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A Review of Industrial MIMO Decoupling Control

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Abstract: In recent decades, MIMO (Multi-Input-Multi-Output) systems become more and more widely used in industrial applications. A variety of decoupling control algorithms have been studied in the literature. Therefore, a review of the most extensively applied coupling interaction analysis and decoupler design methods for industrial processes is necessary to be carried out. In this paper, in order to benefit researchers and engineers with different academic backgrounds, the scattered coupling interaction analysis and decoupling algorithms are collected and divided into different categories with their characteristics, application domains and informative comments for selection. Moveover, some frequently concerned problems of decoupling control are also discussed.

Keywords: Decoupling control, industrial application, interaction analysis, MIMO system.

1. INTRODUCTION

Most of the industry control systems are MIMO systems. One of the most important problems in MIMO systems control is the coupling problem which was first mentioned by Boksenbom and Hood in 1950 [1]. However, coupling was only treated as a complicated design idea and has not been widely explored at that time. As the rapid development of manufacturing, methodologies aiming at eliminating or decreasing multi-loop interaction issues have received a lot of attention in the past decades. In 1980s, Professor Waller said in his report that 'one of the subjects of great research activity in chemical process control in the U.S. today is interaction analysis, in which coupling between inputs and outputs in MIMO systems is studied' [2].

The main idea of the decoupling algorithm proposed by Boksenbom and Hood is making the overall closed-loop transfer function of the controlled MIMO system diagonal [1, 3]. So far, this is still the primary solution of coupling problem. Some other remarkable contributions have been made based on this idea. For example, Mesarovic divided the controlled systems with identical inputs and outputs into two different categories i.e., P-canonical and V-canonical systems based on system transfer function [4]; correspondingly, Sonquist and Morgan proposed a state space approach of decoupling control in [5]; a necessary and sufficient condition of the solvability of square system decoupling problem based on state space was put forward by Falb and Wolovich [6]; then, the equivalent condition for transfer function expressed system was obtained by Gilbert [7]. However, these methods are carried out on top of the assumption that the input and output numbers are identical. In other words, the controlled system is assumed to be square. A general decoupling strategy which released this assumption was given by Wonham and Morse [8] based on geometric approach. A similar control scheme was put forward by Silverman [9]. Other related researches of decoupling algorithms can be found in [10–12], to name a few. Among the extensive researches, the decoupling strategy used on distillation columns has become one of the most popular topics [13, 14].

In this paper, we collect most of the representative coupling analysis and decoupling strategies, and review their characteristics and application domains. Similar review works can be found in Liu [15] and Wang [16]. However, these two books were written in 1983 and 2002, so they did not include the recent studies especially some novel intelligent decoupling methodologies [17, 18].

The rest of this paper is organized as follows: Section 2 introduces some representative interaction analysis methods; Section 3 and Section 4 give detailed description of general purposed and special purposed decoupling strategies together with their characteristic and application do-

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mains, respectively; finally, the conclusion is given in Section 5.

2. INTERACTION ANALYSIS

2.1. Relative gain array (RGA)

The relative interaction between different input and output pairings should be the first problem to be considered in MIMO decoupling control.

The relative gain array (RGA) proposed by Bristol [19] is a widely accepted indicator used in quantifying the interaction degree between different input-output pairings. It only takes the steady state information of the controlled system into account. RGA of an n-input-n-output MIMO system is defined as [20]:

$$\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \dots & \lambda_{1n} \\ \lambda_{21} & \lambda_{22} & \dots & \lambda_{2n} \\ \dots & \dots & \dots & \dots \\ \lambda_{n1} & \lambda_{n2} & \dots & \lambda_{nn} \end{bmatrix}_{n\times n}, \tag{1}$$

where

$$\lambda_{ij} = \frac{\text{open - loop gain between } y_i \text{ and } u_j}{\text{closed - loop gain between } y_i \text{ and } u_j}, \quad (i = 1,2,...,n,\ \ j = 1,2,...,n). \tag{2}$$

There are some other interaction analysis algorithms proposed on top of RGA [21, 22]. But it should be remarked that because RGA only cares about the system steady state information, so it has weak capacity in identifying dynamic interaction between different input-output pairings.

2.2. Direct Nyquist array (DNA)

One alternative method to estimate dynamic interaction between different input-output pairings is the Direct Nyquist Array (DNA). It can give more coupling information than RGA from the frequency perspective. But the computation burden of DNA is also higher than RGA because DNA needs dynamic system transfer functions.

It is recommended that if the dynamic model of a MIMO system is available, interaction analysis methods like DNA should be applied to get more completed information. On the other hand, RGA can give wise guidance if only steady state gains are known.

2.3. Full decoupling and partial decoupling

According to coupling degree, MIMO systems can be divided into two categories: full coupling system and partial coupling system [15]. If any two control loop in a MIMO system have interaction between each other, we call it a full coupling system. Otherwise, it is a partial coupling system. Correspondingly, two kinds of decoupling methods arise, i.e., full decoupling and partial decoupling.

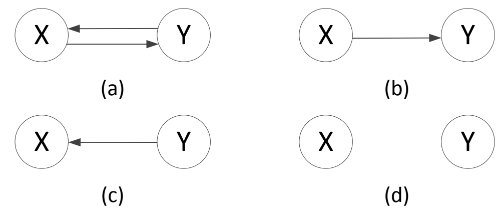

Fig. 1. Full coupling, partial coupling and full decoupling.

Fig. 1(a) represents a full coupling system with two control loops, i.e. X and Y; Fig. 1(b) and Fig. 1(c) are partial coupling cases of the same system. The corresponding full decoupled system is depicted in Fig. 1(d).

Theoretically, full decoupling is always preferred. But for most of the time, it may be hard or unnecessary or even impossible to be achieved because some immeasurable disturbance may exist in the controlled system.

3. GENERAL PURPOSE DECOUPLING ALGORITHMS

After a suitable input-output pairing is achieved in a MIMO system, the design of an appropriate decoupler or controller will be the next important step. An effective MIMO control strategy can be realized either by a centralized MIMO controller with a series of decouplers or a series of SISO decentralized controllers [22, 23].

3.1. Decentralized controller

Assume an n-input-n-output system which is described by $G(s)$ as:

$$G(s) = \{g_{ij}(s),\ \ i = 1...n,\ \ j = 1...n\}, \tag{3}$$

then a corresponding decentralized controller can be achieved as a diagonal matrix $C(s)$:

$$C(s) = diag\{C_{11}(s), C_{22}(s), \dots, C_{nn}(s)\}_{n\times n}. \tag{4}$$

A simplest decentralized control structure of a Two-input-two-output (TITO) system is shown in Fig. 2. Note that the interactions of MIMO process may not be restrained effectively under decentralized control. There are some papers focused on dealing with this problem [24,25].

Nevertheless, until now, there is still no widely accepted method which can tell whether a decentralized controller is appropriate to be used in a MIMO system or not.

3.2. Static decoupling

An MIMO system controlled by a centralized controller should be decoupled first. On this occasion, decoupling algorithms can be divided into two categories i.e., static decoupling and dynamic decoupling. A static decoupler can be designed simply based on steady state gains. So

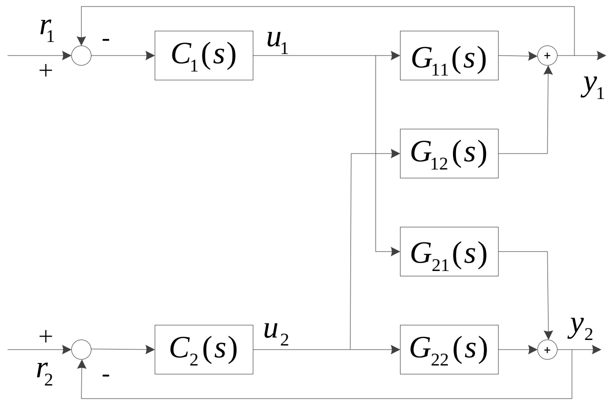

Fig. 2. Simplest decentralized control structure of TITO system.

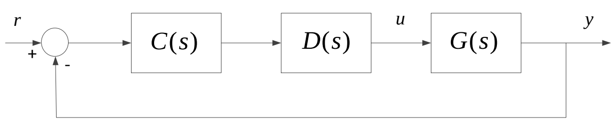

Fig. 3. General structure of a decoupled system.

it will be a wise choice to develop a static decoupler if available information is limited.

Consider a MIMO system whose transfer function is shown in (3). Imagine parameters $k_{ij},\ i=1...n,\ j=1...n$ are steady state gains of $g_{ij}(s)$. Then, the steady state gain matrix $G(0)$ can be obtained as:

$$G(0)=\{k_{ij},\ \ i=1...n,\ \ j=1...n\}. \tag{5}$$

A static decoupler which can make the MIMO system $G(s)$ shown in Fig. 3 decoupled is derived as:

$$D=G^{-1}(0). \tag{6}$$

As it is discussed in [26], a static decoupler may not provide satisfactory decoupling performance in a closed-loop. It may also give rise to some undesirable influence on high frequency response of some MIMO processes. The static decoupler is recommended to be used in systems with integral items [26]. This is because the magnitudes of non-diagonal terms will drop faster than that of diagonal ones along with the increase of frequency.

However, for some industrial processes, static decoupler is more preferred because it needs less information of the controlled system and can also reduce the risk of influence caused by model uncertainties. Meanwhile, the implementation of a static decoupler may be simpler compared with a dynamic one.

3.3. Dynamic decoupling

Compared with static decoupling, a MIMO system with dynamic decoupler always achieves better performance with the expense of acquiring an accurate process model. Generally, there are three kinds of dynamic decoupling algorithms which have been widely studied and applied in industrial processes i.e., ideal decoupling, simplified decoupling and inverted decoupling [27]. Each of these three decouplers has its own properties and limitations.

In this subsection, a TITO system which is one of the most representative MIMO systems is served as an example on account of the paper legibility and preferable expansibility [28].

3.3.1 Ideal decoupling

Consider a general TITO system with controller matrix $C(s)$, decoupler matrix $D(s)$, controlled plant matrix $G(s)$, set-point signals r_i, control signals u_i and outputs y_i as shown in Fig. 4:

$$C(s)=\left[\begin{array}{cc} C_1(s) & 0 \\ 0 & C_2(s) \end{array}\right]_{2\times 2}, \tag{7}$$

$$D(s)=\left[\begin{array}{cc} D_{11}(s) & D_{12}(s) \\ D_{21}(s) & D_{22}(s) \end{array}\right]_{2\times 2}, \tag{8}$$

$$G(s)=\left[\begin{array}{cc} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{array}\right]_{2\times 2}. \tag{9}$$

If the controlled system $G(s)$ is decoupled effectively, the product matrix $M(s)=G(s)D(s)$ which represents the decoupled system should be diagonal. Therefore, $D(s)$ can be obtained as:

$$\begin{aligned} D(s)=&G^{-1}(s)M(s)\\ =&\frac{1}{G_{11}(s)G_{22}(s)-G_{12}(s)G_{21}(s)}\\ &\times\left(\begin{array}{cc} G_{22}(s)M_{11}(s) & -G_{12}(s)M_{22}(s) \\ -G_{21}(s)M_{11}(s) & G_{11}(s)M_{22}(s) \end{array}\right)_{2\times 2}. \end{aligned} \tag{10}$$

The main idea of 'ideal decoupling' is setting $M_{11}(s)=G_{11}(s)$ and $M_{22}(s)=G_{22}(s)$ [13]. So the product matrix can be got as $M(s)=[M_{11}(s),\ 0;\ 0,\ M_{22}(s)]$ which shows the full decoupled system. Then, controller $C_1(s)$, $C_2(s)$ can be tuned in the same way under ideal decoupling. The controller does not need to be retuned even if different loops are set in different modes.

Though ideal decoupling has obvious advantages from the operating point of view [29], the complicated presentation of $D(s)$ which contains sums of transfer functions often appears as a problem. Moreover, the limited applicability problem discussed in [13] and the sensibility to model errors and system dimension of ideal decoupling [30] should not be ignored. Hence, ideal decoupling is rarely used in practice.

3.3.2 Simplified decoupling

Simplified decoupling which is more widely used in the literature is also proposed by Luyben [13]. A common

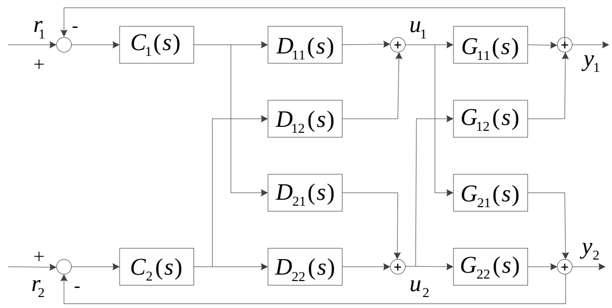

Fig. 4. Ideal decoupling structure.

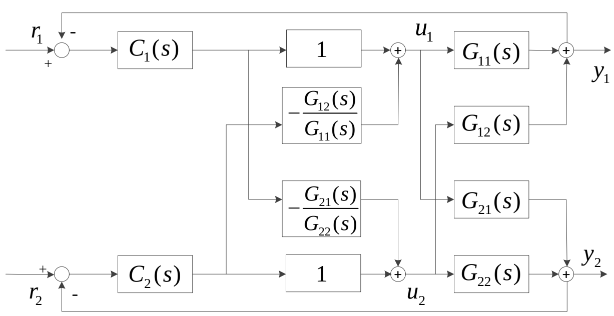

Fig. 5. Simplified decoupling structure.

expression of a simplified decoupled system is illustrated in Fig. 5:

$$D(s) = \begin{bmatrix} 1 & -G_{12}(s)/G_{11}(s) \\ -G_{21}(s)/G_{22}(s) & 1 \end{bmatrix}_{2\times 2}. \tag{11}$$

Only two decouplers have to be generated in simplified decoupling process compared with four of ideal decoupling. Waller *et al.* introduced three alternative configurations of simplified decoupling on account of some realizability problems [14]. Two elements in different columns of matrix $D(s)$ can be set into 1. So the other three alternative simplified decoupler configurations can be obtained as:

$$D(s) = \begin{bmatrix} -G_{22}(s)/G_{21}(s) & 1 \\ 1 & -G_{11}(s)/G_{12}(s) \end{bmatrix}_{2\times 2}, \tag{12}$$

$$D(s) = \begin{bmatrix} -G_{22}(s)/G_{21}(s) & -G_{12}(s)/G_{11}(s) \\ 1 & 1 \end{bmatrix}_{2\times 2}, \tag{13}$$

$$D(s) = \begin{bmatrix} 1 & 1 \\ -G_{21}(s)/G_{22}(s) & -G_{11}(s)/G_{12}(s) \end{bmatrix}_{2\times 2}. \tag{14}$$

Simplified decoupling scheme is easy to be implemented in practice. But there are still some summation elements in the decoupler expression, so controller tuning

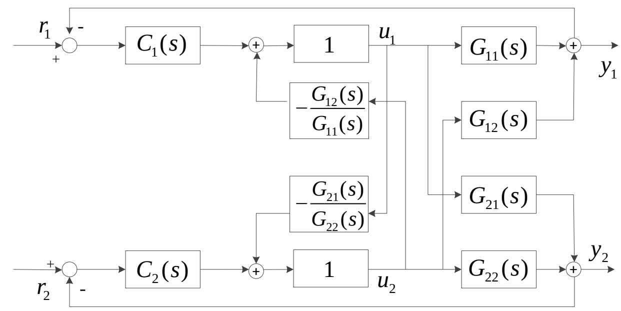

Fig. 6. Inverted decoupling structure.

process may also be difficult. An approximation of summation element was suggested in [27] to reduce burden in controller design stage. Problems of applying the simplified decoupling scheme to high dimension process still exist as the same as ideal decoupling [30].

3.3.3 Inverted decoupling

Another widely used decoupling algorithm which can derive the same decoupled process model as ideal decoupler without complicated $D(s)$ expression is inverted decoupling. It was first proposed by Shinskey [31], and illustrated at length by Wade in [32]. Fig. 6 depicts the structure of inverted decoupling. The specific derivation process can be found in [13]. For simplicity, $D_{11}(s)$, $D_{22}(s)$ can be set into 1, so that $D_{12}(s)$, $D_{21}(s)$ can be yielded as:

$$\begin{aligned} D_{12}(s) &= -\frac{G_{12}(s)}{G_{11}(s)}, \\ D_{21}(s) &= -\frac{G_{21}(s)}{G_{22}(s)}. \end{aligned} \tag{15}$$

Inverted decoupling has the same decoupled transfer function as ideal decoupling and the identical convenient realization as simplified decoupling. So it should possess both advantages of ideal and simplified decoupling [13]. Therefore, three advantages of inverted decoupling are summarized in [32] as: when inverted decoupling is applied, the decoupled system will act as there is no interaction between different control loops and the alternate controllers are in manual mode; each decoupled loop can be kept away from acting as the secondary of other control loops; it can be implemented in DCS as a feedforward input. Moreover, the initialization and bumpless problems will not appear when system mode changes.

There are also several papers discussed about the improvement of inverted decoupling [30, 33, 34]. An extended approach of different configurations of inverted decoupling strategy which has more flexibility was proposed in [33]. Aiming at solving decoupling problems with multiple time delays and nonminimum-phase zeros, another improved inverted decoupling technique was proposed in [34]. Nevertheless, this technique is only valid to a part of

MIMO systems.

On the whole, inverted decoupling has more benefits compared with other dynamic decoupling schemes. With this kind of decoupler, some problems like initialization, bumpless switches between manual and automatic modes, and saturation of manipulated variables are easier to be solved.

3.3.4 Advices on when and how to use dynamic decoupling algorithms

In this subsection, authors will give some remarks and advices on some frequently occurred problems of the dynamic decoupling algorithms which have been discussed [13, 27, 31, 34].

1) Realizability

A decoupler is realizable if the outputs of its elements are not determined by their future input values. In other words, all the items in a decoupler have to be proper. An item as $e^{\tau s}(\tau > 0)$ cannot appear in the decoupled system transfer function [32]. Some studies suggest to solve this problem by adding an additional time delay to the unrealizable items when it is necessary [13]. It can be regarded as a good idea sometimes. However, the stability of MIMO system after inserting another delay term cannot be guaranteed at times.

2) Stability

As shown in [35], the systems with simplified decoupling are nominally stable, but the ones with ideal and inverted decoupling are unstable, especially when RHP zeros appear in the system transfer function. A parameter K which can give stability judgment of an inverted decoupled system has been proposed in [32]. The limitations are strictly stated, and may also be available to ideal decoupling. However, K will be hard to achieve according to its expression.

3) Robustness

A widely accepted method to evaluate control system robustness is singular value analysis which was proposed by Arkun *et al*. [35]. It has already been used in several decoupling processes of distillation columns [14]. Study [35] concluded that ideal decoupling was sensitive to modeling error. Therefore, ideal decoupling method has seldom been applied in real control process. As another form of ideal decoupling, inverted decoupling which removes this weakness has been widely accepted. However, it was verified in study [27] that ideal, simplified and inverted decoupling algorithms might lead to identical robustness when the controllers were tuned to achieve equivalent closed-loop system performance. In this case, controller design complexity may be another factor to be considered.

4) Implementation

It is pointed out in [32] that ideal and simplified decouplers ignore the mismatch of input signal flow rate between computer and controller. MIMO systems using inverted decoupling scheme will still keep decoupled when system operation mode is changed. However, ideal and simplified decouplers do not possess this advantage. This means that the controller parameters should be retuned if the operation mode is changed. One way to solve this problem is switching the operation mode after the decoupled system reaches steady state [27]. Besides, inverted decouplers can be implemented directly by most of the standard blocks configured in modern DCS systems [31].

4. SPECIAL PURPOSE DECOUPLING ALGORITHMS

4.1. Delay system decoupling control

Time delay is a critical and frequently occurred problem in industrial processes. It may lead to serious problems such as offset, sluggish system performance or even unstable oscillations [36]. Moreover, these undesirable performance may become even worse when multi-variable time delays appear in different input-output pairings.

4.1.1 Smith predictor

For SISO systems, there is a widely accepted time delay compensation algorithm named Smith Predictor [37]. This compensation algorithm was improved to be applicable to MIMO systems with multi-variable delays by Ogunnaike and Ray under some specified assumptions [38]. Other developments aiming at multi-variable Smith Predictor can be found in [39, 40]. These decoupling methods are mainly focused on systems with multi-variable delays. These decoupling methods tried to make the MIMO system decoupled first, so the interactive MIMO system control problem would be transformed into multiple single loops system control problem. Then, the Smith Predictor can be designed based on the decoupled system. However, the uncertain accuracy of the predictor, unrealizable matrix inversion expression and complicated decoupling procedure have kept Smith Predictor decoupling away from being extensively applied in industrial processes.

4.1.2 Dead-time compensator

A dead-time compensator (DTC) based on a unity feedback control structure was proposed by Liu *et al*. [41]. It is shown that this analytical decoupling algorithm can realize significant or even absolute decoupling for MIMO system with less computation effort. Similarly, study [30] proposed another alternative improvement of inverted decoupler with DTC for first order plus delay MIMO system. However, two breakpoints should be put here aiming at this scheme. One is that the success probability of this decoupling strategy may be impacted a lot by the accuracy of the system model delay; the other is the expense of the implementation of DTC in practice should be taken into consideration.

4.1.3 Approximate decoupling method

Another novel approximate decoupling method aiming at time delay systems was proposed by Nordfeldt *et al.* [42]. The authors transformed the first-order item with longer time constant T_l into a second-order item by using the difference of T_l and the shorter time constant T_s as:

$$\frac{1}{T_l s+1} \approx \frac{1}{(T_s s+1)((T_l-T_s)s+1)}. \tag{16}$$

In this way, the remained pole $1/(T_s s+1)$ can be eliminated from the matrix column. Nevertheless, the relative size degree of T_l, T_s was not mentioned in the paper. Hence, the decoupling performance affected by this degree may be a problem.

Moreover, some effective decoupling schemes aiming at MIMO system with multi-variable time delays which are proposed based on Internal Model Control will be discussed later. It should be noted that delay terms and non-minimum phase zeros may be included in the controller when the above control algorithms are used, which may lead to some unpredictable problems.

4.2. Intelligent decoupling control

For some complicated MIMO industrial processes with strong nonlinearity, high coupling, uncertainties, or even unstable non-minimum phase and unmeasurable delay, the above mentioned decoupling algorithms may not work. A simple method to solve this kind of problem is making approximation of the complicated system by a first or second-order delay model. The identification process of the controlled model is usually achieved through on-site data and a rigid gain scheduler which helps compensate the nonlinear parts [43,44]. However, the preciseness and accuracy of these methods highly depend on practical condition. Besides, many intelligent decoupling algorithms have been proposed for those complicated systems [45–47]. Among them, adaptive control, fuzzy control, neural network control are the representative ones.

4.2.1 Adaptive decoupling

Adaptive decoupling algorithm was proposed by Borisson in 1979 [48]. Ever since, it has been intensively discussed [49]. In [49], adaptive decoupling controllers based on self-tuning and zero-pole replacement were designed respectively. In [50], interaction caused problem in MIMO system was solved by a feedforward compensator. Practical examples of adaptive decoupling control can be found in [51].

4.2.2 Intelligent decoupling

Recently, some intelligent decoupling methods which were proposed based on fuzzy adaptive control and Neural-Networks (NNs) have been studied [52–54]. The advantage of this kind of decoupling methods is that they can handle uncertainty problems in complicated practical processes. In addition, some other intelligent decoupling control schemes on top of GA (Genetic Algorithm), PSO (Particle Swarm Optimization) and etc can be found in [55].

Nevertheless, in sharp contrast to the extensively discussion of intelligent decoupling controller design method, the robustness and implementation methods of them have barely been studied in the literature. Moreover, the research on nonlinear MIMO systems with uncertainties and strong coupling performance is still absent. Most of the intelligent algorithms are relatively complex and hard to realize in practice, so more effort is needed on this topic.

4.3. Analytical decoupling control

The inverse transfer matrix $G^{-1}(s)$ will be needed in most of the decoupling processes. The inverse of a static gain transfer matrix is always easy to be obtained. However, the form of $G^{-1}(s)$ is quite hard or even cannot be achieved in theory. An adjoint matrix decoupling scheme which could realize diagonal decoupling bypassing the inverse matrix problem has been proposed in [56]. This algorithm was presented based on the characteristic sequence concept. The specific implementation procedure is also given.

The effectiveness of the adjoint matrix decoupling scheme has been proved in [56]. This algorithm may be suitable for processes with high-order and big delay items in their transfer functions. But the implementability and computability should be confirmed by more research effort.

4.4. Internal model control

Based on the Internal Model Control (IMC) theory, study [57] presents some iterative algorithms to deal with the complicated delay decoupling problems. Liu *et al.* proposed a new analytical decoupling controller design method with the configuration of the standard IMC structure for TITO multi-variable time delay systems [58]. The authors have also presented a method of evaluating control system Another effort of IMC decoupling control is robust stability when time delay and other uncertainties occured in control loops. made by Wang *et al* [16]. The system which is decoupled through this algorithm can get satisfactory performance with acceptable overshoots and quick response. However, the computation burden of this method may be quite large. Other recent efforts of IMC based decoupling algorithms can be found in [59].

4.5. Model predictive decoupling control

Model Predictive Control (MPC) is one of the most frequently applied control algorithm in industry processes.

Actually, MPC is not a way to design a decoupler. It is an alternative way of handling interacting loops when the interactions are too severe or the classical decoupling design is too complicated. A number of studies have discussed about how to improve MIMO control performance by MPC [60–62]. In [60], a continuous time predictive control algorithm aiming at MIMO decoupling problem was presented. The control performances of an industrial MIMO system achieved by decentralized PI controller and Dynamic Matrix Control (DMC) scheme were compared in [61]. Another modified MPC control scheme was proposed in [62] to reduce cross-coupling in MIMO system. A remarkable reduction in cross-coupling performance is shown to demonstrate the effectiveness of this control scheme.

Most of the MPC schemes used in MIMO decoupling system are capable to deal with delay items as well as nonminimum-phase items. They do not need a procedure to design the decoupler either. But the parameter tuning processes of the MPC or DMC algorithms applied in practical process are usually relatively hard to handle. Moreover, a state space model which is hard to achieve in industry processes may be needed if MPC is considered to be used.

5. CONCLUSION

In this paper, a comprehensive review of the existing cross-loop interaction analysis and decoupling control methods has been presented. Two categories i.e., general purpose and special purpose decoupling algorithms are introduced with their properties, advantages, and application domains. This survey can serve as a reference or guidance for researchers and engineers with different backgrounds to get involved in this field easily.

It should be pointed out that, though decoupling is an important problem in MIMO process control, there are still cases where decoupling may not be needed [1]. For example, in the airplane control system, coupling is used to boost system performance [63]. On the whole, decoupling is one of the preferred methods to improve the control performance of MIMO systems, but it is not always necessary. The necessity should be decided according to specific applications.

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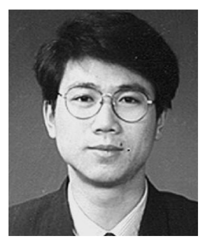

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