SHANGHAI JIAO TONG UNIVERSITY

2024 TCCT 逻辑系统控制专题大会

状态相关衰落信道下异构工业物联网系统的最优控制

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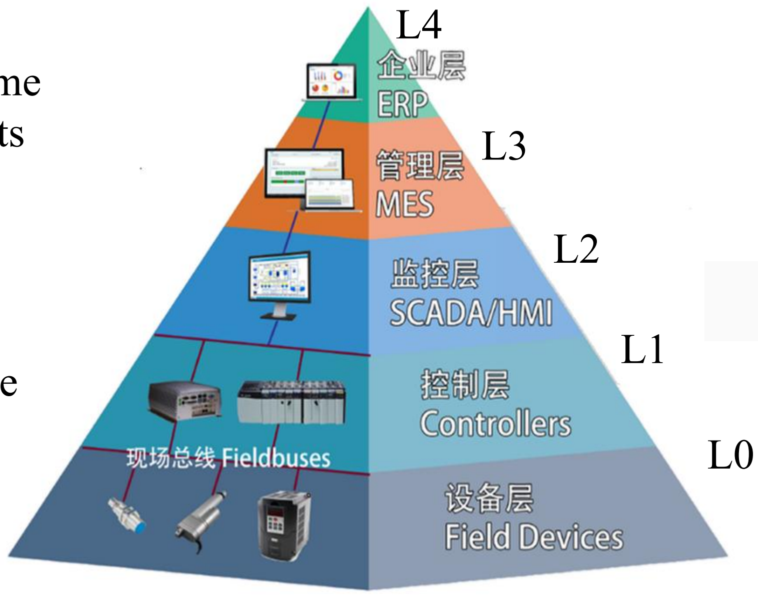
Introduction

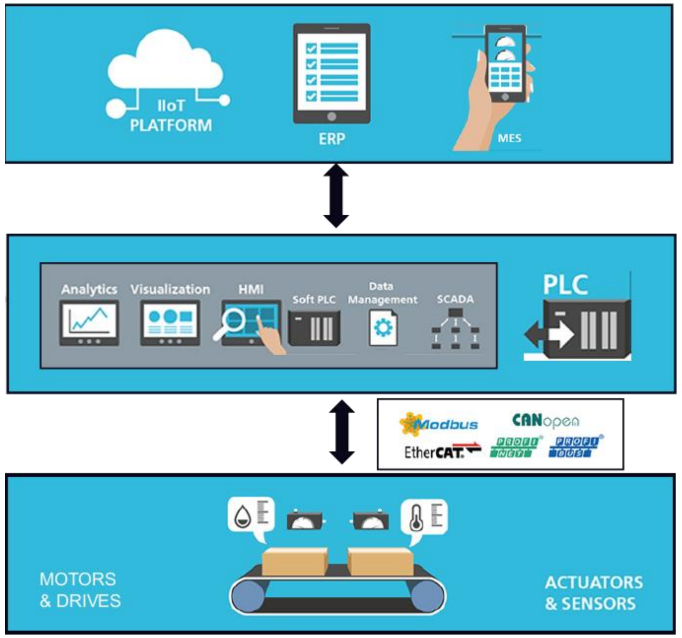
Industrial automation is entering a new era of the Industrial Internet.

Low Real-Time Requirements

High Real-Time Requirements



ISA-95 reference architecture



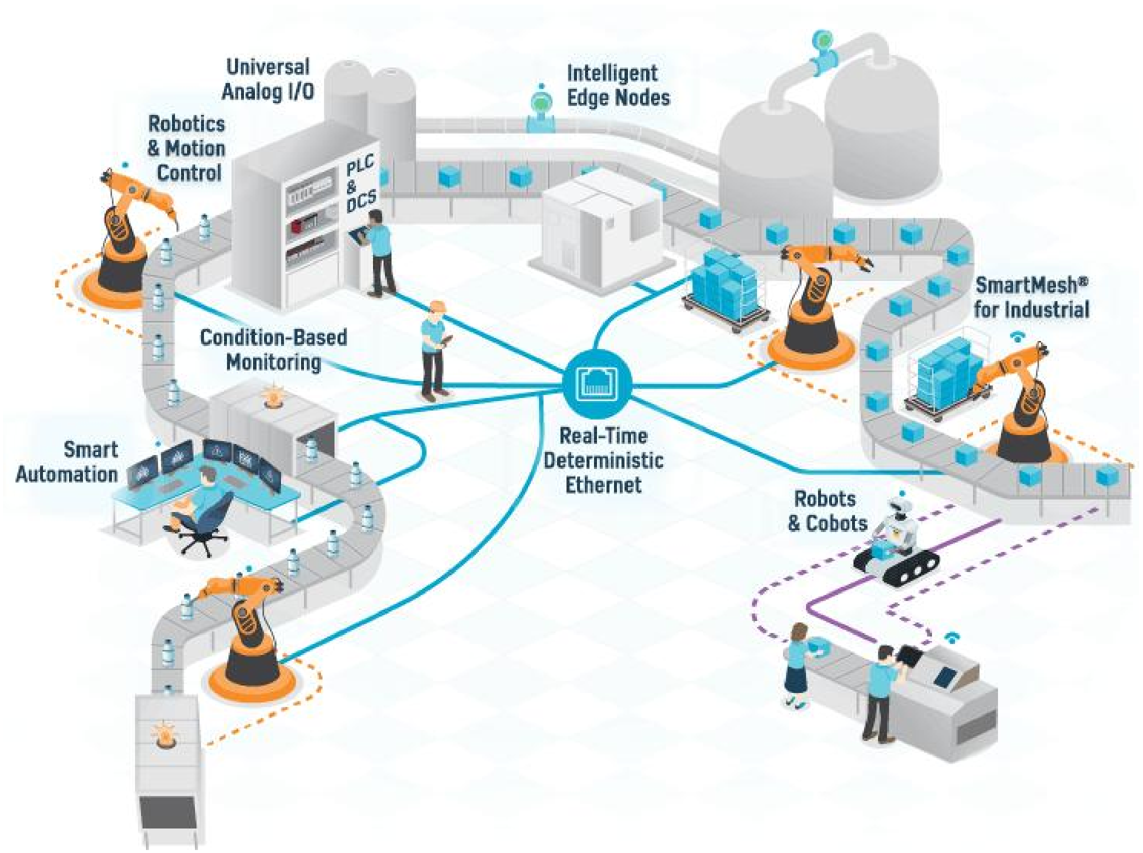
End-Edge-Cloud orchestrated architecture

Enhanced computing, communication, and storage capabilities.

The paradigm of automation systems is shifting from the ISA-95 pyramid to the end-edge-cloud orchestrated architecture.

*Dai, Nishi, Vyatkin, Huang, Shi and Guan, *IEEE Industrial Electronics Magazine*, 2019.

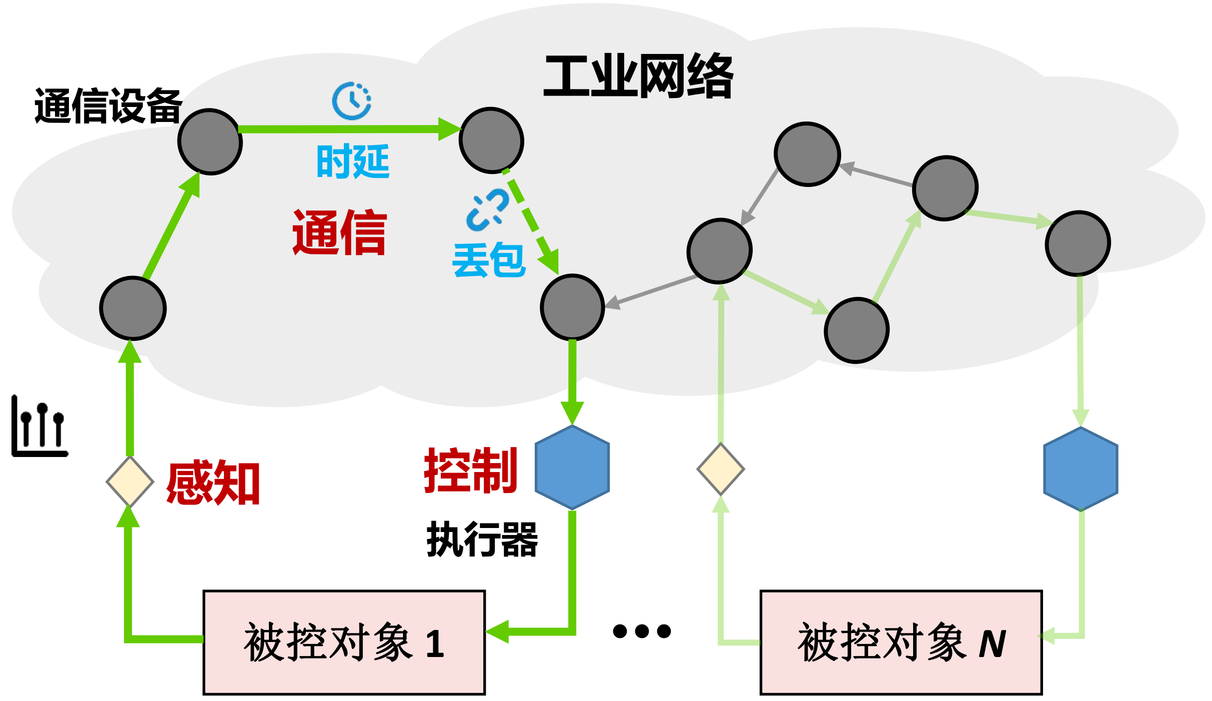
☐ An example



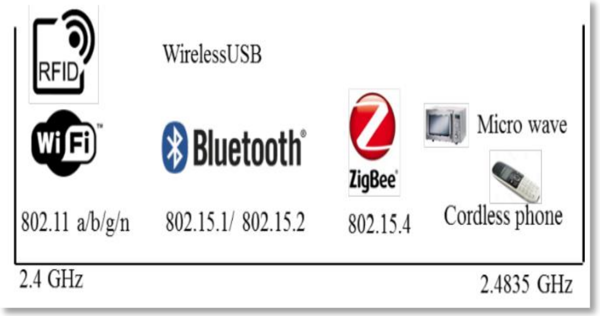
- Facilitate agile connectivity, real-time control, and data optimization
- Enable intelligent applications at both the cloud and field levels
- Ensure tight security, and protect privacy
- Optimized use of sensing, communication, computation, and storage resources

Motivation

□端到端QoS依赖于感知-通信-控制全链路



设备密集



频谱有限

电磁干扰

□感、传、控紧密关联，需要**联合设计**提升系统整体性能

工业现场环境复杂多变、网络资源有限

感知与控制联合设计

□ 物理过程

控制输入

$$\mathbf{x}(t+1) = A_t\mathbf{x}(t) + B_t\mathbf{u}(t) + \mathbf{w}(t)$$

$$\mathbf{y}_i(t) = G_{i,t}[C_{i,t}\mathbf{x}(t) + \mathbf{v}_i(t)], i = 1, 2, \ldots, n$$ ← 传感器数量

$\boldsymbol{x} \in R^p$, $\boldsymbol{y} = [\boldsymbol{y}_1^T, \ldots, \boldsymbol{y}_n^T]^T \in R^l$

感知矩阵：取值为 I 或 O, $G_{i,t} = I$ 表示t时刻选择第i个传感器进行测量

□ 感知的充分度：可观性（状态估计的必要条件）

系统在$[1, T]$上可观当且仅当 $\begin{bmatrix} G_1C_1 \\ G_2C_2A_1 \\ \vdots \\ G_TC_T\Pi_{t=1}^{T-1}A_t \end{bmatrix}$ 列满秩

$$G_t = \begin{bmatrix} G_{1,t} & & \\ & \ddots & \\ & & G_{n,t} \end{bmatrix}, \quad C_t = \begin{bmatrix} C_{1,t} \\ \vdots \\ C_{n,t} \end{bmatrix}$$

Z. Ji, C. Chen, J. He, S. Zhu, X. Guan, *IEEE Trans. Cybernetics,* vol. 52, no. 12, 2022; *IEEE Trans. Autom. Sci. Eng*., vol.20, no.1, 2023;
Z. Ji, C. Chen, S. Zhu, Y. Ma, X. Guan, *IEEE Trans. Signal Inf. Process. Netw.*, vol.9, 2023

□ Kalman 滤波器

$$\hat{\mathbf{x}}_{t+1|t} = A_t \hat{\mathbf{x}}_{t|t} + B_t \mathbf{u}(t)$$

$$\hat{\mathbf{x}}_{t+1|t+1} = \hat{\mathbf{x}}_{t+1|t} + \gamma_t K_t [\mathbf{y}_{t+1} - G_{t+1} C_{t+1} \hat{\mathbf{x}}_{t+1|t}]$$

K_t是Kalman增益，

$\gamma_k = 0$ 或 1

□ 可观性约束的感知-控制联合设计

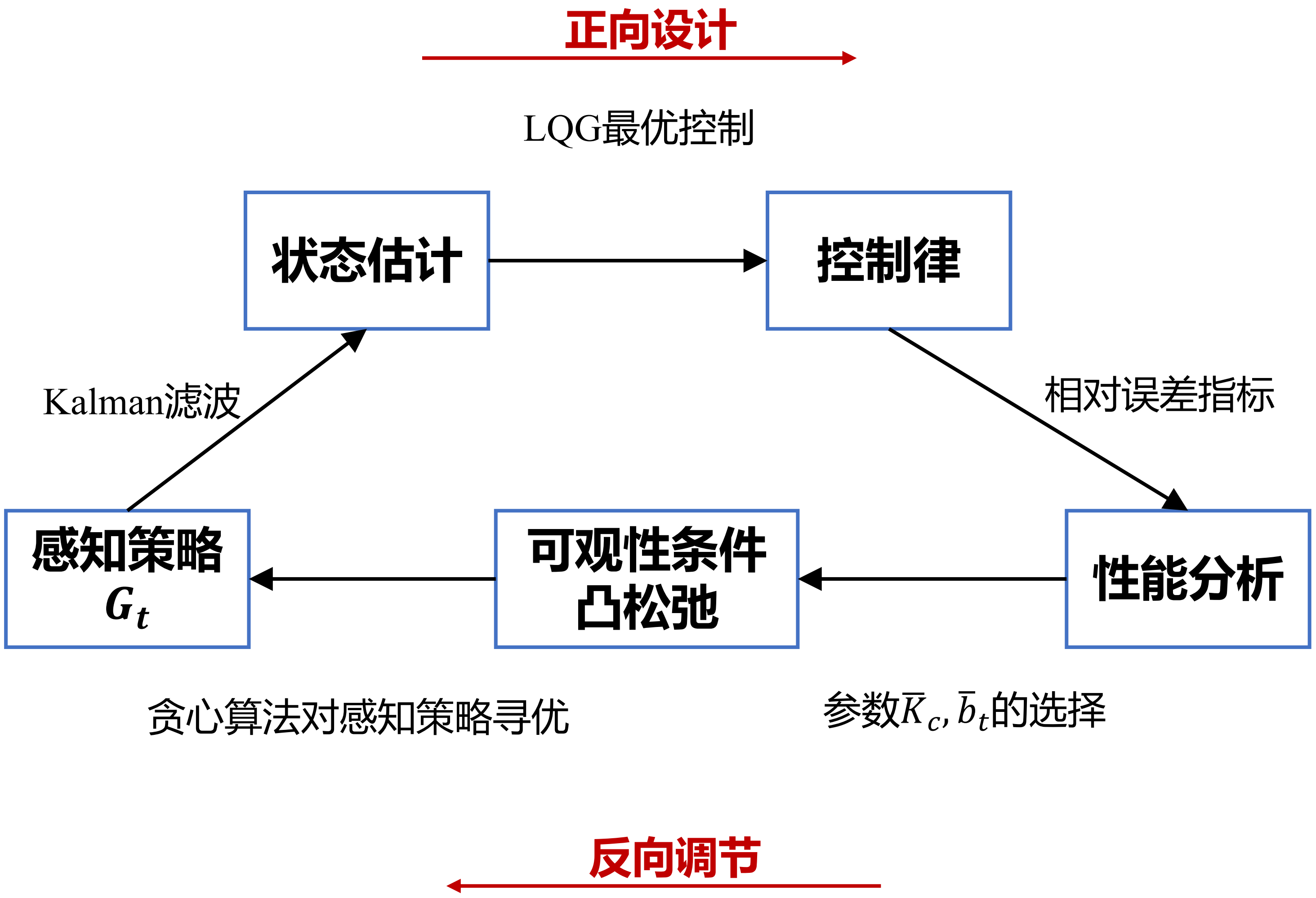
$$\min_{\mathcal{X}=\{\mathbf{u}(t),G_t\}} \quad f(\mathcal{X}) = \sum_{t=1}^{T} \mathbb{E}\left[\left|\left|\mathbf{x}(t+1) - \mathbf{z}(t+1)\right|\right|_{Q_t}^2 + \left|\left|\mathbf{u}(t)\right|\right|_{R_t}^2 \right]$$

s.t. 系统动态

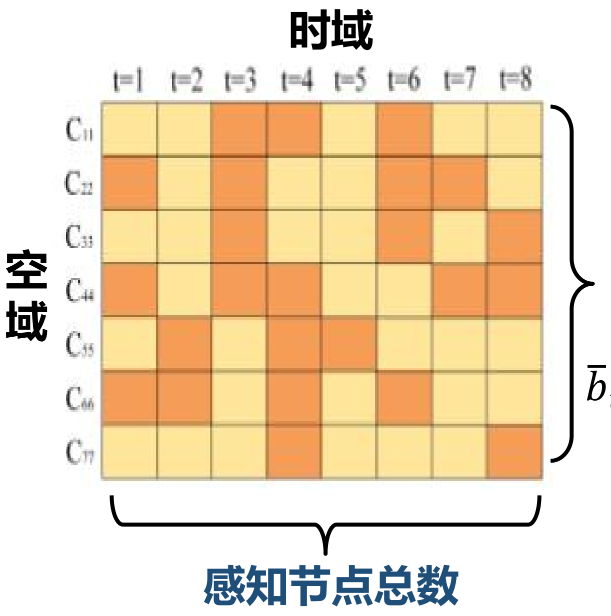
Kalman滤波器

$G_t \in \mathcal{C}$ (可观性条件)

□ 正向设计+反向调节



可观性条件凸松弛



各时刻感知节点最大个数

$$\bar{b}_t \geq \max_{t=1,\dots,T}(rank(G_t))$$

$$\bar{K}_c = \sum_{t=1}^{T} rank(G_t)$$

□ 正向设计：给定感知策略G_t下的LQG控制

$$\min_{\mathcal{X}=\{\mathbf{u}(t)\}} \quad f(\mathcal{X}) = \sum_{t=1}^{T} \mathbb{E}\left[\|\mathbf{x}(t+1)-\mathbf{z}(t+1)\|_{Q_t}^{2} + \|\mathbf{u}(t)\|_{R_t}^{2}\right]$$

s.t. 系统动态

Kalman滤波器

- **最优控制策略$\mathbf{u}(t) = \boldsymbol{K}_t[\boldsymbol{A}_t\hat{\mathbf{x}}_{t|t} - \mathbf{z}(t+1)\,]$**

□ 反向调节：贪心法对感知策略寻优

$$\min_{\mathcal{X}=\{G_t\}} \quad f(\mathcal{X}) \qquad \text{s.t.} \quad G_t \in \mathcal{C}$$

$$\Rightarrow$$

$$\min_{\mathcal{X}=\{G_t\}} \quad \sum_{t=1}^{T} tr[\Upsilon_{\mathrm{k}}\Gamma_{k|k}(\mathcal{S} \cup G_{i,t})] \qquad \text{s.t.} \quad rank(G_{i,t}) \le \bar{b}_t$$

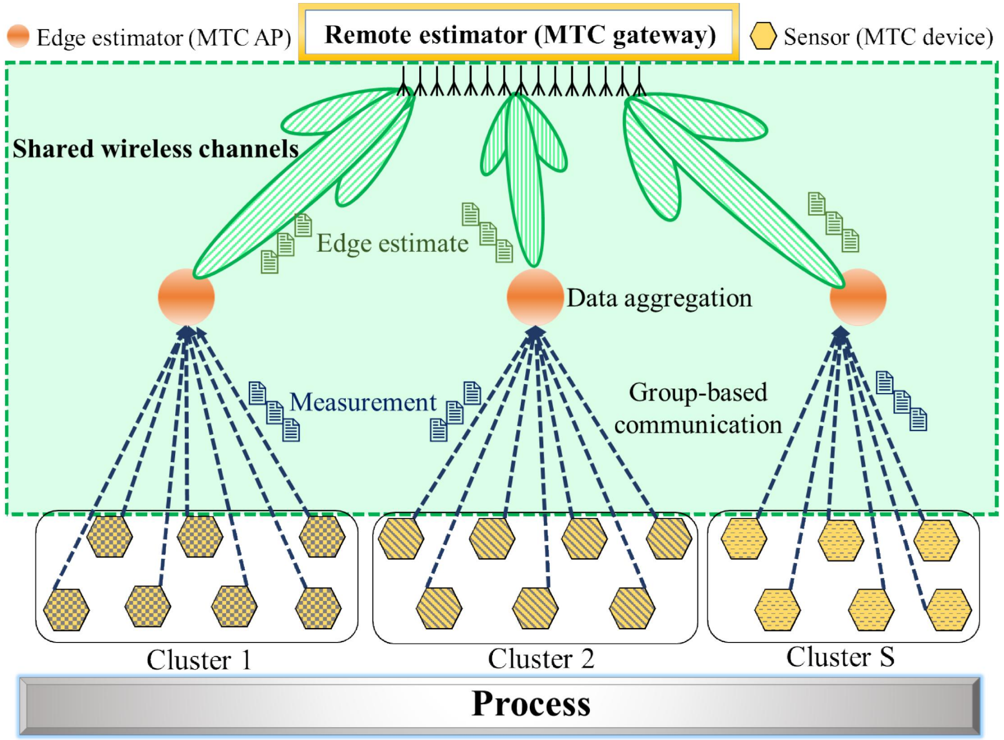
- **相对性能指标**

$$\boxed{\frac{f - f^*}{f_o - f^*} \leqslant e^{-\theta}, \qquad \theta \geqslant \frac{\Delta_{\min}}{\Delta_{\max}}}$$

该上界随着$\bar{b}_t$的下降非增

感知与传输联合设计

☐被动适应环境 vs. 主动改善通信质量?



- **底层（分组通信）：匹配感知工艺的信息分组，传输到边缘估计终端**
- **中间层（边缘估计）：进行边缘预处理和融合，减少冗余信息传输**
- **远端（全局校正）：能量、频谱、时间等传输资源多域优化，实现全局的状态估计**

Lyu, Chen, **Zhu**, et al., *IEEE Trans. Wireless Communications*, vol.17, no.11, 2018; *IEEE Trans. Industrial Informatics*, vol.14, no.6, 2018; Chen, Lyu, **Zhu** and Guan, *IEEE Trans. Industrial Informatics*, vol. 16, no. 7, 2020; Lyu, Dai, Cheng, **Zhu**, et al., *IEEE Internet of Things Journal*, vol. 8, no. 10, 2021

口优化目标：最小化感知误差和能量消耗的加权和

$$\min_{\{p,q,\mathbf{w},\delta,\Delta,\nabla\}} \quad \sum_{t=1}^{\tau} \vartheta_e \mathrm{Tr}\left(\mathbb{E}\{W_t\}\right) + \vartheta_c \mathcal{E}_t$$

- **约束条件：**

传输约束		感知约束
$\sum_{i\in\mathcal{N}_s} \delta_{i,m,t} \le 1$ $\sum_{m\in\mathcal{M}} \delta_{i,m,t} \le 1$	$\sum_{m\in\mathcal{M}} \delta_{i,m,t} p_{i,m,t} \le p_{max}$ $q_{s,t}\|\|\mathbf{w}_{s,t}\|\|^2 + q_{s,0} \le q_{max}$	$\max_{i\in\mathcal{N}_s, s\in\mathcal{S}} (1-\phi_{i,t}) < \aleph_s(A, C_s, F_s)$
信道分配约束	传输功率约束	边缘估计收敛条件

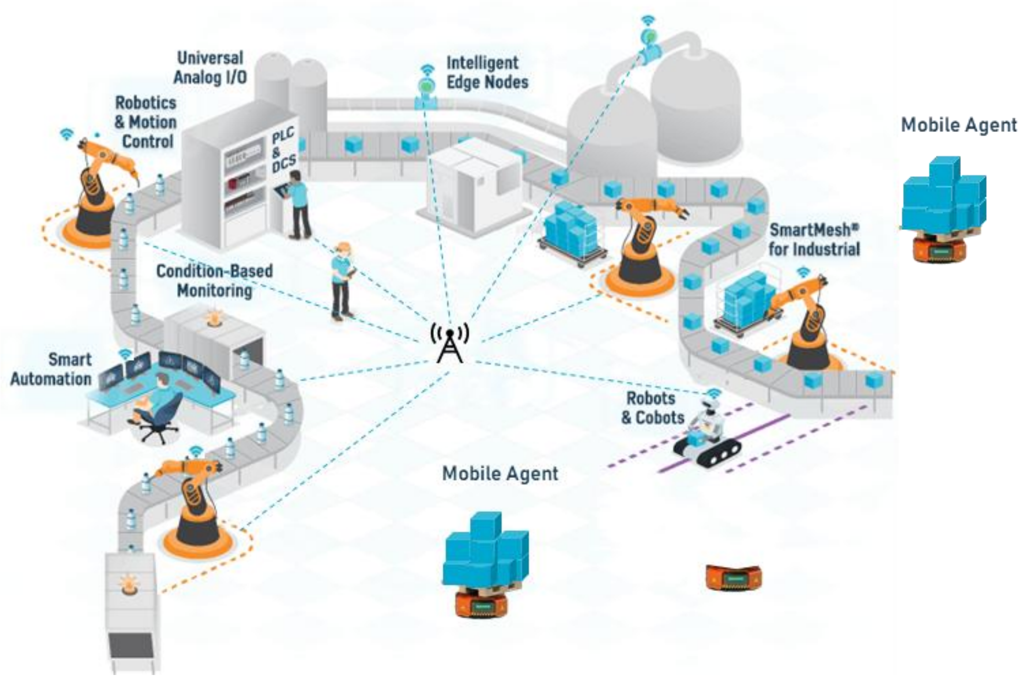
- **优化变量：**

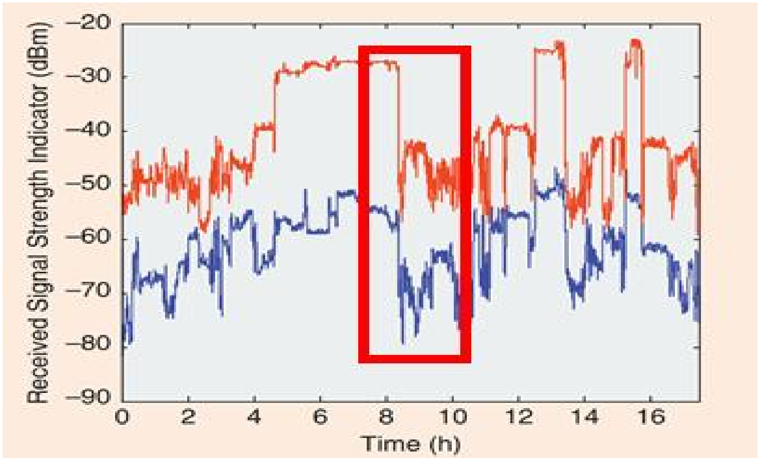
二进制的信道分配变量 (δ)　　连续的传输功率和时间分配变量 $(p, q, \mathbf{w}, \Delta, \nabla)$

混合整数非线性规划

- **采用块协作下降法进行迭代求解， 联合优化信道分配和功率控制，提高传输成功概率**
- **提出了面向感知的适变传输参数设计方法，提升网络系统感知能力**

□ 随着工业物联网与智能制造不断深入融合，机器人、AGV 等融入生产过程的各个环节，与已有的无线控制系统(WCS)构成异构工业物联网系统。



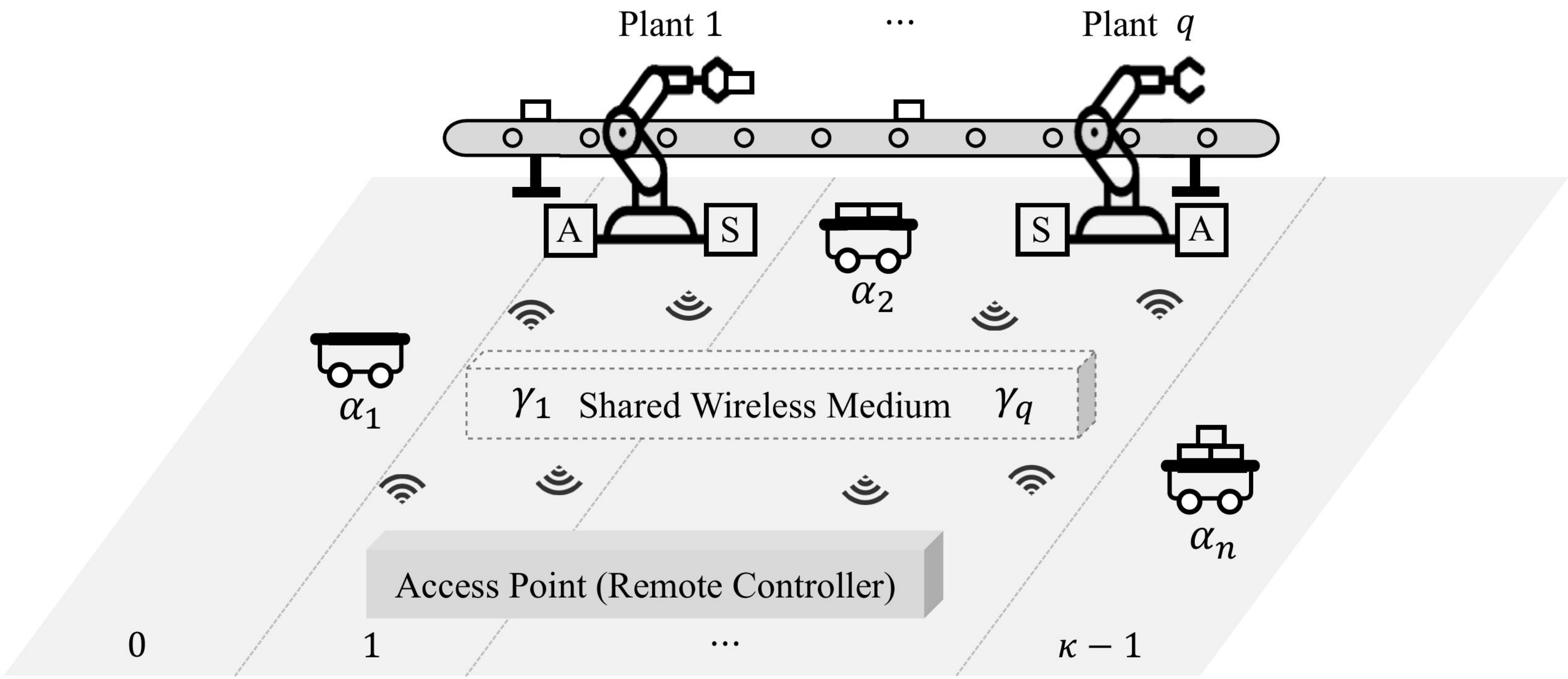


[Ahlén *et al.*, *IEEE Control Syst. Mag.*, 2019]

工厂实测：设备移动遮挡可导致信号强度下降高达30dBm

□ 目标: 为状态受限的移动智能体系统(MAS)设计最优控制器，满足WCS性能要求的同时，最小化异构工业系统成本

系统模型



- ☐ q 个Plant，每个Plant均附有1个传感器(S)和1个执行器(A)
- ☐ 所有S通过共享无线信道将Plant的状态测量传输到接入点(AP)进行控制决策，然后将控制指令下发到A做执行 (关注从S到AP的上行链路传输，假设从AP到A的下行链路传输是完美的)
- ☐ n 个Agent与S、A在工作区内协作执行生产任务
- ☐ 共享无线信道采用离散信道模型，局部信道状态$\gamma_i(k) \in \{0, \cdots, r-1\}$

□多回路WCS模型

控制输入 过程噪声

$$x_i(k+1) = A_i x_i(k) + B_i v_i(k) + \xi_i(k)$$

$$y_i(k) = x_i(k)$$

系统矩阵 $A_i \in \mathbb{R}^{n_i \times n_i}$，输入矩阵$B_i \in \mathbb{R}^{n_i \times m_i}$

- 每个S获取局部信道状态$\gamma_i(k)$，然后依据预设的通信策略 $\varphi_i(k) = h_i\big(\gamma_i(k)\big) \in \{0,1\}$ 接入共享信道传输信息
  - ➢ $\varphi_i(k) = 0$，不传输
  - ➢ $\varphi_i(k) = 1$，以固定功率$\mu_i > 0$传输测量信息
- AP接收S的测量信息
  - ➢ $\lambda_i(k) = 0$，第i个S的测量信息传输失败。控制策略为$v_i(k) = 0$
  - ➢ $\lambda_i(k) = 1$，第i个S的测量信息传输成功。控制策略可取为LQR型 $v_i(k) =- Kx_i(k)$

$$x_i(k+1) = \begin{cases} A_{c,i} x_i(k) + \xi_i(k), & \lambda_i(k) = 1 \\ A_{o,i} x_i(k) + \xi_i(k), & \lambda_i(k) = 0 \end{cases}$$

□WCS性能

$$x_i(k+1)=\begin{cases}A_{c,i}x_i(k)+\xi_i(k), & \lambda_i(k)=1\\ A_{o,i}x_i(k)+\xi_i(k), & \lambda_i(k)=0\end{cases}$$

只要$(A_i,\ B_i)$可控，可使得$A_{c,i}$谱半径小于1。故总存在二次Lyapunov函数$V_i(x_i)=x_i^TQ_ix_i$，其中Q_i正定，以及常数$T>0$，满足下面的WCS性能

期望衰减率　　**持续噪声扰动**

$$\mathbb{E}[V_i(x_i(k+1))|x_i(k)]\le \boxed{\rho_i}V_i(x_i(k))+\boxed{Tr(Q_i\Xi_i),}\ \forall\ x_i(k)\in\mathbb{R}^{n_i},\ \ k\ge K_0$$

这里Q_i为Lyapunov 方程$A_{c,i}^TQ_iA_{c,i}-Q_i=-P_i$的解，其中$P_i$为正定阵，$0<1-\frac{\lambda_{min}(P_i)}{\lambda_{max}(Q_i)}<\rho_i<1.$

□状态依赖衰落信道

现有i.i.d./Markov链衰落信道模型

[Gatsis et al., IEEE TAC, 2014; Zhang and Kassam, IEEE TCOM, 1999]

信道状态独立于物理过程

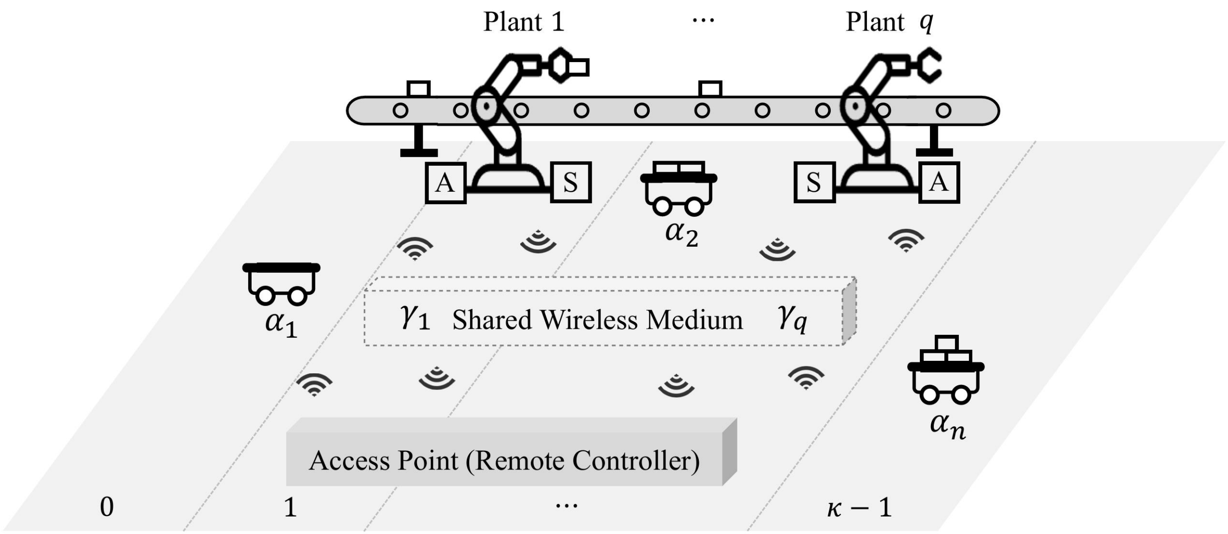
$$E[V_i(x_i(k+1))|x_i(k)] \leq \rho_i V_i(x_i(k)) + Tr(Q_i \Xi_i)$$

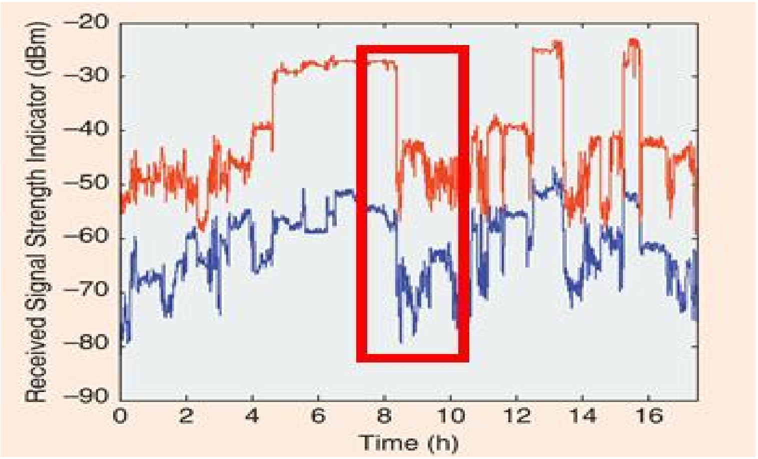
VS.

$$\mathbb{P}\{\lambda_i(k)=1|\alpha(k)=\alpha\} = \bar{\lambda}_i(\alpha)$$

信息传输成功的概率依赖于Agent状态$\alpha(k)$

$$E[V_i(x_i(k+1))|x_i(k), \alpha(k)] \leq \rho_i V_i(x_i(k)) + Tr(Q_i \Xi_i)$$





设备移动遮挡造成无线信号强度下降

口确定$\bar{\lambda}_i(\alpha)$

传输信息

局部信息状态

$\varphi_i(k) = 1$ → $\gamma_i(k) \in \{0, \cdots, r-1\}$

$\lambda_i(k) = 1$

信息传输成功

$\eta_i(k) = 1$ → $\mathrm{SNR}_i(k) \ge \eta_i^0$ ✚ $\varphi_i(k) = 1, \varphi_j(k) = 0, \ \forall j \ne i$

数据包解码成功

信噪比

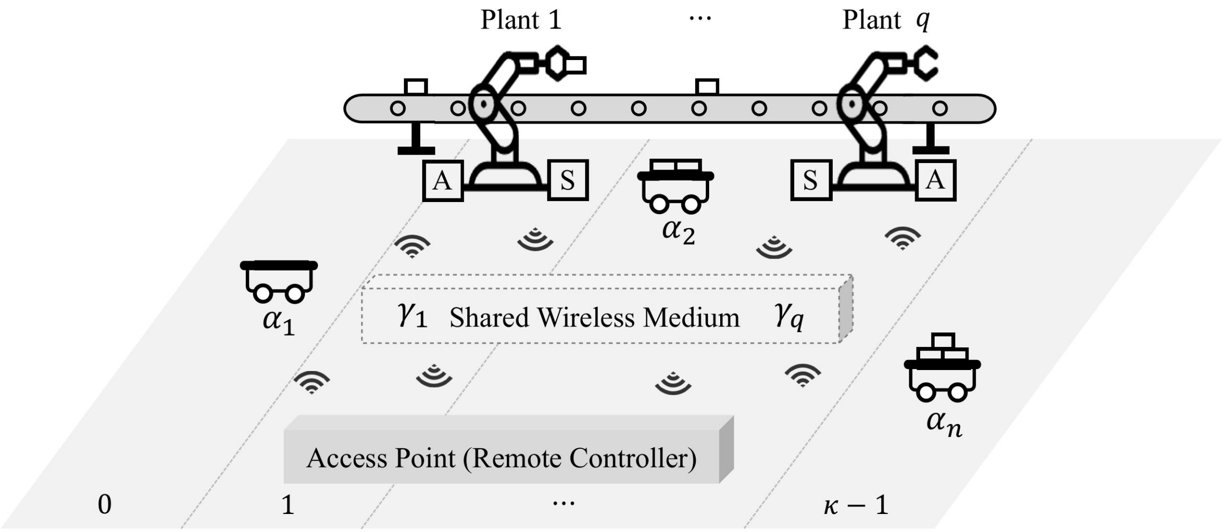
链路间无冲突

$$
\begin{aligned}
\bar{\lambda}_i(\alpha) &= \mathbb{P}\{\varphi_i(k) = 1 | \alpha(k) = \alpha\} \mathbb{P}\{\eta_i(k) = 1 | \alpha(k) = \alpha\} \\
&= \sum_{a=0}^{r-1} \mathbb{P}\{\gamma_i(k) = a | \alpha(k) = \alpha\} \\
&\qquad \times \mathbb{P}\left\{\mathrm{SNR}_i(k) \ge \eta_i^0 \middle| \alpha(k) = \alpha, \varphi_i(k) = 1, \varphi_j(k) = 0, \ \forall j \ne i\right\} \prod_{j \ne i} \mathbb{P}\left\{\varphi_j(k) = 0 \middle| \alpha(k) = \alpha\right\} \\
&= \sum_{a=0}^{r-1} \bar{\gamma}_i(a, \alpha)\, h_i(a)\, \bar{\eta}_i(\alpha)
\end{aligned}
$$

$\bar{\gamma}_i, \bar{\eta}_i$**可由统计方法+信号设计得到**

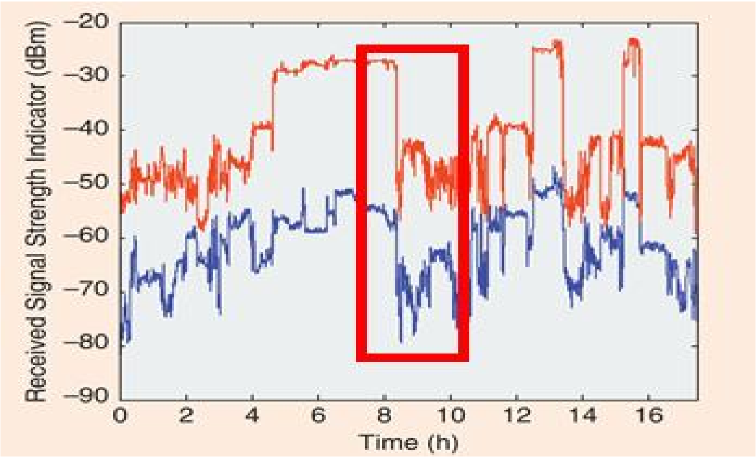
□MAS模型

$$\alpha_i(k+1) = \{_\kappa \sum_{j=1}^{n}\} a_{i,j} \times_\kappa \alpha_j(k) +_\kappa u_i(k), i = 1, \cdots, n$$



有限域的Agent模型

- **有限域：** Agent的位置移动造成阴影衰落，根据所造成的信道增益阴影效应的程度，将工作区划分为κ个单元
- **Agent的状态：** Agent所在单元的索引，而非其具体位置
- **Agent的交互：** $a_{i,j} > 0$表示Agent i, j是邻居



设备移动遮挡造成无线信号强度下降

无穷时域最优控制问题

传输能耗

Agent的控制代价

$$\min_{u} J_u(\alpha_0) = \min_{u} \lim_{K\to\infty} \frac{1}{K} \sum_{k=0}^{K-1} \left\{ \boxed{\sum_{i=1}^{q} \mu_i \mathbb{P}[\varphi_i(k) = 1 | \alpha(k;\alpha_0,u)]} + \lambda \boxed{g(\alpha(k;\alpha_0,\mathbf{u}), u(k))} \right\}$$

异构动态约束 s.t. WCS，MAS 动态

WCS性能约束 $E[V_i(x_i(k+1)) | x_i(k), \alpha(k;z_0,u)] \le \rho_i V_i(x_i(k)) + Tr(Q_i \Xi_i),$

$\forall x_i(k),\ \forall i,\ \forall k \ge K_0$

MAS状态约束 $\alpha(k;z_0,\mathbf{u}) \in \mathcal{C}_\alpha, \forall k$

MAS输入约束 $u(k) \in \mathcal{C}_u(\alpha(k;\alpha_0,\mathbf{u})), \forall k$

连续的WCS与逻辑的MAS耦合在一起，使得最优控制问题求解困难

性能分析

□WCS性能→集合镇定

$$\mathbb{E}[V_i(x_i(k+1))|x_i(k),\alpha(k;\alpha_0,\mathbf{u})] \le \rho_i V_i(x_i(k)) + Tr(Q_i\Xi_i)$$

$$\mathbb{E}\left[V_i\left(x_i(k+1)\right)\middle|x_i(k),\alpha(k;\alpha_0,\mathbf{u})\right] = \mathbb{P}\{\lambda_i(k)=1|\alpha(k;\alpha_0,\mathbf{u})\}x_i^T(k)A_{c,i}^T Q_i A_{c,i} x_i(k) + \mathbb{P}\{\lambda_i(k)=0|\alpha(k;\alpha_0,\mathbf{u})\}x_i^T(k)A_{o,i}^T Q_i A_{o,i} x_i(k) + Tr(Q_i\Xi_i)$$

$$\mathbb{P}\{\lambda_i(k)=1|\alpha(k;\alpha_0,\mathbf{u})\} \ge s_i,\ s_i = \sup_{y\in\mathbb{R}^{n_i}, y\neq 0} \frac{y^T(A_{o,i}^T Q_i A_{o,i} - \rho_i Q_i)y}{y^T(A_{o,i}^T Q_i A_{o,i} - A_{c,i}^T Q_i A_{c,i})y}$$

保证WCS性能要求的无线传输成功概率下界

$$\alpha(k;\alpha_0,\mathbf{u}) \in \Omega(s) = \{\alpha \in \mathcal{C}_\alpha | \bar{\lambda}_i(\alpha) \ge s_i,\ i=1,2,\dots,q\}$$

保证WCS性能要求的受限MAS局势集合

□集合镇定

定理: 给定初始状态$\alpha_0 \in \mathcal{C}_\alpha$，在状态依赖衰落信道以及MAS的状态约束及输入约束下，

WCS的控制性能要求得以保证，当且仅当MAS系统是受限$I(\Omega(s))$-镇定的，

其中$I(\Omega(s))$是$\Omega(s) = \{\alpha \in \mathcal{C}_\alpha | \bar{\lambda}_i(\alpha) \geq s_i = \sup_{y\in\mathbb{R}^{n_i}, y\neq 0} \frac{y^T(A_{o,i}^T Q_i A_{o,i} - \rho_i Q_i)y}{y^T(A_{o,i}^T Q_i A_{o,i} - A_{c,i}^T Q_i A_{c,i})y}, i = 1,2, \ldots, q\}$的最大受限控制不变集，即存在控制序列$\mathbf{u} \in \mathcal{C}_u(\alpha(k;\alpha_0,\mathbf{u}))$和常数$K_0 > 0$，使得$\alpha(k;\alpha_0,\mathbf{u}) \in \mathcal{C}_\alpha, \forall k < K_0$且$\alpha(k;\alpha_0,\mathbf{u}) \in I(\Omega(s)), \forall k \geq K_0$。

□可行性分析

□有限域MAS模型是非线性的，利用半张量积进行线性化

状态转移矩阵

$$\alpha_i(k+1) = \{_\kappa \textstyle\sum_{j=1}^{n}\} a_{i,j} \times_\kappa \alpha_j(k) +_\kappa u_i(k) \quad \Longrightarrow \quad \alpha(k+1) = Fu(k)\alpha(k)$$

有限域MAS模型　　　　双线性MAS模型

定理:给定初始状态$\alpha_0 \in \mathcal{C}_\alpha$，MAS系统是受限$I(\Omega(s))$-镇定的当且仅当$I\big(\Omega(s)\big) \cap \mathcal{R}(\alpha_0) \neq \emptyset$，其中$\mathcal{R}(\alpha_0)$是从初始状态$\alpha_0$出发可达的受限状态集合。如果MAS系统是受限$I(\Omega(s))$-镇定的，则$\mathcal{C}(G[\Phi]) \neq \emptyset$，其中$\mathcal{C}(G[\Phi])$是导出子图$G[\Phi]$的所有环的集合。

Algorithm 1 : Calculation of LCCIS $I(\Omega(s))$

Input: $\Omega(s)$, F

Output: $I(\Omega(s))$

1: $\Lambda_0 \leftarrow \Omega(s)$, $i \leftarrow 1$

2: Calculate $\Lambda_i = \{\alpha \in \Lambda_{i-1} : \mathcal{R}_1(\alpha) \cap \Lambda_{i-1} \neq \emptyset\}$

3: **if** $\Lambda_i == \Lambda_{i-1}$ **then** $I(\Omega(s)) \leftarrow \Lambda_i$ and Break

4: **else** $i \leftarrow i + 1$ and Back to Step 2

Algorithm 2 : Calculation of constrained reachable set $\mathcal{R}(\alpha_0)$

Input: $\mathcal{R}_0(\alpha_0)$

Output: $\mathcal{R}(\alpha_0)$

1: $\mathcal{R}(\alpha_0) \leftarrow \emptyset$, $k \leftarrow 1$

2: Calculate $\mathcal{R}_k(\alpha_0) = (\cup_{\alpha \in \mathcal{R}_{k-1}(\alpha_0)} \mathcal{R}_1(\alpha)) \setminus \mathcal{R}(\alpha_0)$

3: $\mathcal{R}(\alpha_0) \leftarrow \mathcal{R}(\alpha_0) \cup \mathcal{R}_k(\alpha_0)$

4: **if** $\mathcal{R}_k(\alpha_0) == \emptyset$ **then** Break

5: **else** $k \leftarrow k + 1$ and Back to Step 2

Algorithm 3 : Construction of optimal input sequence $\mathbf{u}^*$

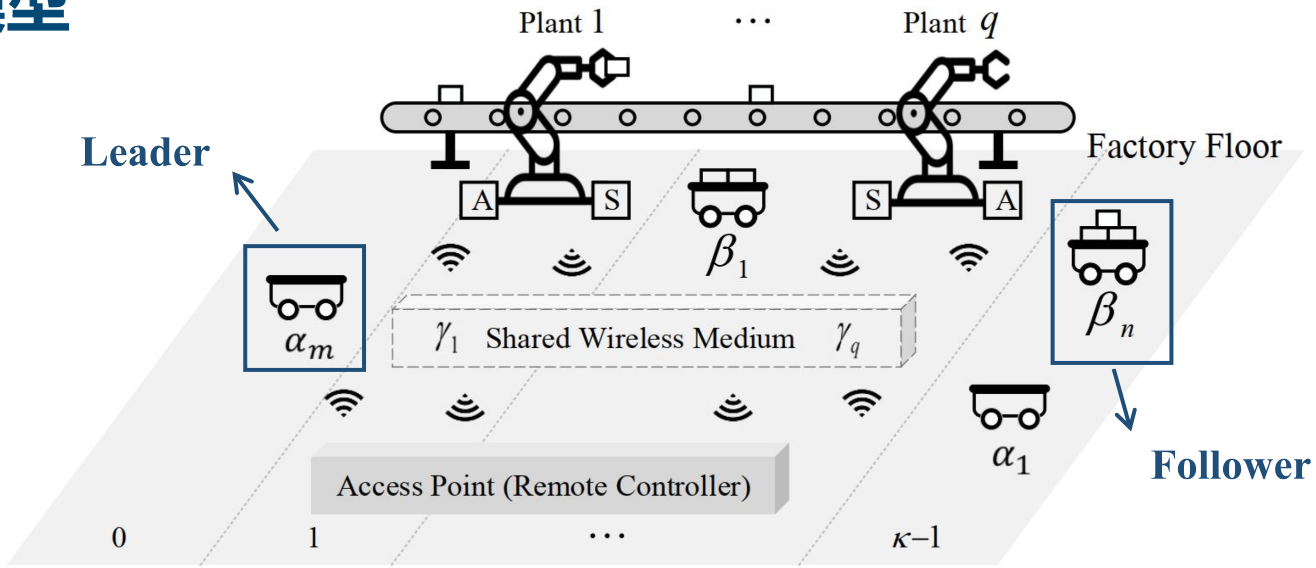
Input: $G[\Phi]$, $\alpha_0 = \delta_N^{a_0}$, $\mathcal{R}_i(\alpha_0)$, $i = 1, \cdots, r$
Output: $\mathbf{u}^*$

1: Compute strongly connected components of $G[\Phi]$ as $G[\mathcal{V}_i] = (\mathcal{V}_i, \mathcal{E}_i, w)$, $i = 1, \cdots, s$
2: **for** $i \leftarrow 1$ to s **do**
3: Initial $(|\mathcal{V}_i| + 1) \times |\mathcal{V}_i|$ arrays H_i and I_i with ∞
4: $H_i[0, a_i] \leftarrow 0$, $\delta_N^{a_i} \in \mathcal{V}_i$ is a source vertex in $G[\mathcal{V}_i]$
5: **for** $k \leftarrow 1$ to $|\mathcal{V}_i|$ **do**
6: **for** $\delta_N^a \in \mathcal{V}_i$ **do**
7: $H_i[k, a] \leftarrow \min_{(\delta_N^b, \delta_N^a) \in \mathcal{E}_i} H_i[k-1, b] + w(\delta_N^b, \delta_N^a)$
8: $I_i[k, a] \leftarrow b^*$, b^* is the minimizer in Line 7
9: Solve (18) and get ϵ_i^*, $\alpha_i^* \leftarrow \delta_N^{b_{i,|\mathcal{V}_i|}}$
10: $\iota \leftarrow \arg\min_{i=1}^{s} \epsilon_i^*$
11: Create an array c^* of size $|\mathcal{V}_\iota| + 1$ with $c^*[|\mathcal{V}_\iota|] \leftarrow b_{\iota,|\mathcal{V}_\iota|}$
12: **for** $k \leftarrow |\mathcal{V}_\iota|$ to 1 **do** $c^*[k-1] \leftarrow I_\iota[k, c^*[k]]$
13: Initialize an integer array A of size $N + 1$ with 0
14: **for** $k \leftarrow 0$ to $|\mathcal{V}_\iota|$ **do** $b_{\iota,k} \leftarrow c^*[k]$
15: **if** $A[b_{\iota,k}] = 0$ **then** $A[b_{\iota,k}] \leftarrow k$
16: **else** $\varphi \leftarrow A[b_{\iota,k}]$, $\psi \leftarrow k - 1$ and **Break**
17: A simple minimum-mean cycle is $\mathcal{C}^* = \{\delta_N^{c^*[\varphi]}, \delta_N^{c^*[\varphi+1]}, \cdots, \delta_N^{c^*[\psi]}, \delta_N^{c^*[\varphi]}\}$
18: **if** $\alpha_0 \in \mathcal{C}^*$ **then**
19: $\varsigma \leftarrow 0$, $\bar{c}^*[k] \leftarrow c^*[k]$, and go to Line 28
20: **else** $\varsigma \leftarrow \arg\min_{i=1}^{r} \{\mathcal{R}_i(\alpha_0) \cap \mathcal{C}^* \neq \emptyset\}$
21: Create an array t^* of size $\varsigma + 1$ with $t^*[0] \leftarrow a_0$ and $t^*[\varsigma] \leftarrow a$, $\delta_N^a \in \mathcal{R}_\varsigma(\alpha_0) \cap \mathcal{C}^*$
22: **for** $k \leftarrow \varsigma - 1$ to 1 **do**
23: $t^*[k] \leftarrow a$, $\delta_N^a \in \mathcal{R}_k(\alpha_0)$, $t^*[k+1] \in \mathcal{R}_1(\delta_N^a)$
24: The trajectory before enter $\mathcal{C}^*$ is $\mathcal{T}^* = \{\delta_N^{t^*[0]}, \delta_N^{t^*[1]}, \cdots, \delta_N^{t^*[\varsigma-1]}\}$
25: The length of $\mathcal{C}^*$ is $l \leftarrow \psi - \varphi + 1$
26: Create an array $\bar{c}^*$ of size $l + 1$
27: Rearrange the element of $\mathcal{C}^*$ as $\mathcal{C}^* = \{\delta_N^{\bar{c}^*[0]}, \delta_N^{\bar{c}^*[1]}, \cdots, \delta_N^{c^*[l]}\}$, $\bar{c}^*[0] = \bar{c}^*[l] = t^*[\varsigma]$
28: An optimal input sequence is $\mathbf{u}^* = \{u^*(k) : k \in \mathbb{N}\}$ with

$$u^*(k) \in \begin{cases} U_{t^*[k], t^*[k+1]}, & k = 0, \cdots, \varsigma - 1; \\ \bar{U}_{\bar{c}^*[k-(\varsigma+jl)], \bar{c}^*[k-(\varsigma+jl)+1]}, & k = \varsigma + jl, \\ & \cdots, \varsigma + (j+1)l - 1, j \in \mathbb{N} \end{cases}$$

where $U_{a,b}$, $\bar{U}_{a,b}$ are defined in (15) and (16), respectively

□领航-跟随MAS模型



Leader $\alpha_l(k+1) = u_l(k),\ l = 1, \cdots, m$

Follower $\beta_i(k+1) = \{_\kappa \sum_{j=1}^{n}\} a_{i,j}^{\sigma(k)} \times_\kappa \beta_j(k) +_\kappa \{_\kappa \sum_{l=1}^{m}\} b_{i,l}^{\sigma(k)} \times_\kappa \alpha_l(k), i = 1, \cdots, n$

- 切换拓扑 $\sigma(k) \in \{1, \cdots, w\}$：邻居集合随Agent移动而变
- $a_{i,j}^{\sigma(k)}, b_{i,j}^{\sigma(k)}$刻画了Agent间动态时变的交互关系

王淑玲，李沛哲，朱善迎，陈彩莲，关新平，*自动化学报*, 2024(已录用)；

口向量形式

$$\beta_i(k+1) = \{_\kappa \sum_{j=1}^{n}\} a_{i,j}^{\sigma(k)} \times_\kappa \beta_j(k)$$

$$+_\kappa \{_\kappa \sum_{l=1}^{m}\} b_{i,l}^{\sigma(k)} \times_\kappa \alpha_l(k), i = 1, \cdots, n$$

$$\alpha_i(k+1) = u_i(k),\ i = 1, \cdots, m$$

领航-跟随MAS模型

状态转移矩阵

$$\beta(k+1) = Fz(k)$$

$$\alpha(k+1) = u(k)$$

双线性MAS模型

□集合镇定判据——关于$\boldsymbol{\beta(k)}$

定义: 若对于任意$\beta_0 \in \mathcal{S}$，存在序列$\alpha = \{\alpha(k): (\alpha(k), \beta(k)) \in \mathcal{M}, k \in \mathbb{N}\} \subseteq \mathcal{C}_\alpha$使得$\boldsymbol{\beta(k; \beta_0, \alpha) \in \mathcal{S}}$，$\forall \boldsymbol{k} \in \mathbb{N}$，称集合 $\mathcal{S} \subseteq \mathcal{C}_\beta$ 为MAS关于集合$\mathcal{M} \subseteq \mathcal{C} = \mathcal{C}_\alpha \times \mathcal{C}_\beta$的一个**受限控制不变集**。

⬇

构造$\boldsymbol{I(\Omega(s)) \subseteq \mathcal{C}_\beta}$: 关于集合$\Omega(s)$的**最大受限控制不变集**

⬇

定理:状态依赖衰落信道下WCS性能要求满足，当且仅当存在$u \subseteq \mathcal{C}_\alpha, T$, 使得$\beta(k; z_0, u) \in \mathcal{C}_\beta, \forall k < T$; $\beta(k; z_0, u) \in I(\Omega(s)), \forall k \geq T$。

将原最优控制问题转化为MAS的最优受限集合镇定问题，消除了两系统间的耦合

最优控制器设计

口基于图论的可行性分析

- 初始位置$z_0 = \bar{\alpha} \ltimes \delta_N^{\bar{a}}$
- 受限状态转移图$\mathcal{G}_1 = (V, E)$

$$V = \{v_a = \delta_N^a:\ \delta_N^a \in C_\beta\},$$

$$E = \{(v_a, v_b) \in V \times V: \delta_N^b \in R_1(\delta_N^a; \mathcal{C}_\alpha)\} \setminus \boxed{\{(v_{\bar{a}}, v_b): v_b \neq Fz_0\}}$$

删除违背初始条件的边

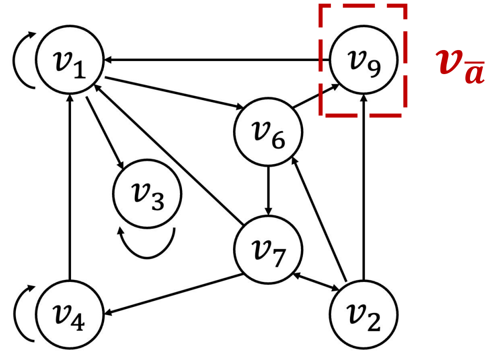
定理:状态依赖衰落信道下WCS性能要求得以保证，当且仅当$\boldsymbol{I(\Omega(s)) \cap V(T_{v_{\bar{a}}}) \neq \emptyset}$。

- $T_{v_{\bar{a}}}$：$\mathcal{G}_1$中以$v_{\bar{a}}$为根的广度优先生成树
- $\mathcal{R}(z_0)$：从初始位置出发的状态能达集，$\mathcal{R}(z_0) = V(T_{v_{\bar{a}}})$

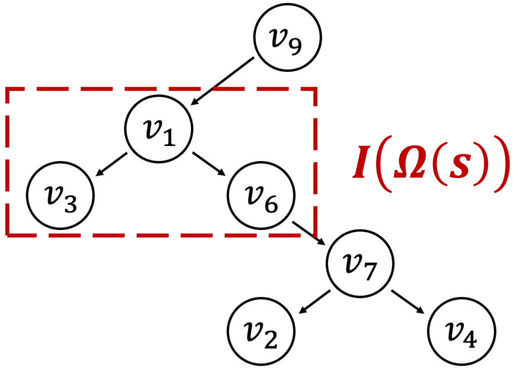
$$\beta(k+1) = Fz(k) \qquad \alpha(k+1) = u(k)$$

$$I(\Omega(s)) = \{\delta_9^1,\ \delta_9^3, \delta_9^6\}$$

$\mathcal{G}_1$



$T_{v_{\bar{a}}}$



√

□最优控制器设计

Algorithm 1 : Construction of optimal input sequences

Input: Constrained STG $\mathcal{G}_1$, weighted STG $\mathcal{G}_2$, ~~initial state~~ profile $\beta_0 = \delta_N^{a_0}$

Output: Optimal input sequences $u^* = \{u^*(k) : k \in \mathbb{N}\}$

1: Find the simple minimum-mean cycle in $\mathcal{G}_2$ as c^*

2: Find the shortest path from v_{a_0} to c^* by proceeding breadth-first search on $\mathcal{G}_1$ as $\mathcal{P} = \{v_{a_0}, \cdots, v_{a_{\iota_1}}, v_{b_0}\}$, where $\{v_{a_i} : i = 0, \cdots, \iota_1\} \cap c^* = \emptyset$, $c^* = \{v_{b_j} : j = 0, \cdots, \iota_2\}$

3: Set

$$u^*(k) \in \begin{cases} \Pi_{a_{k+1},a_{k+2}}(\mathcal{G}_1), & k = 0, \cdots, \iota_1 - 1; \\ \bar{\Pi}_{b_{k-\iota(\epsilon)},b_{k-\iota(\epsilon)+1}}(\mathcal{G}_2), & k = \iota(\epsilon), \cdots, \iota(\epsilon) + \iota_2, \end{cases}$$

where $\iota(\epsilon) = \iota_1 + \epsilon(\iota_2 + 1)$, $\epsilon \in \mathbb{N}$, $a_{\iota_1+1} = b_{\iota_2+1} = b_0$, $\Pi_{a,b}(\cdot)$, $\bar{\Pi}_{a,b}(\cdot)$ are defined in (15) and (17), respectively

权重：单步状态转移的最小成本

加权受限状态转移图$\mathcal{G}_2 = (I(\Omega(s)) \cap \mathcal{R}(z_0), E, \boxed{w})$

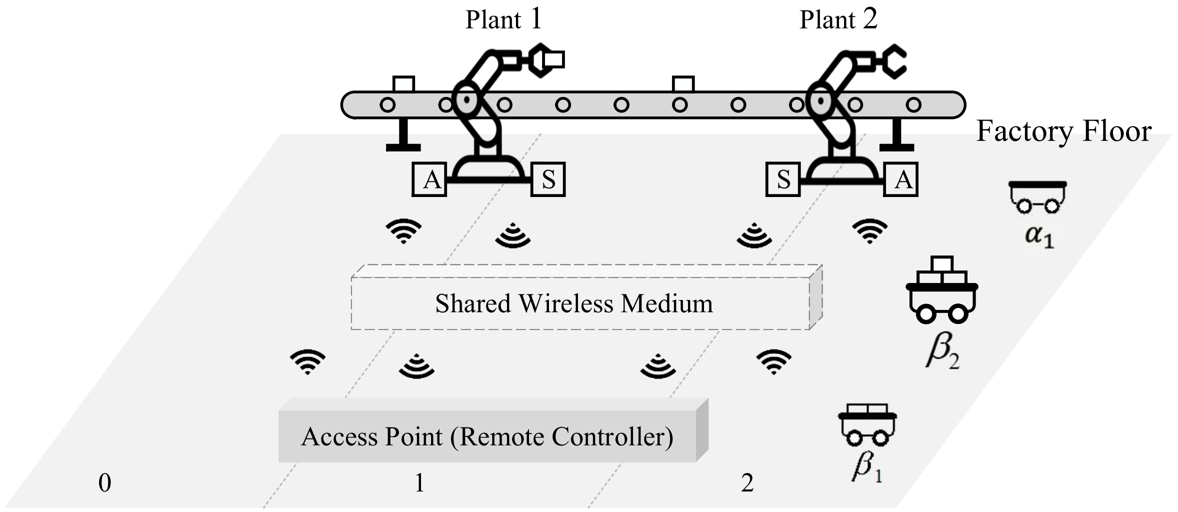
寻找$\mathcal{G}_2$中的简单最小平均环c^*

状态进入环c^*

状态重复环c^*

定理:算法1所构造的u^*是无穷时域最优控制问题的解，且最优值$J_{u^*}(z_0) = \bar{w}(c^*)$。

仿真结果



- 工作区: {0,1,2}
- 一个Control Agent, 两个State Agent
- 初始位置$\big(\alpha_1(0), \beta_1(0), \beta_2(0)\big) = (2,2,2)$
- 状态约束 $\big(\alpha_1(k), \beta_1(k), \beta_2(k)\big) \notin \{(i,1,1),(i,2,1), i = 0,1,2\}$

■ 闭环系统矩阵

$$A_{c,1} = \begin{bmatrix} -0.1 & -0.1 \\ 0.1 & 0.2 \end{bmatrix},\ A_{c,2} = 0.2$$

开环系统矩阵

$$A_{o,1} = \begin{bmatrix} -1 & -0.4 \\ -0.5 & 0.3 \end{bmatrix},\ A_{o,2} = 1$$

■ WCS性能要求:

衰减率: $\rho_1 = 0.95,\ \rho_2 = 0.9$

■ 保证上述性能要求的**无线传输成功概率下界:**

$$s_1 = 0.28,\ s_2 = 0.10$$

■ 状态依赖衰落信道$\mathbb{P}\{\lambda_i(k)=1|z(k)\}=\Lambda_i z(k)$, 其中

$\mathbb{P}\{\lambda_1(k)=1|(\alpha_1(k),\beta_1(k),\beta_2(k))=(2,2,02\}=0.15$

$$\Lambda_1=[\underbrace{0.31\cdots0.31}_{7}\underbrace{0.10\cdots0.10}_{7}\ \underbrace{0.30\cdots0.30}_{7}\ \underbrace{0.15\cdots0.15}_{6}];$$

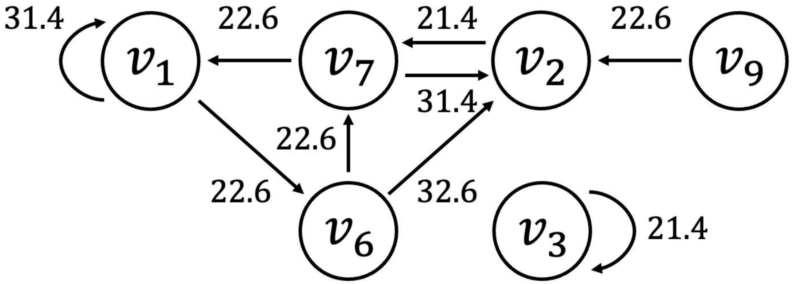
$$\Lambda_2=[\underbrace{0.13\cdots0.13}_{7}\ \underbrace{0.27\cdots0.27}_{7}\ \underbrace{0.13\cdots0.13}_{7}\ \underbrace{0.25\cdots0.25}_{6}]$$

$\mathbb{P}\{\lambda_2(k)=1|(\alpha_1(k),\beta_1(k),\beta_2(k))=(2,2,2)\}=0.25$

■ 保证WCS性能要求的MAS受限局势$(\alpha_1,\beta_1,\beta_2)$构成的集合:

$$\Omega(s)=\{(0,0,0),(0,0,1),(0,0,2),(0,1,0),(0,1,2),(0,2,0),(1,1,2),(1,2,0),(1,2,2),(2,0,0),(2,0,1),(2,0,2)\}$$

■ 加权受限状态转移图$\mathcal{G}_2$：



最小平均环$c^* = \{(0,2)\}$，平均权重$\overline{w}(c^*) = 21.4$

MAS模型

$\alpha_i(k+1) = u_i(k), i = 1, \cdots, m$

$\beta_i(k+1) = \{_\kappa \Sigma_{j=1}^{n}\} \, a_{i,j}^{\sigma(k)} \times_\kappa \beta_j(k)$

$+_\kappa \{_\kappa \Sigma_{l=1}^{m}\} \, b_{i,l}^{\sigma(k)} \times_\kappa \alpha_l(k), i = 1, \cdots, n$

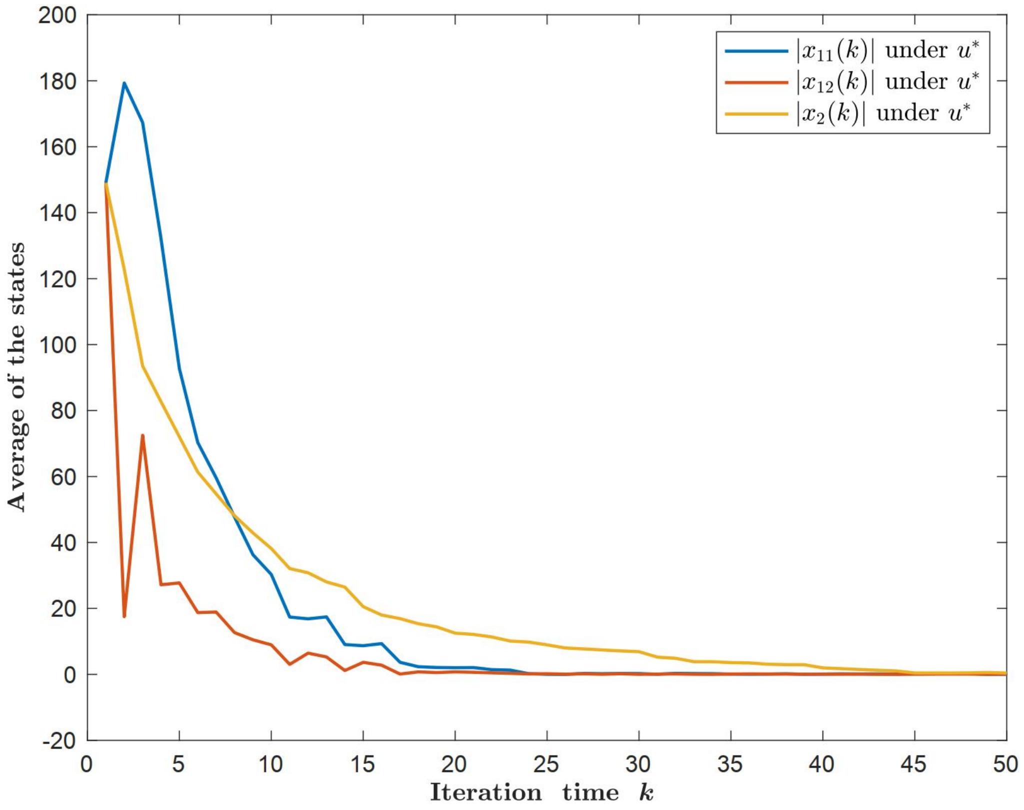
■ 最优控制序列：$u^*(0) = 1, u^*(k) = 0, k \geq 1$

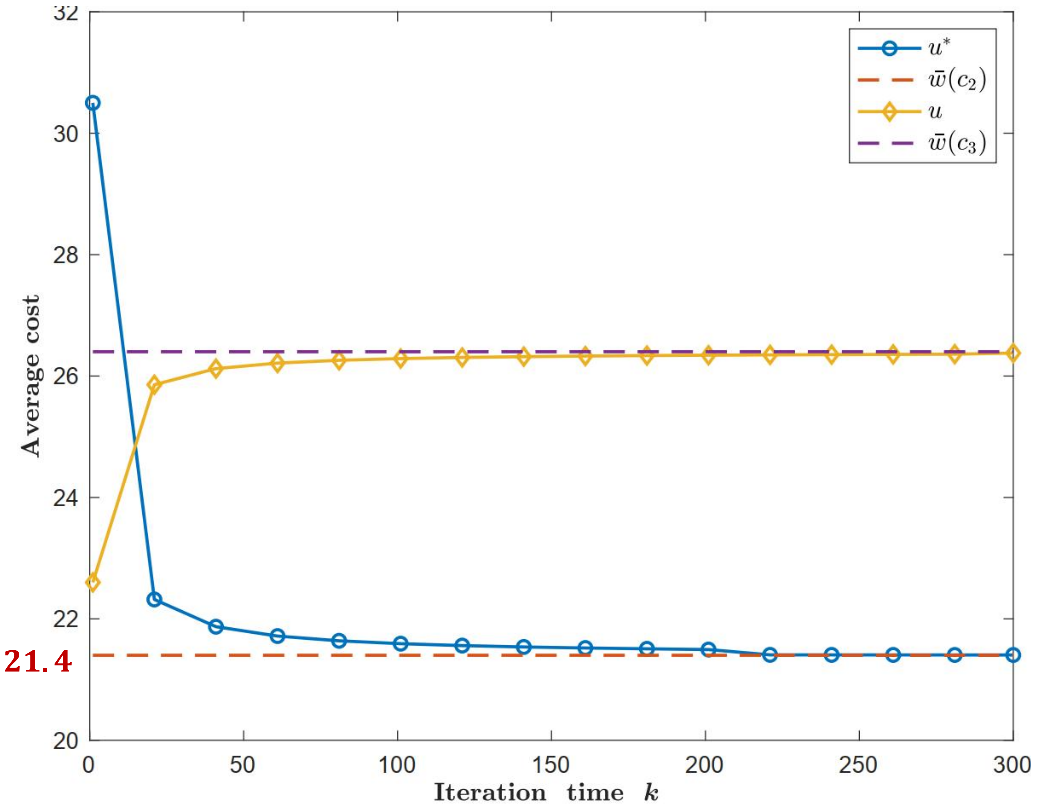
■ 位置转移$(\alpha_1(0), \beta_1(0), \beta_2(0)) \rightarrow (\alpha_1(1), \beta_1(1), \beta_2(1)) \rightarrow \cdots$：

$$(2,2,2) \rightarrow (1,0,0) \rightarrow \boxed{(0,0,2) \rightarrow (0,0,2) \rightarrow \cdots \in \boldsymbol{\Omega}(\boldsymbol{s})}$$

$\mathbb{P}\{\lambda_1(k) = 1 \mid (\alpha_1(k), \beta_1(k), \beta_2(k))\}$:	0.15	0.10	0.31	0.31 $\cdots$	$> \boldsymbol{s}_1$
$\mathbb{P}\{\lambda_2(k) = 1 \mid \alpha_1(k), \beta_1(k), \beta_2(k))\}$:	0.25	0.27	0.13	0.13 $\cdots$	$> \boldsymbol{s}_2$

有限时间收敛到最优！





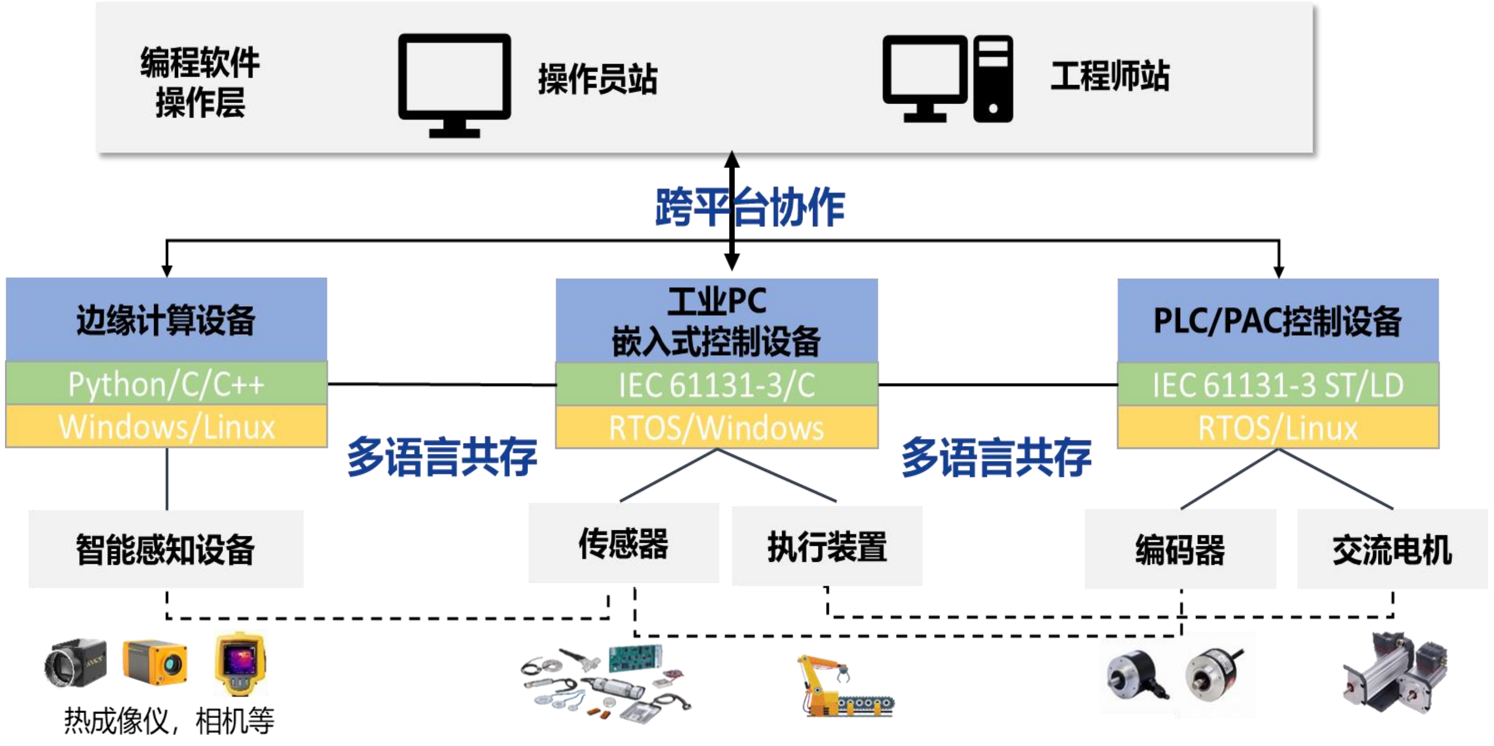
- 保证WCS性能要求
- 实现有限时间收敛

- 最小化系统无穷时域平均成本
- 无穷时域平均成本依赖于最小平均环c^*的平均权重

感知计算控制多类型设备统一管理

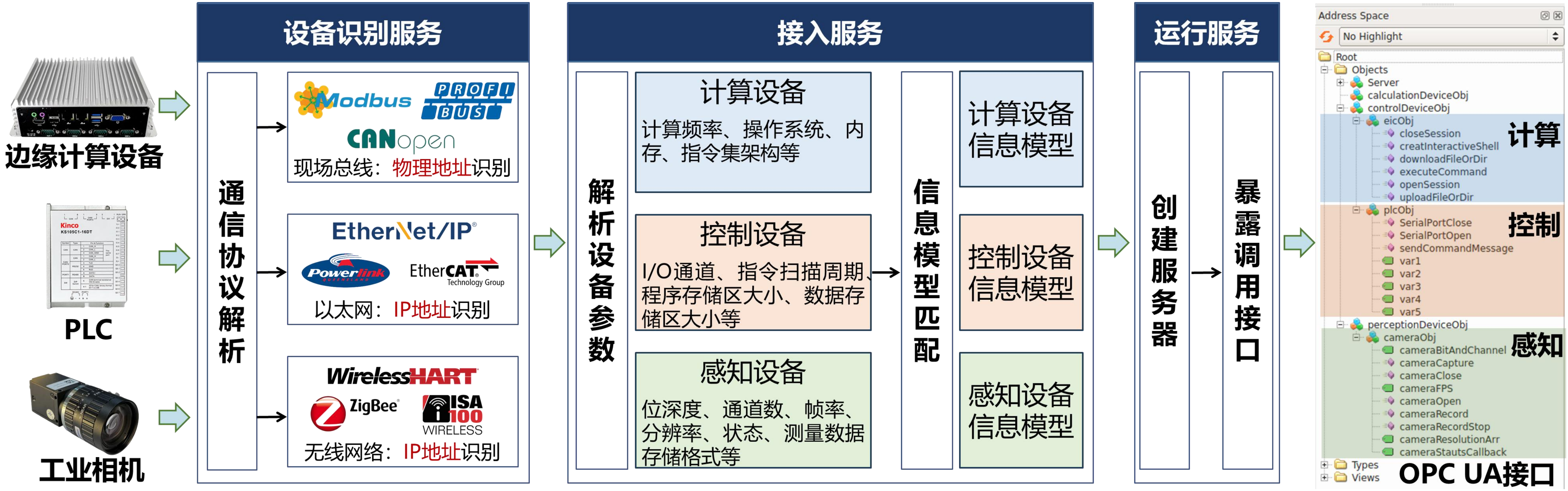
当前分离的设备管理模式无法满足工业网络系统智能化发展需求！

- 设备类型多样，描述方式差异大
- 感算控设备使用不同语言编程，硬件体系架构多样
- 软硬件高度集成，设备配置软件“专机专用”



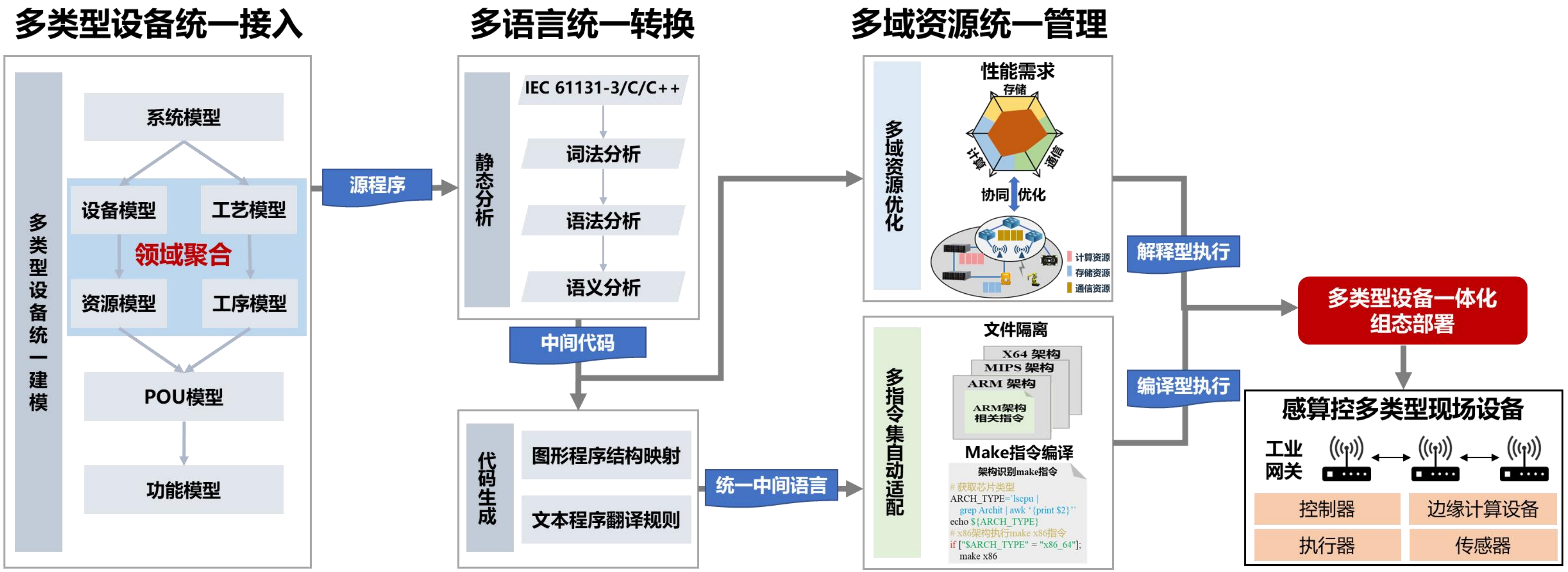
异构多设备协同

口感算控设备统一管理:



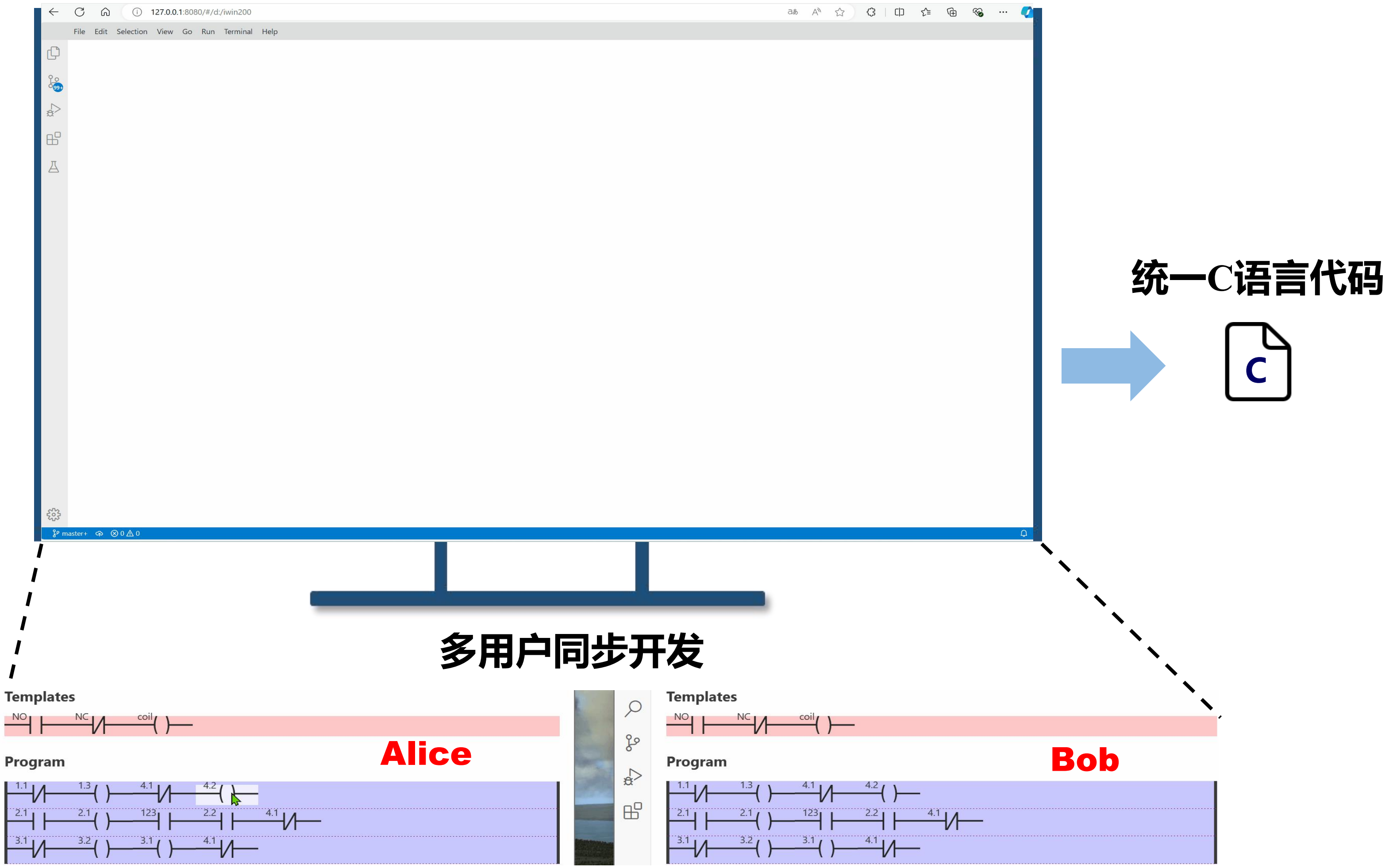
初步解决了多类型设备配置复杂度高的问题，通过统一的设备信息模型和交互接口，提升设备间跨平台协同效率

口通过设备统一接入，程序统一转换，多域资源统一配置，实现设备软硬件解耦



形成面向感知-计算-控制融合的组态部署一体化架构，提升设备间跨平台协同效率

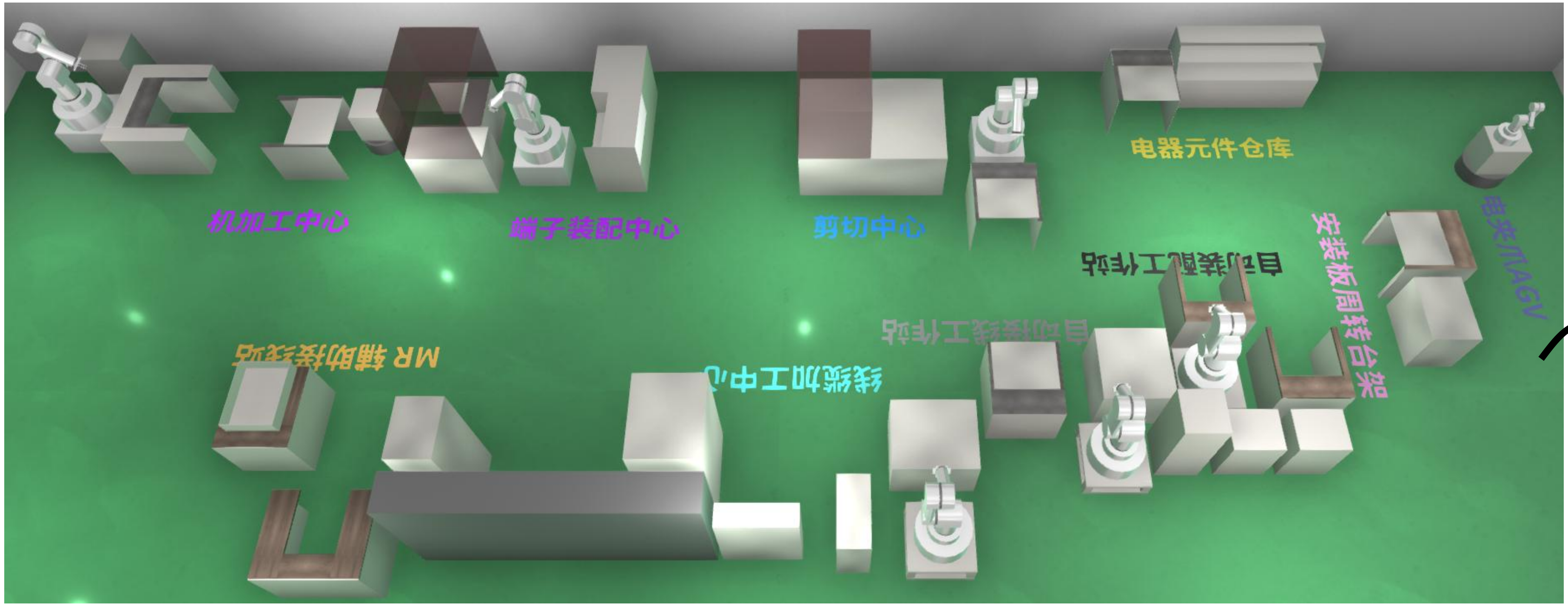
口开发工控集成组态可编程软件2.0



- 支持Web编程
- 支持插件化、跨设备组态
- 支持IEC 6113-3、Python 6种编程语言
- 支持感算控多类型设备接入
- 支持X64、ARM 2种处理器架构设备统一管理
- 支持多用户同步开发

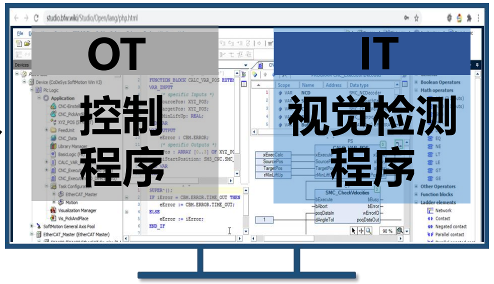
应用验证：定制化柔性自动化生产系统

机加工中心 | 端子装配中心 | 剪切中心 | 电气元件仓库



MR辅助接线站 | 线缆加工中心 | 自动接线工作站 | 自动装配工作站

线缆、导轨、电控柜等元件定制化生产



- 运行状态统一管理
- IT-OT程序同时兼容
- 多设备程序一键下发更新

1个管控平台，1个元件仓库，8个工作岛

致谢

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谢谢！
敬请批评指正！

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