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An effective direct closed loop identification method for linear multivariable systems with colored noise

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A R T I C L E I N F O

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A B S T R A C T

Multivariable control systems with colored noise widely exist in the most industrial fields, while the system identification under the closed loop conditions is needed in many cases. In view of the above two situations, it needs to find a convenient and effective method to solve the problem. Firstly, the design of the external input signals ensures the identifiability of closed loop system. Secondly, to make the direct method feasible for closed loop identification, the noise model selected is reasonably flexible and independently parameterized. On this basis, this paper proposes an improved method combining the direct closed loop identification approach with the iterative least squares parameter estimation algorithm, which can be an practical solution to the closed loop identification of multivariable systems with colored noise. The presented algorithm based hierarchical identification principle has a strong anti-jamming capability to effectively deal with colored noise existed in the system. Finally, the illustrative examples are given to demonstrate the effectiveness and accuracy of the proposed algorithm.

1. Introduction

In the process control, performing identification experiments under output feedback (i.e., in closed loop) is particularly necessary while open loop identification is not allowed by factors of the stability, security and economy [1]. On the other hand, closed-loop conditions shape additional challenges for system identification [2–4]. The fundamental problem is that of the correlation between the disturbances and the manipulated variables through the feedback. The correlation actually point to a "biased plant" because of the feedback effect. Thus, more research efforts have been made to overcome these potential shortcomings, which give us a good direction to develop the closed loop multivariable identification. Generally, the closed loop identification methods correspondingly are classified into the following three approaches [5]:

(i) *The direct approach*: The effect of feedback is ignored and the process is identified directly from the input and output data using any open-loop identification technique.
(ii) *The indirect approach*: Some closed-loop transfer functions are identified, and the open loop parameters are determined using the knowledge of the linear controller.
(iii) *The joint input-output approach*: Regard the input and output jointly as the outputs from a system driven by some extra input or set-point signal and noise. Recover knowledge of the system and the controller from this joint model.

Among these three approaches, the direct approach is popular due to its simplicity, and does not require the knowledge and the form of the controller. In this way, this method appears practical, but it also requires challenges and aspects to be satisfactorily addressed. Based on the earlier researches, the direct method can be used to provide asymptotically unbiased results, provided that the true process model and the true disturbance model are used and identified simultaneously. While the issues related to the true process model can be addressed by selecting the suitable descriptions of the model based on the actual situation, this paper focuses on the design of the noise model that should be reasonably flexible, independently parameterized [6–8]. At the same time, we also need to suitably design the external input signals or dither signals to meet the identifiability of the system [9,10].

Since pseudo-random sequence theory has been widely applied to the field of system identification. Each of the input signals generated by multi-dimensional inverse M sequence generator is approximate to a cyclic white noise without D.C component and interaction [11]. We superpose these specific signals on the input terminal of process which can ensure a sufficient incentive of feedback channel. Then the open loop identification method can be used in this way.

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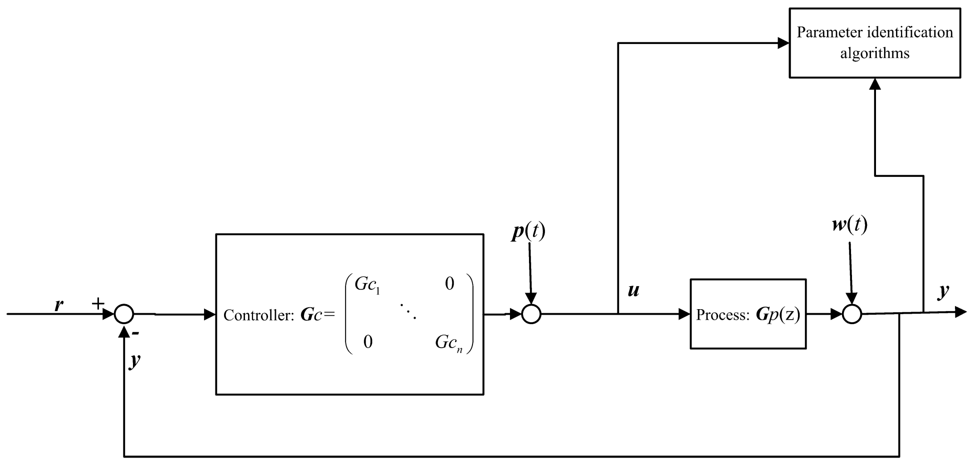

Fig. 1. Direct identification for a $n \times n$ multivariable closed loop system. Vector $\boldsymbol{w}(t)$ refers to unknown colored noise sequence, $\boldsymbol{r}$ is the reference signal, $\boldsymbol{u}$ and $\boldsymbol{y}$ are respectively the input and the output of the controlled process, $\boldsymbol{p}(t)$ represents the input test signal.

Like the recursive approach, the iterative algorithm is a large class of identification methods. It is usually used to identify the system which contains unknown terms of the model information vector. So the iterative identification principle can be applied for all the equation error type models and output error type models. Then the basic idea of iterative identification is to adopt the interactive estimation theory and the hierarchical identification principle to refresh parameter estimates using batch data. Least squares algorithm based on iterative principles is an improved least squares method [12–20]. It has a strong anti-jamming capability to effectively deal with colored noise exited in the system.

In short, we use the direct identification method and the least squares based iterative parameter estimation algorithm to identify the closed loop multivariable systems with colored noise. An $n \times n$ multivariable closed loop system with the decentralized controller is considered in this paper [21]. The process model involved is a general equation error model and we do not care about the specific form of the noise model. Thus, the process model considered is different from the model in [22].

This paper is organized as follows: In Section 2, the direct approach for closed loop identification and the design of the input test signal are introduced. Least squares algorithm based on the iterative principle is described in Section 3. Section 4 does the analysis of bias elimination to overcome the theoretical limitations toward a "biased plant" in closed loop identification. Illustrative examples of closed loop multivariable systems are given in Section 5, which contain a linear 2×2 system and a Ogunnaike and Ray (OR 3×3) process [23] with delay set to zero. Finally, conclusions are drawn in Section 6.

2. The direct identification method and the design of input test signal

The direct method uses the process input–output data obtained in the closed loop conditions to conduct the identification algorithm directly. It is equivalent to put the process in the open loop environment. Extended to the closed loop multivariable system, we can create a block diagram of identifying the model parameters. A $n \times n$ multivariable closed loop system with the decentralized controller is shown as Fig. 1, where vector $\boldsymbol{w}(t)$ refers to the unknown colored noise sequence existed in the system, $\boldsymbol{r}$ is the reference signal, $\boldsymbol{u}$ and $\boldsymbol{y}$ are respectively the input and the output of the controlled process, and $\boldsymbol{p}(t)$ represents the input test signal. Thus, the direct method is to use $\boldsymbol{u}$ and $\boldsymbol{y}$ to identify the controlled multivariable process.

Although the direct identification seems relatively easy to implement, it needs to ensure the identifiability of closed loop system. To solve this problem, we use the multi-dimensional inverse M sequence generator to generate the input test signal $\boldsymbol{p}(t)$.

For a multivariable process in the closed loop, we superpose multi-dimensional inverse M sequences on the input terminal of process which can ensure a sufficient incentive of feedback channel. In this way, it can meet the identifiable conditions of closed loop structure and can still use the open loop identification method.

Multi-dimensional inverse M sequence generator [11] is illustrated in Fig. 2, where M is an M-sequence generator, P is the pulse generator. Further, D_i $(i = 1, 2, \ldots, p)$ is the 2-divider, and $Q_i(t)$ is the initial state pulse of the M-sequence generator. $M(t), P_i(t), IM_i(t), \quad i = 1, 2, \ldots, p$ are all the periodic signals with amplitude equal to 1. The r level output of 2-divider is a square wave signal with the period, $T_r = 2^r \Delta$. Thus, we define:

$$P_r(t) = \begin{cases} 1 & 0 < t < 2^{r-1}\Delta \\ -1 & 2^{r-1}\Delta < t < 2^r\Delta \end{cases} \tag{1}$$

The r-dimensional inverse M sequence is given as following:

$$IM_r(t) = P_r(t) \oplus M(t), \quad r = 1, 2, \ldots, p \tag{2}$$

where $IM_r(t)$ is known as one of the inverse M sequences. For extended application, we can set the amplitude levels for the generated signals. Let $R_{IMr_1 IMr_2}(\tau)$ be the cross-correlation function of any two inverse M sequences. And the properties of the signals are shown below.

(i) The nature of zero-mean: $\frac{1}{T_{IMr}} \int_0^{T_{IMr}} IM_r(t)dt = 0$
(ii) The nature of the unrelated: $R_{IMr_1 IMr_2}(\tau) = 0, \quad r_1 \neq r_2$

Assume that $\boldsymbol{IM}(t) = [IM_1(t), IM_2(t), \ldots, IM_p(t)]^{\mathrm{T}}$, then the input test signal $\boldsymbol{p}(t)$ is obtained along with $p(t) = \boldsymbol{IM}(t)$. Thus, it concludes that specific design of each component of $\boldsymbol{p}(t)$ is approximate to a cyclic white noise without D.C component and interaction. In the practical applications, the signal generator is simple in structure. And by the design of the external test signal having a sufficient incentive, the direct method for closed loop identification becomes possible.

3. Least squares algorithm based on the iterative principle

Generally, we do not care about the specific form of the noise model and hope to obtain the more precise parameter estimates