Hybrid Control of a Mixed Continuous-Batch Process

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Abstract
This paper deals with a control problem related with a mixed continuous-batch process, a pilot plant of our Lab, where both continuous decisions and scheduling takes place. We tried to find a solution in the framework of non-linear model predictive control formulating the control problem by means of an hybrid model in terms of integer and continuous variables. As the system must be controlled in real-time, mixed integer optimization algorithms proved to be too slow, so, an alternative formulation in terms of real variables was set up. The paper describes the process, the control problem formulation, and the optimization alternatives and provides results of some test for evaluation of the proposed approach.

Keywords: MLD Systems, Hybrid Predictive Control, Mixed continuous-batch processes.

1. Introduction

Many processes, even those of continuous nature, involve signals or working rules that make them different from the classical continuous operating environment where only magnitudes represented by real variables and modelled by DAE are present. In practice, these processes include on/off valves or other binary actuators, are subjected to logical operational rules, or are mixed with sequential operations. As a result, classical control does not fit very well with the overall operation of the plant and other approaches like hybrid control must be considered.

Hybrid systems have received a lot of attention in the latest years. There are several approaches to hybrid systems control. Some of them set hierarchical levels, leaving the continuous parts in the bottom and the discrete decision variables in the upper ones (Grossmann, et al., 1993). Other approaches take advantage of the fact that prepositional logic expressions can be formulated in a systematic way as linear inequalities of binary variables (Clocksin and Mellish, 1981). An important contribution in this line is (Bemporad and Morari, 1999), where MLD systems are defined and analysed and the

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problem is solved as a MIQP. Other contributions can be seen in (Colmenares, et al., 2001; Zhu et al., 2000). More recently (Morari et al., 2003) have presented a solution for piece-wise affine and mixed logical dynamic systems based on parametric programming.

In this paper a particular problem, where continuous processes operate together with a set of batch units following a given sequence of stages, is presented from a process control perspective. Here the timing and scheduling of the operation is a key factor combined with continuous control. The problem refers to a small pilot plant but it has the relevant characteristics of an industrial scale setup of many process factories where a significant number of bottleneck problems occur. The standard control approach, based on a continuous process model and continuous manipulated variables, fails due to the discrete (integer) or logical nature of the new elements. In the same way, scheduling of the batch units alone cannot cope with the regulatory control of other variables. It is then important to reformulate the control problem finding adequate representations of this hybrid system as well as practical paths to solve and analyse it. The aim of the paper is to present a formulation using the predictive control framework as well as some results of its operation.

The paper is organised as follows: section two describes the process and its control and operation aims, section 3 deals with the formulation and alternatives of the hybrid controller, and section 4 presents results showing the plant response to a set of disturbances. Finally the paper ends with some short conclusions and references.

2. Process Description and Control Aims

The selected process can be seen in Fig.1: It is a small lab plant that consists of two batch processes operating in parallel plus a supply tank and a storage one with recyle. At a small scale, it resembles real plants where a continuous unit feeds a set of batch ones that are followed by a separation unit with recyle. The process has an uncontrolled flow $q_1$ that mix with the recirculating flow $q_{31}$ in a tank that can feed two batch units where the raw material is processed with different cycle times. After finishing the operation, they can be discharged in the bottom tank, where it mixed with a third current $q_{23}$ and (after an ideal separation) the final product leaves as $q_{32}$ and the rest is recirculated.

In our problem we do not focus the attention in the individual control of the two batch units, which are commanded by a (PLC) that follows a prescribed filling-warming-discharging strategy. We are interested in the overall management of the plant so that it can process a given inflow ($q_1$) and deliver the desired product ($q_{32}$) out of the system at a desired temperature while keeping the levels of the other two extreme tanks within a given range and the temperature of the supply tank as close as possible to a given set point operating smoothly in spite of disturbances. The decision variables for this purpose are the opening of the continuous valves $V_{23}$ and $V_{31}$ and the discrete times for starting and discharging the batch units, that is the $u_{ij}$ on/off valves. An additional on/off input valve can be actuated in emergencies.
3. Hybrid Predictive Control

We approach the problem in the framework of predictive control using a model of the plant to predict the future evolution of the system. Based on this prediction, at each time step, the controller selects a sequence of future command inputs through an online optimization procedure, which aims at maximizing the tracking performance subject to given constraints. The cost function was a quadratic function of the prediction error of the temperatures and levels of both tanks. In addition to the classical range constrains on the system variables other operational constraints includes the logic of the batch operation, for instance, pump $B_{11}$ cannot be turned on if the left batch reactor is not empty and must be off a certain time after. In a similar way, discharge pump $B_{21}$ cannot be turned on before a certain minimum operation time, etc.

A first approach of the predictive controller for this plant was implemented like a mixed integer optimisation problem (Colmenares, et al., 2001) using a discretised linear model.
of the process. The prepositional logic involving both continuous and discrete variables was transformed into linear inequalities with additional 0-1 variables, and the decision variables linked to charge/discharge valves of the batch units where represented also by integer variables. The problem was then posed and solved as a MIQP. This approach implies a lot of computations and the problem cannot be solved on-line taking into account that the sampling time is 30s.

As an alternative, the problem was reformulated including the logic of operation in a simplified simulation model and giving the charge/discharge valves a prespecified shape, see Fig.2, where the decision variables were the times for turning them on and off, $Tc_1$ or $Td_1$ in Fig.2. Additional constrains on these times allow to implement the process and operation constraints. In this way, we could consider only real optimization variables, eliminating the 0/1 ones, and introducing as new decision variables the charge and discharge times of the batch units.

![Fig.2 Typical shape of on/off batch reactor valve positions along time](image)

![Fig.3 Optimisation setup](image)
The resulting NMPC problem is solved then using an NLP optimization algorithm (SQP) using the scheme of Fig.3. The simulation package integrates the model equations along the prediction horizon taking as initial conditions the current process state and evaluating the formulated objective at the end of the integration. Path constraints are implemented as penalty functions.

3. Simulation Results

Several simulation studies were performed in order to verify the performance of the proposed controller. In the following, figures results of an experiment where the input flow changes as in Fig.4 (left) are presented. In the same figure, the level in one reactor
can be seen, which gives an idea of the start and stop times of this reactor. In Fig. 5 the
time evolution of the levels in both, the upper and lower tanks are shown, which are
maintained fairly well inside the operating range, represented by the dotted lines. Fig.6
gives the same evolution for the temperatures in the same tanks which evolve around
the set points. Finally, Fig.8 represents the recirculating flow (left) and the input flow to
the lower tank (right). Their strong changes can be explained partially, by the fact that
no penalty was placed in their speed of change and because of the strong changes that
loading and unloading the batch reactors represents for the tanks. In a similar way to the
continuous case, where the prediction horizon covers, at least, the settling time of the
process, here the prediction horizon covers three full cycles of the system operation.

4. Conclusions

A hybrid control for a mixed continuous-batch process has been presented where the
associated optimization can be formulated as a NLP problem. The experiments show
promising results able to be implemented in real-time.

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