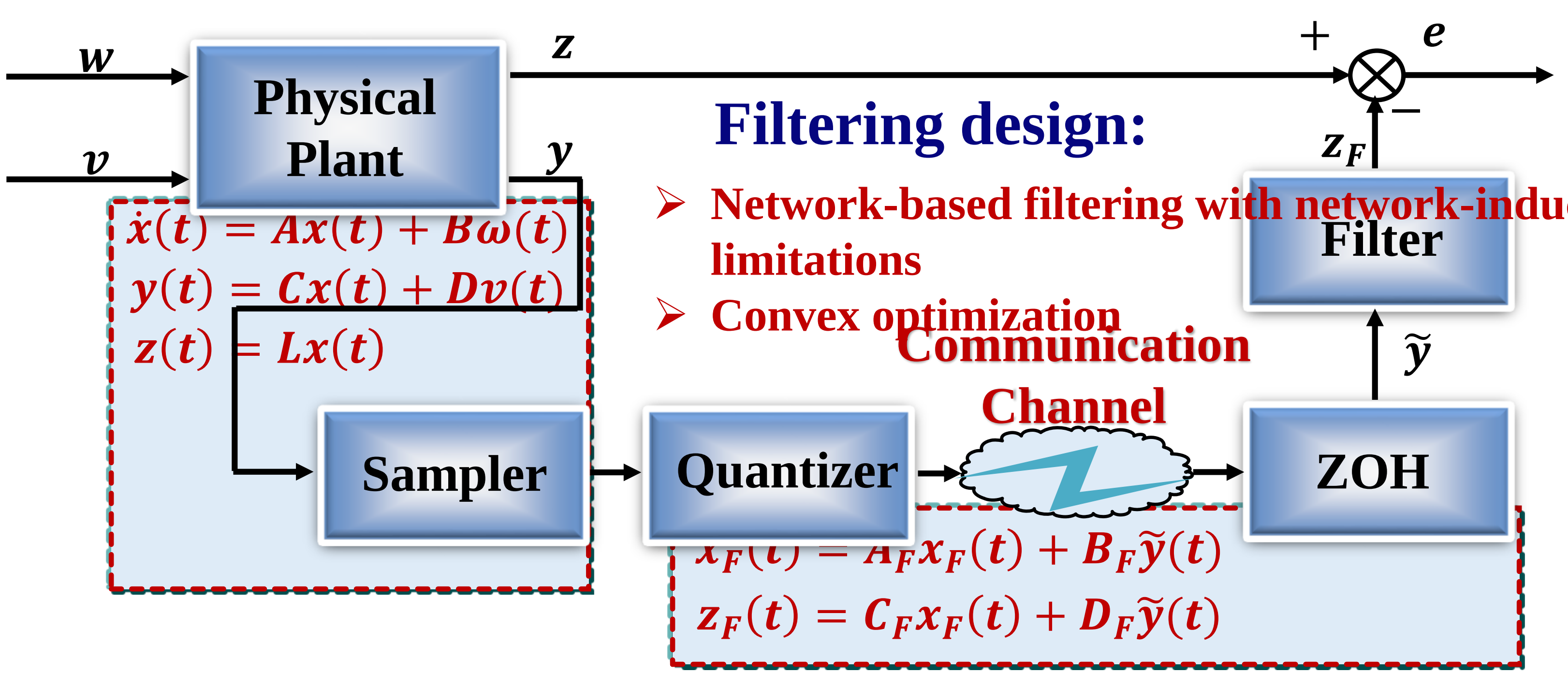
Network-based filter design

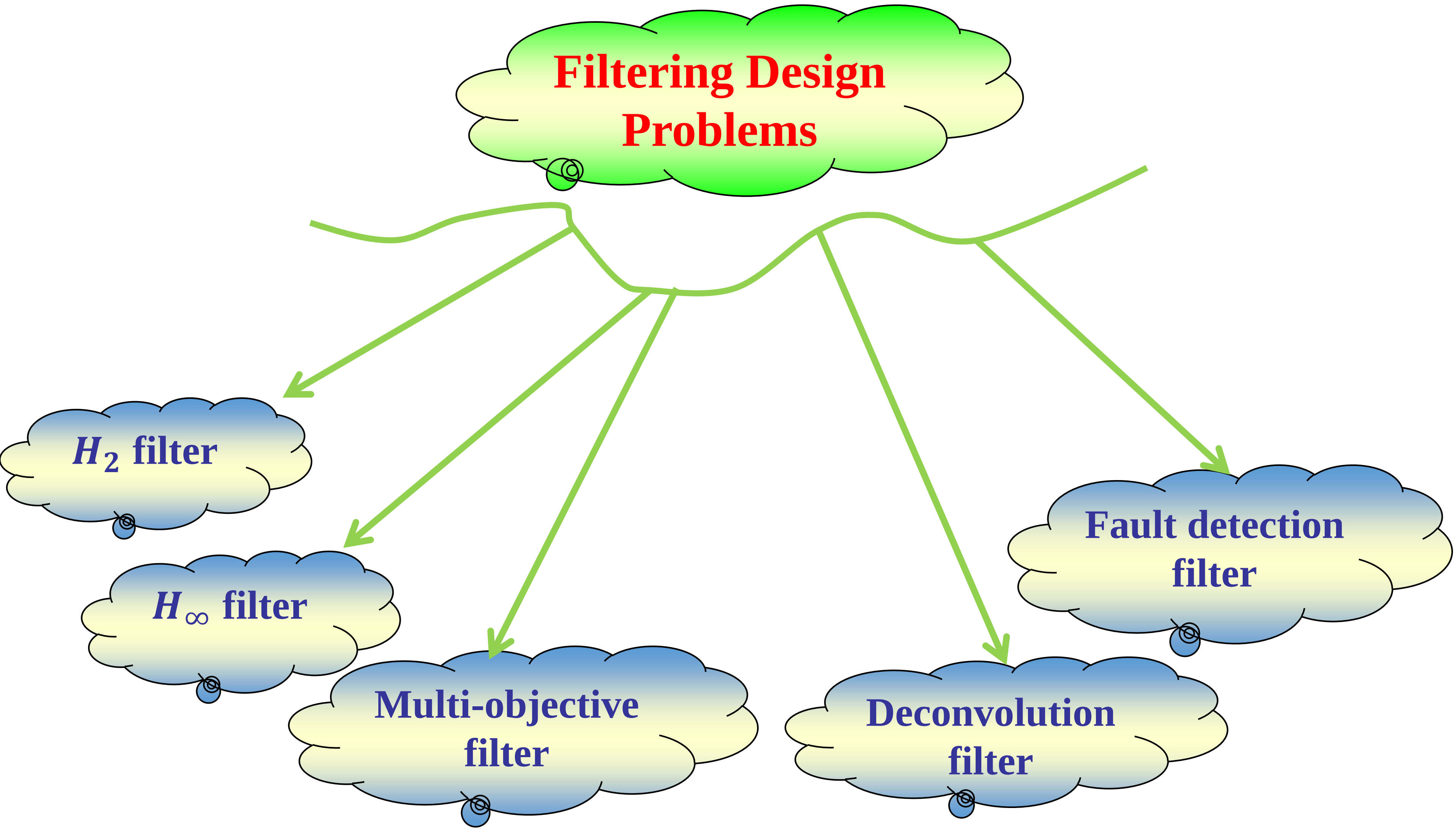
Filtering design:

- Network-based filtering with network-induced limitations
- Convex optimization



Network-based Estimation

Problems solved in this framework:



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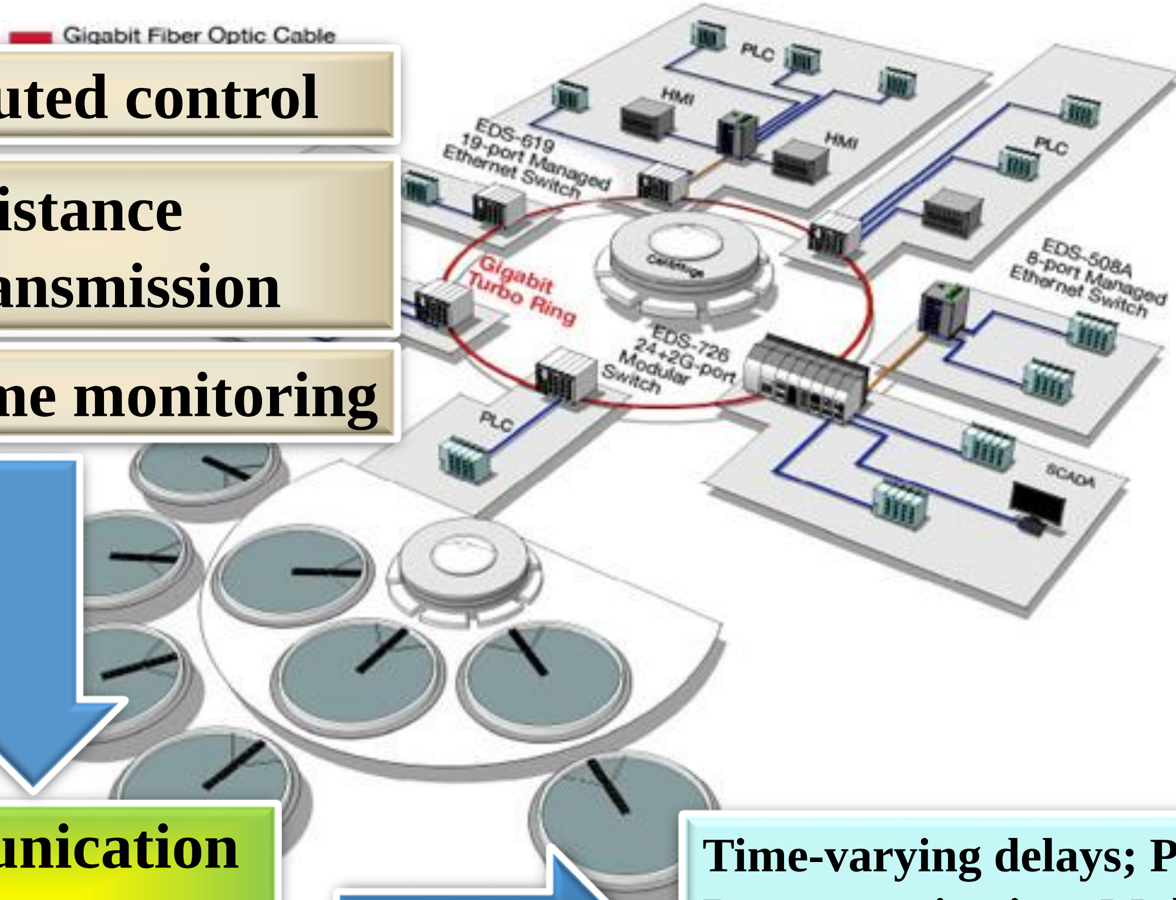
Networked Process Control

Networked Industrial Processes



Distributed control

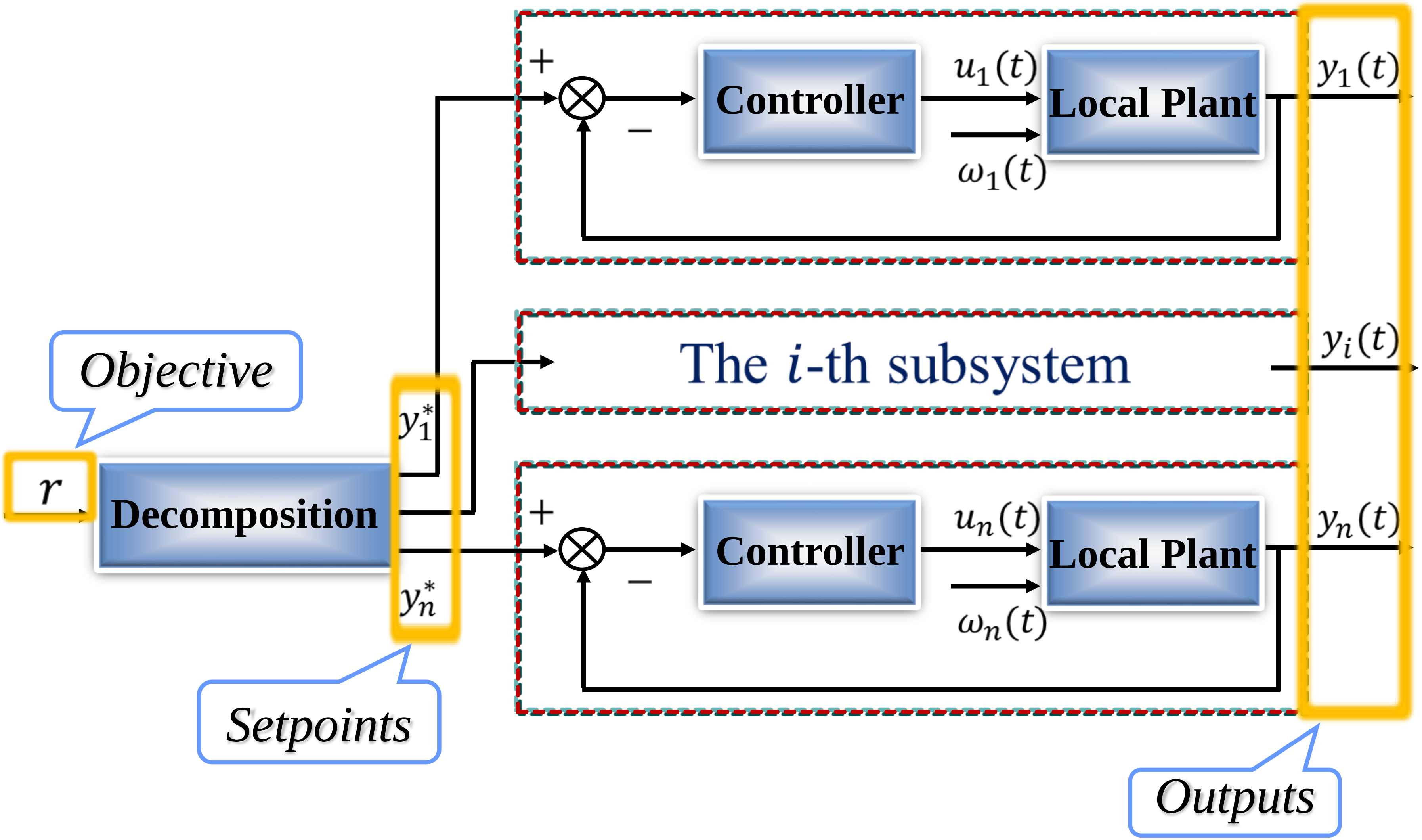
Long-distance data transmission

Real time monitoring

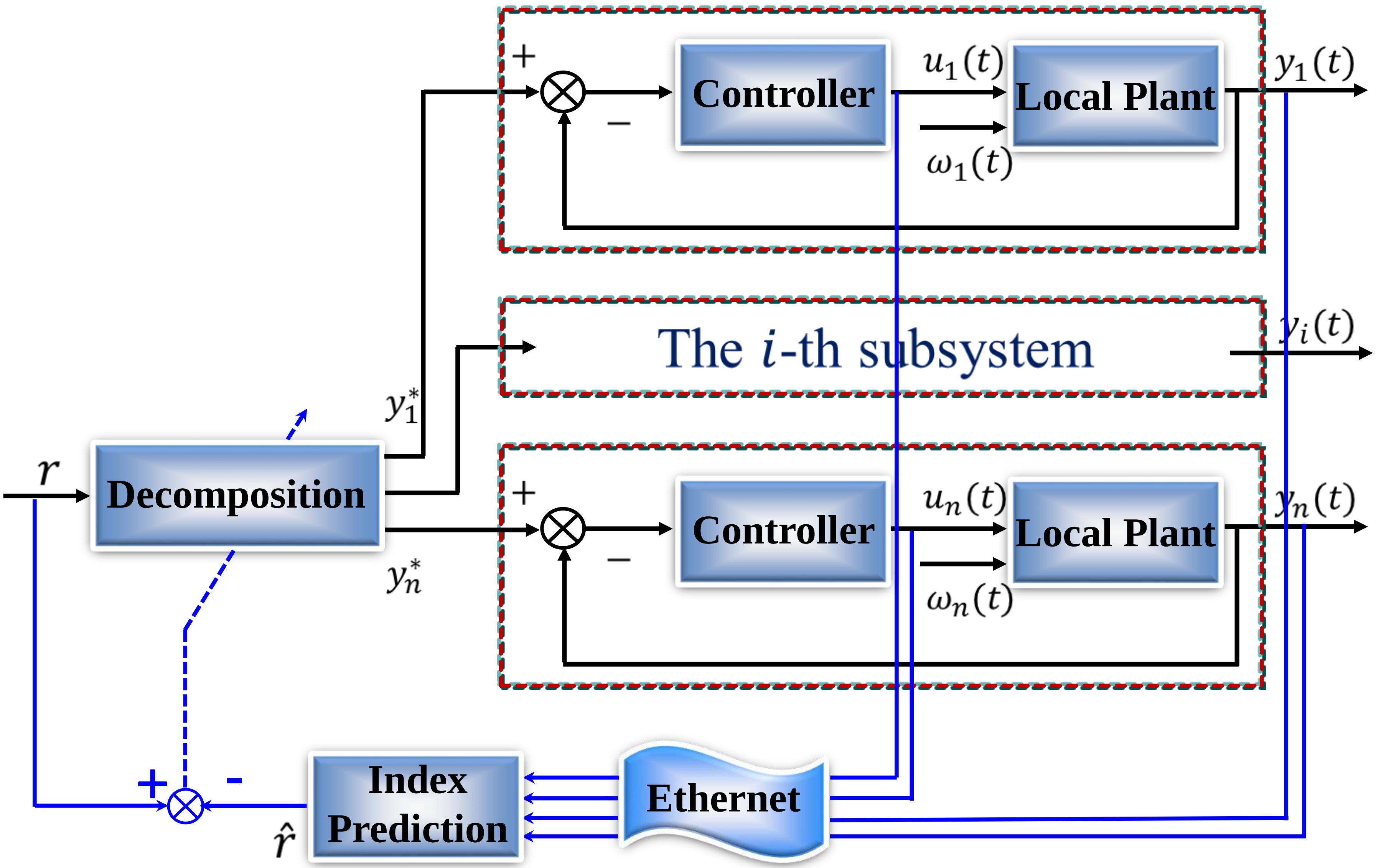
Communication via Industrial Ethernet

Time-varying delays; Packet dropouts; Data quantization; Multirate sampling; Network safety; Asynchronous communication etc.

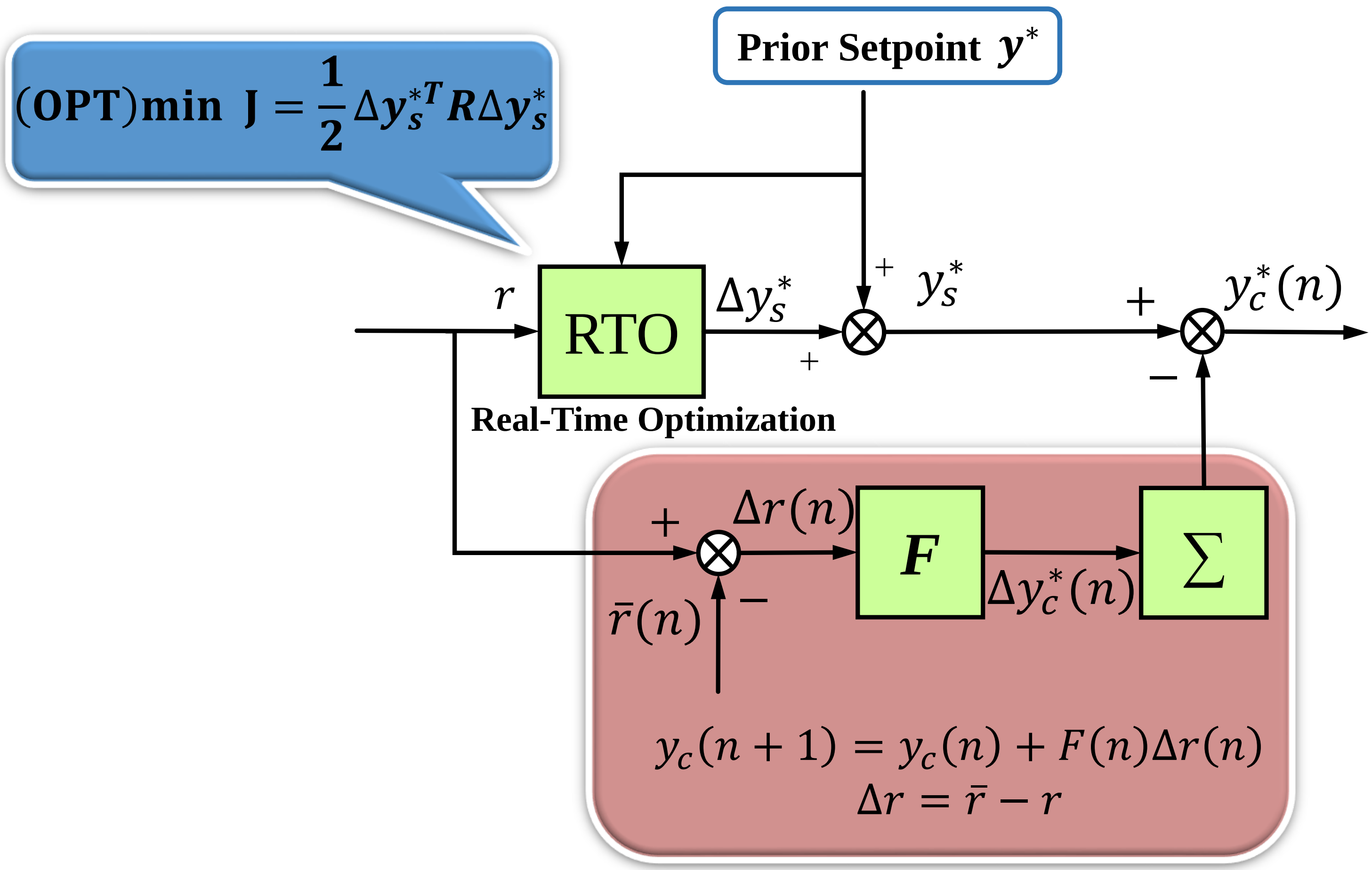
Conventional Control Scheme



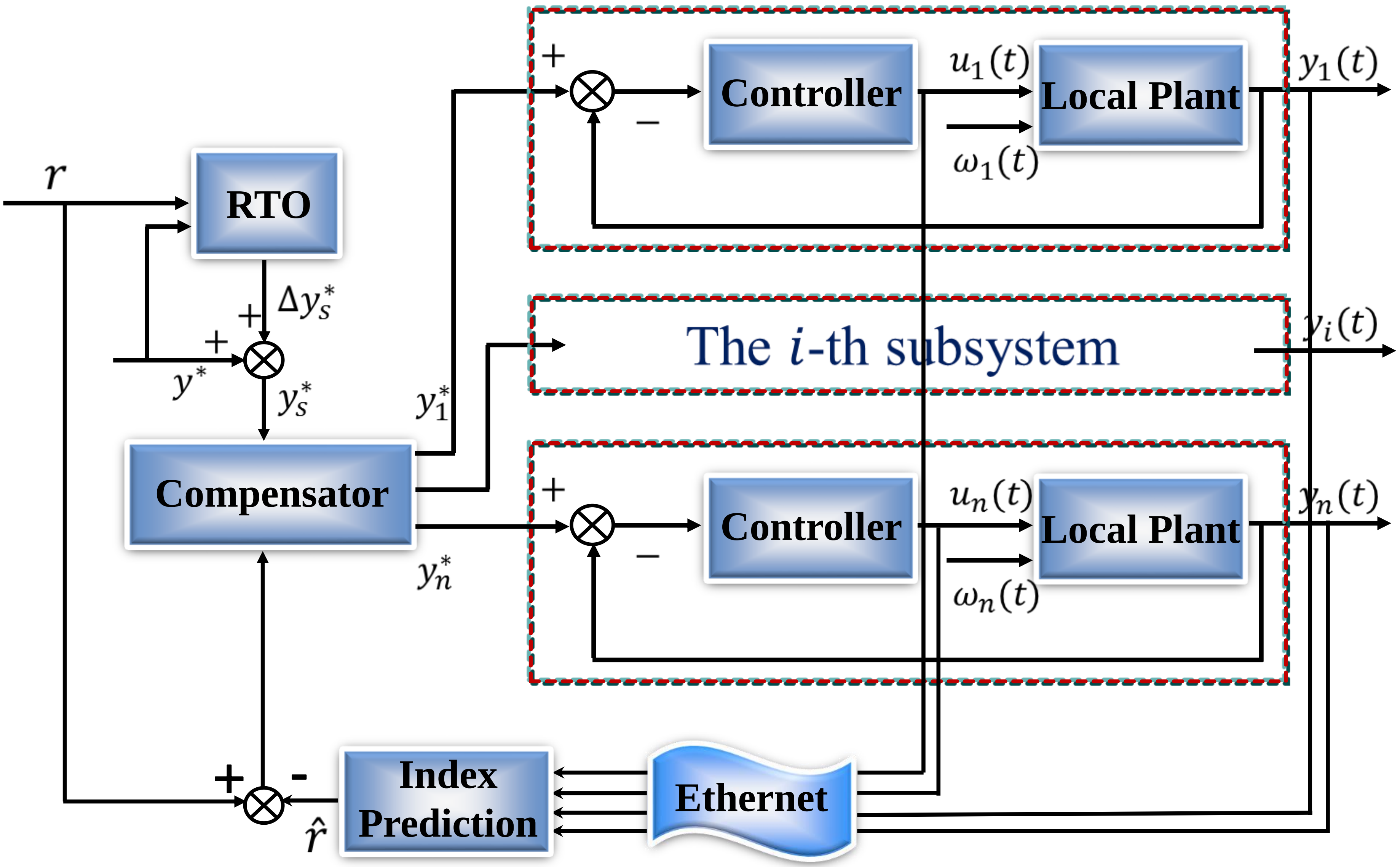
Network-Based Integrated Control Scheme



Networked Process Control



Multi-subsystems Case



Key Issues

Networked Integrated Control Scheme

Device Layer
- Linear subsystems
- Nonlinear subsystems
- Actuator/sensor faults

Communication Channel
- Asynchronous networks
- Multi-rate sampling
- Network-induced phenomena

Operation Layer
- Linear index decomposition
- Nonlinear index decomposition
- Index optimization

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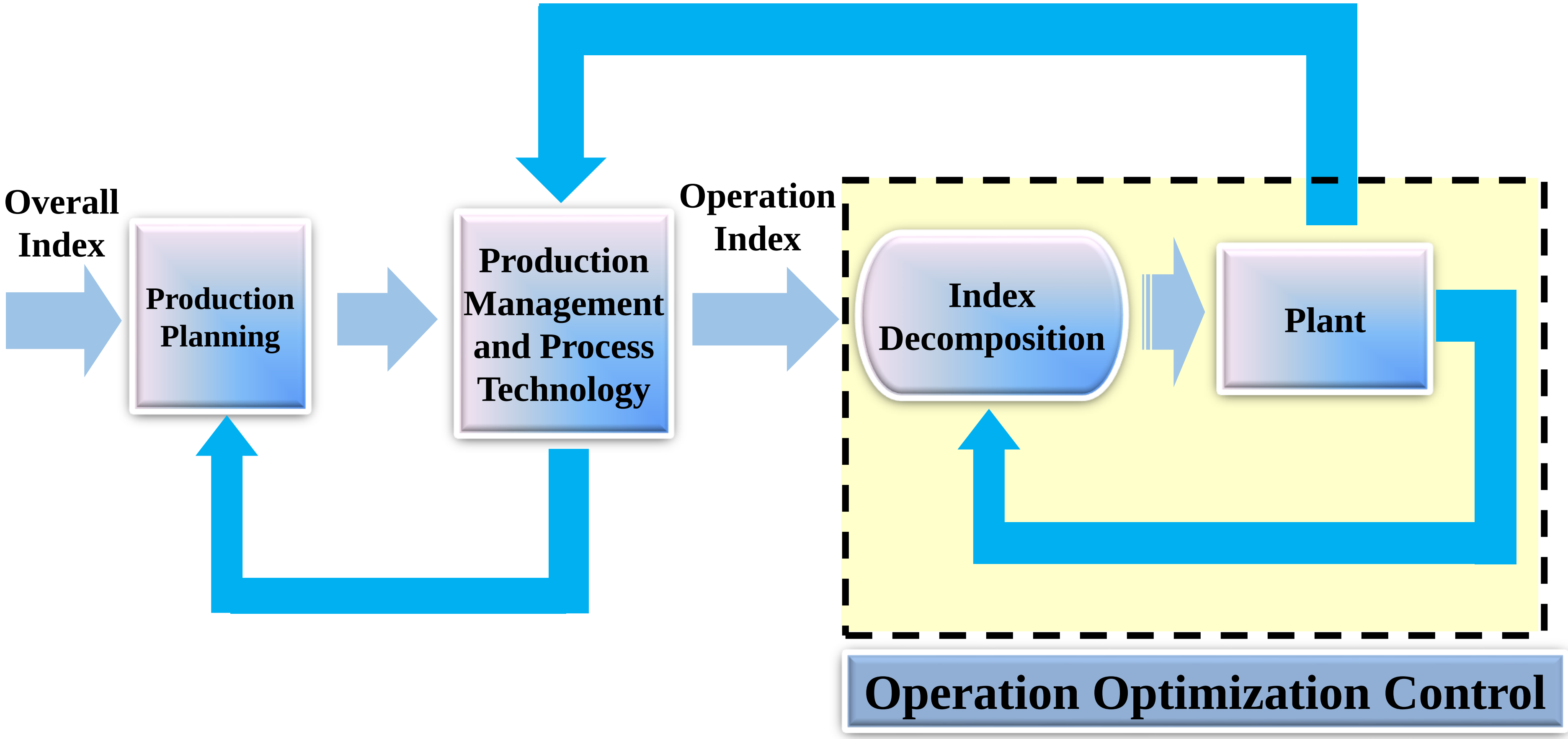
Future Work



- Multiple network issues
- Network security for industrial control systems
- Three layers: management, operation and device layers

THANKS