8 Conclusions and Future Work

The major objective of this thesis is to develop advanced PnP process monitoring and control systems for industrial automation processes. In Chapter 1, brief introductions on major developments and basic concepts of process monitoring, FTC and PnP control techniques are presented. In order to accommodate the increasing complexity of modern industrial processes, a preferable PnP control design would be to develop PnP process monitoring and control modules based on the existing designs, which requires the scalability of the existing designs and the modularity of later designs.

The basis of this thesis is presented in Chapter 2 and 3. In Chapter 2, following the mathematical description of automation processes, the model-based and data-driven process monitoring techniques are briefly introduced. Parallel to Chapter 2, the basics of FTC structure are expressed in Chapter 3. These two chapters serve as the fundamentals of this thesis.

In Chapter 4, based on the formulated PnP control problem, the scalability and modularity of a general control system are investigated. Then, an advanced PnP process monitoring and control architecture (PnP-PMCA) with modularized components is developed, which is an integrated design of process monitoring and control with scalable structure. In addition, possible industrial implementation and appropriate PnP control strategies are introduced.

Chapter 5 focused on the study of the "plug-in" module of process monitoring system, which plays an essential role in the PnP control problem. In order to achieve self-configuration, adaptive and iterative online configuration approaches are proposed. The adaptive approach has a high convergence speed but also requires huge online computational load at each sampling instant. Comparing with the adaptive approach, the iterative scheme avoids the numerical sensitivity problem and significantly reduces the online computational load, but has a lower convergence speed. In addition, considering the industrial processes are generally complex systems with unknown deterministic disturbance, a reliable process monitoring scheme is developed for stationary processes to ensure a better PnP monitoring performance.

The study of the "plug-in" process control modules are presented in Chapter 6. Being dual to the process monitoring module, a general control performance assessment system is developed, which could evaluate the current control performance. Based on that, appropriate control strategies could be performed. Since the closed-loop stability is a critical issue when the control systems are modified, an indicator which reflects the closed-loop stability must be chosen and monitored by the control performance assessment system when the "plug-in" modules have been plugged into the existing closed-loop or online updated. Based on the investigation of the internal stability of the proposed PnP-PMCA, a reliable stability boundary of the closed-loop is determined which can serve as a safety limit in the proposed control performance assessment system to monitor the closed-loop stability. Furthermore, iterative configuration approaches are developed for the performance control modules. The proposed iterative configuration approaches do not only

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deliver an improved control performance with stability guarantee but also require low online computational cost.

The proposed PnP-PMCA and the PnP control strategies are finally implemented on industrial benchmark processes to evaluate their performance and effectiveness. In particular, in the case study on the rolling mill benchmark system, additional "plug-in" modules for eccentricity monitoring and compensation are constructed based on the PnP-PMCA. Moreover, in the real-time implementation on the BLDC motor test rig, the "plug-in" modules of PnP-PMCA are realized in different PCs. All of the proposed monitoring and performance optimization approaches show their superior performance.

This thesis attempts to build a framework of PnP process monitoring and control for industrial automation processes. The PnP process monitoring and control modules in the component level are investigated based on the assumption that the original closed-loop has been stabilized by the existing control system.

- The results achieved in this thesis are based on the linear system descriptions and the proposed approaches are efficient if the real process is working around the operating point. Therefore, extensions of the proposed methods to the nonlinear processes are of practical importance and requires more research attention.

- In order to develop a comprehensive PnP process monitoring and control system, not only the effects of the PnP modules on the closed-loop stability should be assessed and monitored, but also the stability of the original closed-loop should be analyzed and monitored. In addition, aiming at the efficiency and the safety of the overall system, design of PnP modules in the subsystem level and the system level to achieve economic-indicator-oriented process monitoring and supervisory control is of great interests in the future work.

A Proof of Theorem 4.2

Theorem 4.2: *Given a plant model* $\mathbf{G}(z)$ *with minimal realization as defined in* (4.1), *and the feedback controller* $\mathbf{K}(z) = \left[\begin{array}{c|c} \mathbf{A_c} & \mathbf{B_c} \\ \hline \mathbf{C_c} & \mathbf{D_c} \end{array}\right]$ *which ensures the well-posedness and internal stability of the closed-loop. Chosen* $\mathbf{F}$ *and* $\mathbf{L}$ *such that* $\mathbf{A}+\mathbf{BF}$ *and* $\mathbf{A}-\mathbf{LC}$ *are stable which lead to the following double coprime factorization of* $\mathbf{G}(z)$*:*

$$\begin{bmatrix} \mathbf{M}(z) & -\hat{\mathbf{Y}}(z) \\ \mathbf{N}(z) & \hat{\mathbf{X}}(z) \end{bmatrix} = \left[\begin{array}{c|cc} \mathbf{A}+\mathbf{BF} & \mathbf{B} & \mathbf{L} \\ \hline \mathbf{F} & \mathbf{I} & \mathbf{0} \\ \mathbf{C}+\mathbf{DF} & \mathbf{D} & \mathbf{I} \end{array}\right], \tag{A.1}$$

$$\begin{bmatrix} \mathbf{X}(z) & \mathbf{Y}(z) \\ -\hat{\mathbf{N}}(z) & \hat{\mathbf{M}}(z) \end{bmatrix} = \left[\begin{array}{c|cc} \mathbf{A}-\mathbf{LC} & -(\mathbf{B}-\mathbf{LD}) & -\mathbf{L} \\ \hline \mathbf{F} & \mathbf{I} & \mathbf{0} \\ \mathbf{C} & -\mathbf{D} & \mathbf{I} \end{array}\right]. \tag{A.2}$$

Then the following statements are true:

a) *If the feed-forward controller* $\mathbf{V_s}(z) \in \mathcal{RH}_\infty$ *and the parameterization matrix* $\mathbf{Q_s}(z) \in \mathcal{RH}_\infty$ *in the FTCA are chosen as*

$$\mathbf{V_s}(z) = \left[\begin{array}{cc|c} \mathbf{A}-\mathbf{BD_zD_cC} & \mathbf{BD_zC_c} & \mathbf{BD_zD_c} \\ \mathbf{B_c}(\mathbf{DD_zD_c}-\mathbf{I})\mathbf{C} & \mathbf{A_c}-\mathbf{B_cDD_zC_c} & \mathbf{B_c}(\mathbf{I}-\mathbf{DD_zD_c}) \\ \hline -(\mathbf{D_zD_cC}+\mathbf{F}) & \mathbf{D_zC_c} & \mathbf{D_zD_c} \end{array}\right], \tag{A.3}$$

$$\mathbf{Q_s}(z) = \left[\begin{array}{cc|c} \mathbf{A}-\mathbf{BD_zD_cC} & \mathbf{BD_zC_c} & \mathbf{L}-\mathbf{BD_zD_c} \\ \mathbf{B_c}(\mathbf{DD_zD_c}-\mathbf{I})\mathbf{C} & \mathbf{A_c}-\mathbf{B_cDD_zC_c} & \mathbf{B_c}(\mathbf{DD_zD_c}-\mathbf{I}) \\ \hline -(\mathbf{D_zD_cC}+\mathbf{F}) & \mathbf{D_zC_c} & -\mathbf{D_zD_c} \end{array}\right], \tag{A.4}$$

where $\mathbf{D_z} := (\mathbf{I}+\mathbf{D_cD})^{-1}$*, then the FTCA shown in Fig. 4.6 is equivalent to the standard feedback control loop shown in Fig. 4.2.*

b) *If the feed-forward controller* $\mathbf{V}(z) \in \mathcal{RH}_\infty$ *and the parameterization matrix* $\mathbf{Q}(z) \in \mathcal{RH}_\infty$ *in the PnP-PMCA are chosen as*

$$\mathbf{V}(z) = \mathbf{0}, \tag{A.5}$$

$$\mathbf{Q}(z) = \left[\begin{array}{cc|c} \mathbf{A}-\mathbf{BD_zD_cC} & \mathbf{BD_zC_c} & \mathbf{L}-\mathbf{BD_zD_c} \\ \mathbf{B_c}(\mathbf{DD_zD_c}-\mathbf{I})\mathbf{C} & \mathbf{A_c}-\mathbf{B_cDD_zC_c} & \mathbf{B_c}(\mathbf{DD_zD_c}-\mathbf{I}) \\ \hline \mathbf{D_zD_cC}+\mathbf{F} & -\mathbf{D_zC_c} & \mathbf{D_zD_c} \end{array}\right], \tag{A.6}$$

where $\mathbf{D_z} := (\mathbf{I}+\mathbf{D_cD})^{-1}$*, then the PnP-PMCA shown in Fig. 4.5 is equivalent to the FTCA shown in Fig. 4.6 where*

$$\mathbf{V_s}(z) = \left[\begin{array}{cc|c} \mathbf{A}-\mathbf{BD_zD_cC} & \mathbf{BD_zC_c} & \mathbf{BD_zD_c} \\ \mathbf{B_c}(\mathbf{DD_zD_c}-\mathbf{I})\mathbf{C} & \mathbf{A_c}-\mathbf{B_cDD_zC_c} & \mathbf{B_c}(\mathbf{I}-\mathbf{DD_zD_c}) \\ \hline -(\mathbf{D_zD_cC}+\mathbf{F}) & \mathbf{D_zC_c} & \mathbf{D_zD_c} \end{array}\right], \tag{A.7}$$

$$\mathbf{Q_s}(z) = \mathbf{0}. \tag{A.8}$$

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Proof. To proof Theorem 4.2, the equivalency of the FTCA shown in Fig. 4.6 and the standard feedback control loop shown in Fig. 4.2 is studied first.

To show the equivalency of the FTCA and the standard feedback control loop, it is only necessary to show the control signals of the closed-loops are identical. Consider the plant model $\mathbf{G}(z)$ in the standard feedback control loop which is well-posed and internally stabilized by the existing controller $\mathbf{K}(z)$:

$$\begin{aligned} \mathbf{x}_{\mathbf{c},k+1} &= \mathbf{A_c x}_{\mathbf{c},k} + \mathbf{B_c e}_k, && \text{(A.9)} \\ \mathbf{u}_k &= \mathbf{C_c x}_{\mathbf{c},k} + \mathbf{D_c e}_k. && \text{(A.10)} \end{aligned}$$

Since $\begin{bmatrix} -\hat{\mathbf{N}}(z) & \hat{\mathbf{M}}(z) \end{bmatrix}$ forms an SKR of the system $\mathbf{G}(z)$ which can be realized into an observer-based residual generator:

$$\begin{aligned} \hat{\mathbf{x}}_{k+1} &= \mathbf{A}\hat{\mathbf{x}}_k + \mathbf{B u}_k + \mathbf{L r}_k, && \text{(A.11)} \\ \hat{\mathbf{y}}_k &= \mathbf{C}\hat{\mathbf{x}}_k + \mathbf{D u}_k, && \text{(A.12)} \\ \mathbf{r}_k &= \mathbf{y}_k - \mathbf{C}\hat{\mathbf{x}}_k - \mathbf{D u}_k. && \text{(A.13)} \end{aligned}$$

Due to the fact that $\mathbf{y}_k = \hat{\mathbf{y}}_k + \mathbf{r}_k$, after substitution into the state-space representation of the controller $\mathbf{K}(z)$, the control signal $\mathbf{u}_k$ can be obtained as:

$$\mathbf{u}_k = -\mathbf{D_z D_c C}\hat{\mathbf{x}}_k + \mathbf{D_z C_c x}_{\mathbf{c},k} + \mathbf{D_z D_c}\boldsymbol{\omega}_k - \mathbf{D_z D_c r}_k, \quad \text{(A.14)}$$

where $\mathbf{D_z} = (\mathbf{I} + \mathbf{D_c D})^{-1}$ and the inverse is guaranteed by the well-posedness of the closed-loop. Substitute Eq. (A.14) into the state-space representations of $\mathbf{G}(z)$ and $\mathbf{K}(z)$, it follows the dynamics of the closed-loop:

$$\begin{aligned} \begin{bmatrix} \hat{\mathbf{x}}_{k+1} \\ \mathbf{x}_{\mathbf{c},k+1} \end{bmatrix} &= \begin{bmatrix} \mathbf{A} - \mathbf{B D_z D_c C} & \mathbf{B D_z C_c} \\ \mathbf{B_c}\left(\mathbf{D D_z D_c} - \mathbf{I}\right)\mathbf{C} & \mathbf{A_c} - \mathbf{B_c D D_z C_c} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{x}}_k \\ \mathbf{x}_{\mathbf{c},k} \end{bmatrix} \\ &+ \begin{bmatrix} \mathbf{B D_z D_c} & \mathbf{L} - \mathbf{B D_z D_c} \\ \mathbf{B_c}\left(\mathbf{I} - \mathbf{D D_z D_c}\right) & \mathbf{B_c}\left(\mathbf{D D_z D_c} - \mathbf{I}\right) \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega}_k \\ \mathbf{r}_k \end{bmatrix}, && \text{(A.15)} \\ \mathbf{u}_k &= \begin{bmatrix} -\mathbf{D_z D_c C} & \mathbf{D_z C_c} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{x}}_k \\ \mathbf{x}_{\mathbf{c},k} \end{bmatrix} + \begin{bmatrix} \mathbf{D_z D_c} & -\mathbf{D_z D_c} \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega}_k \\ \mathbf{r}_k \end{bmatrix}, && \text{(A.16)} \end{aligned}$$

Recall that the standard feedback control loop is assumed to be well-posed and internally stable, the system matrix of the dynamics of the closed-loop

$$\begin{bmatrix} \mathbf{A} - \mathbf{B D_z D_c C} & \mathbf{B D_z C_c} \\ \mathbf{B_c}\left(\mathbf{D D_z D_c} - \mathbf{I}\right)\mathbf{C} & \mathbf{A_c} - \mathbf{B_c D D_z C_c} \end{bmatrix} \quad \text{(A.17)}$$

is stable.

On the other hand, assume that the Youla parameterization matrix $\mathbf{Q_s}(z) \in \mathcal{RH}_\infty$ and feed-forward controller $\mathbf{V_s}(z) \in \mathcal{RH}_\infty$ have the following state-space realization, respectively:

- State-space representation of $\mathbf{Q_s}(z) \in \mathcal{RH}_\infty$:

$$\begin{aligned} \mathbf{x}_{\mathbf{r},k+1} &= \mathbf{A_r x}_{\mathbf{r},k} + \mathbf{B_r r}_k, && \text{(A.18)} \\ \mathbf{u}_{\mathbf{r},k} &= \mathbf{C_r x}_{\mathbf{r},k} + \mathbf{D_r r}_k, && \text{(A.19)} \end{aligned}$$

  where $\mathbf{x_r} \in \mathcal{R}^{n_r}$ and n_r respectively represent the state vector and the system order of $\mathbf{Q_s}(z)$.

- State-space representation of $\mathbf{V_s}(z) \in \mathcal{RH}_\infty$:

$$\begin{aligned}
\mathbf{x}_{\mathbf{v},k+1} &= \mathbf{A_v}\mathbf{x}_{\mathbf{v},k} + \mathbf{B_v}\boldsymbol{\omega}_k, &\text{(A.20)}\\
\mathbf{u}_{\mathbf{v},k} &= \mathbf{C_v}\mathbf{x}_{\mathbf{v},k} + \mathbf{D_v}\boldsymbol{\omega}_k, &\text{(A.21)}
\end{aligned}$$

  where $\mathbf{x_v} \in \mathcal{R}^{n_v}$ and n_v respectively represent the state vector and the system order of $\mathbf{V_s}(z)$.

Consequently, the control signal of the FTCA can be obtained as:

$$\mathbf{u}_k = \mathbf{F}\hat{\mathbf{x}}_k + \mathbf{C_r}\mathbf{x}_{\mathbf{r},k} + \mathbf{D_r}\mathbf{r}_k + \mathbf{C_v}\mathbf{x}_{\mathbf{v},k} + \mathbf{D_v}\boldsymbol{\omega}_k, \tag{A.22}$$

which should be identical to Eq. (A.16). To this end, split $\begin{bmatrix} \hat{\mathbf{x}}_k \\ \mathbf{x}_{\mathbf{c},k} \end{bmatrix}$ into

$$\begin{bmatrix} \hat{\mathbf{x}}_k \\ \mathbf{x}_{\mathbf{c},k} \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{x}}_{\mathbf{r},k} \\ \mathbf{x}_{\mathbf{c},\mathbf{r},k} \end{bmatrix} + \begin{bmatrix} \hat{\mathbf{x}}_{\omega,k} \\ \mathbf{x}_{\mathbf{c},\omega,k} \end{bmatrix}, \tag{A.23}$$

where $\begin{bmatrix} \hat{\mathbf{x}}_{\mathbf{r},k} \\ \mathbf{x}_{\mathbf{c},\mathbf{r},k} \end{bmatrix}$ is the component driven by residual signal $\mathbf{r}$ and $\begin{bmatrix} \hat{\mathbf{x}}_{\omega,k} \\ \mathbf{x}_{\mathbf{c},\omega,k} \end{bmatrix}$ is the component driven by reference signal $\boldsymbol{\omega}$. As a result, the Youla parameterization matrix $\mathbf{Q_s}(z) \in \mathcal{RH}_\infty$ and the feed-forward controller $\mathbf{V_s}(z) \in \mathcal{RH}_\infty$ can be determined as:

$$\begin{aligned}
\mathbf{V_s}(z) &= \left[\begin{array}{cc|c} \mathbf{A} - \mathbf{B}\mathbf{D_z}\mathbf{D_c}\mathbf{C} & \mathbf{B}\mathbf{D_z}\mathbf{C_c} & \mathbf{B}\mathbf{D_z}\mathbf{D_c} \\ \mathbf{B_c}(\mathbf{D}\mathbf{D_z}\mathbf{D_c} - \mathbf{I})\mathbf{C} & \mathbf{A_c} - \mathbf{B_c}\mathbf{D}\mathbf{D_z}\mathbf{C_c} & \mathbf{B_c}(\mathbf{I} - \mathbf{D}\mathbf{D_z}\mathbf{D_c}) \\ \hline -(\mathbf{D_z}\mathbf{D_c}\mathbf{C} + \mathbf{F}) & \mathbf{D_z}\mathbf{C_c} & \mathbf{D_z}\mathbf{D_c} \end{array}\right], \\
\mathbf{Q_s}(z) &= \left[\begin{array}{cc|c} \mathbf{A} - \mathbf{B}\mathbf{D_z}\mathbf{D_c}\mathbf{C} & \mathbf{B}\mathbf{D_z}\mathbf{C_c} & \mathbf{L} - \mathbf{B}\mathbf{D_z}\mathbf{D_c} \\ \mathbf{B_c}(\mathbf{D}\mathbf{D_z}\mathbf{D_c} - \mathbf{I})\mathbf{C} & \mathbf{A_c} - \mathbf{B_c}\mathbf{D}\mathbf{D_z}\mathbf{C_c} & \mathbf{B_c}(\mathbf{D}\mathbf{D_z}\mathbf{D_c} - \mathbf{I}) \\ \hline -(\mathbf{D_z}\mathbf{D_c}\mathbf{C} + \mathbf{F}) & \mathbf{D_z}\mathbf{C_c} & -\mathbf{D_z}\mathbf{D_c} \end{array}\right],
\end{aligned}$$

which proves the first statement of Theorem 4.2. Based on the first statement, the second statement is thus straightforward.

□

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