498a Predictive Control of Particulate Processes with Actuator/Sensor Faults

Adiwinata Gani, Prashant Mhaskar, and Panagiotis D. Christofides

Particulate processes are prevalent in a number of process industries including agricultural, chemical, food, minerals, and pharmaceuticals. Examples of particulate processes include the crystallization of proteins for pharmaceutical applications, the emulsion polymerization reactors for the production of latex, and the titania powder aerosol reactors used in the production of white pigments. One of the key attributes of particulate systems is the co-presence of a continuous phase and a dispersed phase, which leads to the occurrence of physico-chemical phenomena such as particle nucleation, growth, coagulation, and breakage which are absent in homogeneous processes and lead to a distributed characterization of the physical and chemical properties of the particulate product such as particle size, shape, morphology, porosity, molecular weight, etc. The mathematical models of particulate processes are typically obtained through the application of population, material and energy balances and consist of systems of nonlinear partial integro-differential equations that describe the evolution of the PSD, coupled with systems of nonlinear ordinary differential equations (ODEs) that describe the evolution of the state variables of the continuous phase.

It is well understood that the physico-chemical and mechanical properties of materials made with particulates are strongly dependent on the characteristics of the corresponding particle size distribution (PSD). For example, a nearly mono-disperse PSD is required for titania pigments to obtain the maximum hiding power per unit mass. Also, in coatings the product's composition, molecular weight and particle size distributions often need to be maintained in specific ranges to ensure the coating has a desired level of film formation, film strength, and gloss. These considerations motivate controlling the particle size distribution to achieve desired product characteristics. The PBMs, however - owing to their infinite-dimensional nature - cannot, in general be directly used for the synthesis of practically implementable controllers, and this has motivated significant research work on the development of a general order reduction procedure, based on combination of the method of weighted residuals and approximate inertial manifolds, which allows deriving low-order ODE approximations that capture the dominant dynamics of particulate processes [1]. The low-order controllers can be subsequently used to design readily-implementable controllers that incorporate constraints on the process state variables (which reflect performance considerations) and manipulated inputs (which reflect physical limitations of control actuators).

In current industrial practice, the achievement of optimal performance, subject to input and state constraints, relies to a large extent on the use of model predictive control (MPC) policies which are well known for their ability to handle multi-variable interactions, constraints, and optimization requirements, all in a consistent, systematic manner. Unlike open-loop model-based optimal control policies (where the optimal operating conditions are calculated off-line), in MPC, the control action is computed by solving repeatedly, on-line, a constrained optimization problem at each sampling time. Owing to this, MPC has the ability to suppress the influence of external disturbances and tolerate model inaccuracies (because of the use of feedback) and force the system to follow the optimal trajectory that respects constraints on the operating conditions.

In [2,3] we focussed on the development and application of predictive algorithms for control of PSDs in continuous and batch particulate processes described by PBMs. For continuous particulate processes, we considered the control objective of asymptotic stabilization under constraints and develop a hybrid predictive control methodology that employs logic-based switching between MPC and a fall-back bounded controller with a well-defined stability region. The strategy was successfully used to stabilize a continuous crystallizer at an open-loop unstable steady-state. For batch particulate processes, the control objective is to achieve PSD with desired characteristics subject to both control and product quality constraints. An optimization-based predictive control strategy that incorporates these constraints explicitly in the controller design was formulated and applied to batch crystallizers of potassium sulfate crystals and hen egg-white Lysozyme (protein) crystals. The work in [2,3] however, assumed perfect operation of sensors and actuators; in practical applications, however, the sensors and actuators may exhibit faults, such as measurements being available infrequently and/or failure of an actuator. These faults can impact negatively on the stabilizing (causing instability) as well as performance (manifested in the violation of constraints) properties of a given control design.

Motivated by the above considerations, this work focuses on the control of continuous and batch particulate processes, analyzes the stabilization and constraint handling properties of predictive control designs subject to actuator/sensor faults, and proposes methods to redesign the controller so that it continues to achieve stabilization/constraint satisfaction in case of actuator/sensor faults. To this end, we first present a population balance model describing the evolution of crystals in continuous and batch systems. Then, model reduction techniques are used to derive a reduced-order moments model for the purpose of controller design. Online measurements of the continuous-phase variables such as solute concentration and reactor temperature are assumed to be available, and a Luenberger-type observer is used to estimate the moments of the crystal size distribution based on the available measurements. A predictive controller, that uses the available state estimates, is designed to achieve the performance objectives while respecting constraints on the manipulated input variables and on the process state variables, subject to sensor/actuator faults. Simulation results are presented that demonstrate its application, and robustness of the predictive controller to plant-model mismatch is investigated.

References:

[1] Christofides, P. D., Model-Based Control of Particulate Processes, Kluwer Academic Publishers, The Netherlands, 2002.

[2] Shi, D., N. H. El-Farra, P. Mhaskar, M. Li and P. D. Christofides, Predictive Control of Particle Size Distribution in Particulate Processes, Chem. Eng. Sci., in press.

[3] Shi, D., P. Mhaskar, N. H. El-Farra and P. D. Christofides, Predictive Control of Crystal Size Distribution in Protein Crystallization, Nanotechnology, in press.