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Iterative learning control applied to batch processes: An overview

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Abstract

With the recent emphasis on batch processing by emerging industries like the microelectronics and biotechnology, the interest in batch process control has been renewed. This paper gives an overview of the iterative learning control (ILC) technique, which can be used to improve tracking control performance in batch processes. The fundamental concepts and review of the various ILC algorithms are presented, with a particular focus on a model-based algorithm called Q-ILC and an application involving a rapid thermal processing (RTP) system. The study indicates that one can solve a seemingly very difficult multivariable nonlinear tracking problem with relative ease by intelligently combining the ILC technique with basic process insights and standard system identification techniques. Some related techniques in the literature are brought forth with the hope of unifying them. We aslo suggest some remaining challenges.

Keywords: Tracking control; Iterative learning control; Model-based control; Batch process control

1. Introduction

Batch processes have historically lagged continuous processes in terms of development and deployment of advanced optimization and control tools. Whereas significant developments have occurred during the past few decades in the industrial practice of continuous process control (Morari & Lee, 1999; Qin & Badgwell, 2003), the same has not been the case for batch processes, which have continued to rely on old techniques like ladder-logics and PID control. Part of this can be attributed to the comparatively lower production volume through batch processing. Another reason for this may be that batch processes present a set of challenges uncommon in continuous processes, including nonstationary operating recipes, the consequent exposure to process nonlinearity, and significant variations in the initial charge condition (Berber, 1996). These challenges are not easily met by the standard linear optimal control theories and tools, which are widely adopted for continuous industrial process control today.

However, the role of batch processing is ever-increasing in today's diversified manufacturing environment. Besides the fine or specialty chemicals, new industries that have emerged from the VLSI technology, bio-technology, and material science are mostly batch-processing-oriented. In accordance with its increased importance, its operation support tools need to be upgraded. Such a shift in the trend has already started taking place, as evidenced by the extensive use of run-to-run control and multivariate monitoring in some of the new industries. However, much more can be done, even with existing technologies today. For example, iterative learning control (ILC), the topic of this paper, has not enjoyed a serious look by the practitioners thus far despite its vast potentials for improving tracking control performance in batch processes.

This paper presents an overview of ILC in the context of trajectory tracking problems in batch processes. Although basic theories of ILC have been firmly laid out in the literature, it is not always straightforward to apply them to achieve success in practice. ILC is discussed in the context of a multiple point temperature tracking problem in a rapid thermal processing (RTP) system. By doing so, the objective is to bring forth the unique capabilities of ILC

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for batch process control and at the same time some of the subtle challenges one may face in applying the technique. Fortunately, such challenges are not insurmountable and the standard linear ILC technique can provide an excellent performance for what appears to be a very difficult nonlinear trajectory tracking problem. Some related techniques like repetitive control and two-dimensional control are pointed out, highlighting the similarities and differences. Finally, some open issues left for future research are introduced.

2. Exemplary problem: temperature tracking control for an RTP system

In the operation of RTP systems, one of the most important challenges is to achieve uniform temperature distribution across the wafer surface while tracking a reference trajectory with a temperature range of several hundred degrees. From the system theoretic viewpoint, it is a nonlinear, multivariable control problem involving a batch system with fast dynamics and noisy measurements. Added to this are the facts that a single RTP system can be used for different wafer fabrications demanding different temperature trajectories to be followed and the characteristics of a RTP system may vary significantly by reasons like contamination. All these factors combine to make reliable modeling of the system very difficult (Cho & Gyugyi, 1997). In the presence of significant model errors, traditional feedback control techniques, though successfully applied in some commercial RTP equipments (Peuse, Miner, Yam, & Elia, 1998), may not provide satisfactory temperature tracking performance, as evidenced in some of the previous studies (Breedijk, Edgar, & Trachtenberg, 1993; Dilhac, Ganibal, Bordeneuve, & Nolhier, 1992; Schaper, Moslehi, Sarawat, & Kailath, 1994; Stuber, Trachtenberg, & Edgar, 1994).

The experimental RTP equipment with a computer interface system used in this example is shown in Fig. 1. The silicon wafer is heated by an array of 38 bar-type tungsten-halogen lamps, the maximum power of 1 kW each. The lamps are assembled together by four or five to comprise a total of 10 independent groups, as shown in the figure. The chamber wall is cooled with circulating cooling water. The electric power inputs to the 10 groups, denoted by $u_1, \ldots, u_{10}$, are therefore the manipulated inputs. Wafer temperature was measured at eight points with K-type thermocouples (TCs) glued on the backside of the wafer surface. As a consequence, the experimental RTP equipment is configured as an 8×10 MIMO system. In the commercial RTP operation, however, such a wafer with embedded thermocouples would be available only for testing purposes. In actual production runs, in situ temperature measurements would have to be provided by pyrometers, and for economic reasons and by spatial constraint, the number of such sensors per equipment may be limited. Hence, in addition to the full 8×10 system, the possibility of limiting the temperature measurements to just three locations were investigated, too. In this case, selection of the measurement points becomes an important issue.

Radiative heat transfer equations can be used to construct a fundamental or semi-empirical model representing heat balances. Due to the space limitation, the readers are referred to the open literature for the details of such models (Cho, Lee, Joo, & Lee, 2005; Lee, Lee, Chin, Choi, & Lee, 2001). Given the idiosyncratic designs of individual equipments, however, it is more realistic to try to develop a control model from system identification, which is the approach adopted here.

It is worth noting that the temperature control problem in most commercial RTP systems is highly ill-conditioned (Cho, Joo, Won, & Lee, 2005). It is because the systems are designed to be easily controllable only along the equi-temperature direction. The principal direction of the gain matrix of an RTP system does not exactly coincide with a uniform temperature profile across the wafer. Hence, in order to achieve the uniformity, it is necessary to manipulate the secondary gain directions. For this reason, it is best to utilize all the available degrees of freedom, as doing so could improve the conditioning of the gain matrix.

3. Iterative learning control

ILC is a general technique for improving transient tracking performance of a system that executes a same operation repeatedly. In its basic formulation, a target system has the following characteristics: (i) each run lasts for a fixed length of time; (ii) the reference trajectories (to be followed by the outputs) remain the same from run to run; (iii) the process state is reset to a same value at the start of each operation. ILC techniques developed under such assumptions can be used effectively on a process with some disturbances and initialization errors as well as occasional changes in the reference trajectories, however. Temperature tracking problems in many chemical batch processes can be tailored to fit into this category.

3.1. Historical account

It seems that the first technical contribution on ILC was the patent work by Garden (1971) three decades ago. Although a few independent contributions followed after that (Miller & Mallick, 1978; Uchiyama, 1978), it seems to have gone unnoticed by the larger control community until Arimoto, Kawamura, and Miyazaki (1984) proposed the so-called D-type learning algorithm as a teaching mechanism for robot manipulators. This seminal work launched ILC into the mainstream control community and established it as a new branch of control technology. Significant body of work followed after that, which is summarized below. However, it is not claimed that the list of references to be complete or unbiased.