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Hybrid non-linear model predictive control of a run-of-mine ore grinding mill circuit[☆]

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ABSTRACT

A hybrid non-linear model predictive controller (HNMPC) is developed for a run-of-mine ore grinding mill circuit. A continuous-time grinding mill circuit model is presented with a hydrocyclone cluster as the primary classifier. The discrete-time component is the switching of hydrocyclones in the hydrocyclone cluster. The resulting model is a hybrid non-linear model with both continuous and discrete dynamics. A simulation of the HNMPC shows the advantages of using the hydrocyclone cluster as an additional manipulated variable. The advantages of the HNMPC is illustrated by comparing its performance to a non-linear MPC where no switching of hydrocyclones is possible. The genetic algorithm based HNMPC showed increased controller stability in its ability to incorporate discrete dynamics into the controller directly. The methods discussed in this paper can be used to incorporate different types of discrete dynamics into advanced grinding mill circuit controllers due to the modular presentation of the model and HNMPC controller design.

1. Introduction

A run-of-mine (ROM) ore milling circuit is used to grind incoming ore bearing precious minerals to within a specification, e.g. 70% of the product particles must be smaller than 75 µm. The fine product produced from the milling circuit allows for the separation of the precious minerals from the gangue material (le Roux et al., 2013). In order to improve the recovery rate of the valuable metals in the downstream processes, the particles discharged from the grinding mill circuit should have a consistent quality, i.e. remain within specification (Chen et al., 2007). Efficient control of the grinding mill circuit is therefore essential to achieve the desired product specifications in terms of throughput and quality.

Generally, the better the quality of a product, the lower the throughput of the plant, and vice versa (Coetzee et al., 2010). Because of the interaction between the control objectives for quality and throughput, the aim is to maintain quality as close to the minimum specification as set by the downstream processes, thereby maximizing throughput even in the presence of large disturbances (Coetzee et al., 2010). In addition to these control objectives, a grinding mill circuit controller should also aim to increase energy efficiency and at all times ensure process stability (Matthews and Craig, 2013).

The downstream process requirements play a critical role in the steady-state optimisation objective of the grinding mill circuit. Although the local optimisation objectives for the grinding mill circuit is to maintain a constant product fineness and maximise throughput, the key revenue generating variable for the mineral processing plant is the concentrate grade of the downstream process (the separation circuit). In McIvor and Finch (1991), Sosa-Blanco et al. (2000) the product size distribution specification for the grinding mill circuit is continuously set by the separation circuit to improve the separation circuit's economic performance. An economic objective function is used in Muñoz and Cipriano (1999) where a predictive controller sets the targets for an advanced regulatory controller on the grinding circuit. The objective function optimised the income generated from the plant as a function of the feed ore grade to the grinding circuit, the separator tailings grade and the recovery of the plant.

The economic evaluation of a grinding mill circuit is done by using the relationship between the grinding mill circuit product particle size and the separation concentrate recovery and grade curve (Wei and Craig, 2009). Economic plant-wide optimisation for a mineral processing plant is therefore limited to the operating range of the grinding mill circuit (le Roux et al., 2016). Due to this limitation, grinding mill circuit controllers should be designed to optimise over a wide range of steady-state regions, incorporate various different controlled- and manipulated variables (MVs), and benefit from all dynamics in the circuit

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to reject upstream disturbances quickly. These findings are in line with Skogestad (2000) where a systematic procedure is given to find suitable controlled variables (CVs) in order to construct a control architecture capable of achieving the plant-wide economic optimisation objective.

The norm for industrial milling circuit control is single-loop proportional-integral-derivative (PID) controllers despite strong interactions between the loops (Wei and Craig, 2009). Single loop PID controllers do not allow for any trade-off between the control objectives. Therefore, if one of the loops hit a constraint, the other loops cannot attempt to offset the resulting set-point error. A variety of multivariable controllers were developed to achieve the optimal trade of between the control objectives and improvements in product quality, throughput, and power consumption (Chen et al., 2007; Craig et al., 1992; Muller and de Vaal, 2000; Hadizadeh et al., 2017).

The design of advanced multivariable controllers involves identifying additional MVs to improve the circuit's operating region (Craig et al., 1992; Naidoo et al., 2014; Le Roux et al., 2016; Botha et al., 2015). In Craig et al. (1992) the range of quality control was increased by independently manipulating the mill's water feed-rate instead of fixing the water feed-rate as a ratio of the ore feed-rate. Similarly in Botha et al. (2015) the range of quality control was increased by manually switching cyclones in a hydrocyclone cluster. Power consumption reduction while maintaining quality was achieved in Estrada (2014) by alternating between different stockpiles as ore feed and whether a secondary grinding stage is used or not. In Naidoo et al. (2014) and Le Roux et al. (2016) the mill speed is used as an additional MV to reduce mill power consumption, and to independently control quality and throughput.

One of the most common advanced process control methods is model predictive control (MPC). MPC is a control technique where optimal control is applied in an iterative fashion (Qin and Badgwell, 2003). The control problem is solved at each iteration based on the plant measurements, predicted states and the past control actions. The controller predicts the plant outputs (according to some dynamic plant model) over a prediction horizon given a vector of control moves. During controller execution an optimiser will estimate the optimal control moves over a control horizon, that drive the process to the desired operating point (defined by reference setpoints and optimisation objectives) according to an objective function based on the predicted plant outputs. Once the optimal control move vector is calculated only the first move is implemented and the process is repeated at the next execution interval (Seborg et al., 2010). Non-linear MPC (NMPC) follows the same principle of operation as a linear MPC, except a non-linear model is used to predict the plant outputs and the solver should be able to cope with possible local minima and non-linear models. The block diagram in Fig. 1 illustrates the NMPC principle.

The robust non-linear model predictive controller (MPC) developed in Coetzee et al. (2010) showed that even in the presence of large disturbances and model mismatch it was possible to efficiently control a grinding mill circuit. The controller was capable of controlling over a larger operating region than linear MPC controllers such as the ones in Chen et al. (2007) and Muller and de Vaal (2000). Furthermore, due to the large non-linearities in the grinding mill circuit, a non-linear MPC capable of predicting and controlling the non-linear dynamics is highly desirable.

The key drawbacks in using model based predictive controllers is model mismatch because of the difficulty to estimate model parameters and complex solutions with unrealistic execution intervals (Coetzee et al., 2010; Qin and Badgwell, 2003; Garcia et al., 1989). The reduced complexity model in le Roux et al. (2013) was proven qualitatively accurate and uses as few parameters and states as possible. The model made it possible to design the robust non-linear MPC of Coetzee et al. (2010). Although the controller was not feasible for online application at the time, technological improvements (in the form of multi-core processors) have made it possible to implement non-linear MPC controllers with complex models in real time (Coetzee, 2014). A drawback of non-linear MPC controllers is that discrete components in the circuit cannot be integrated directly in the controller (Muller and Craig, 2014). This leaves certain tasks to operator intervention and could result in sub-optimal operation.

Hybrid model predictive control (HMPC) is capable of controlling a process by predicting according to continuous- and discrete-time events, and manipulating continuous and discrete components (Xiao et al., 2010; Muller and Craig, 2017). In Estrada (2014) a linear HMPC was implemented to select which stockpile to feed from or if the secondary grinding stage should be active. Similarly, Karelovic et al. (2015) gives a framework for HMPC of grinding mill circuits, where linear steady-state models are considered. The models are converted to a specific class of hybrid systems and then specialised packages such as HYSDEL are used to generate and solve the objective function (Karelovic et al., 2015; Bemporad and Morari, 1999). These set methods of solving the hybrid model and control problem ensure reasonable controller execution time.

The work in this study builds on Botha et al. (2015) where the benefits of switching hydrocyclones in and out of a cluster are shown. The novel approach in this paper is the on-line switching of hydrocyclones in a cluster with the use of HNMPC. The controller benefits from a larger operating region due to the non-linear model, and being able to switch the discrete components thereby further increasing the operating region. The aim is to show that more effective control of a grinding mill circuit can be achieved in the presence of disturbances compared to conventional non-linear MPC. A full non-linear model is used to capture the dynamic continuous time properties of the circuit, and the model is adapted to contain the discrete dynamics of the

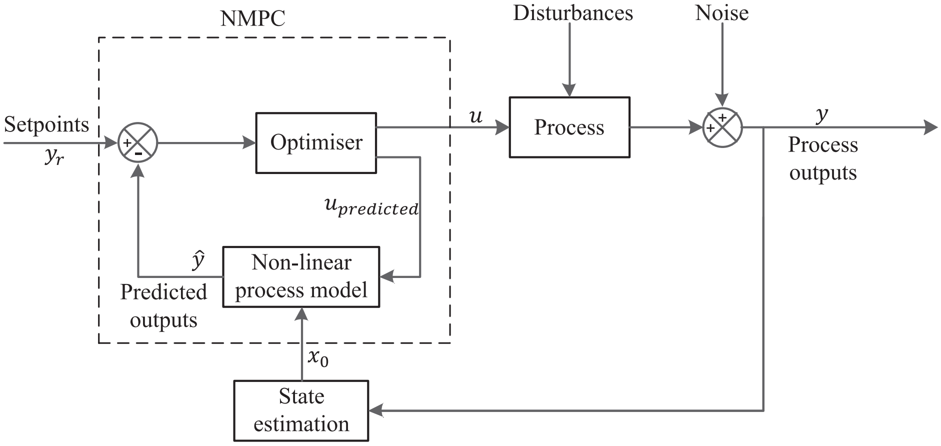

Fig. 1. Non-linear model predictive control.