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Model predictive control of a coal dense medium drum separator ⋆

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Abstract: Coal processing is typically performed by making use of gravity separation. A technology used to process larger sized coal particles (typically above 25mm) is a dense medium drum (DMD) separator. These plants make use of a medium set at a specific density to separate coal from gangue.
This paper shows how nonlinear model predictive control (NMPC) can be applied to an industrial DMD plant with a process objective to both increase yield while minimising ash content (i.e. improving grade). The results are significant as the DMD yield improved by 7.5% while ash content improved by 1.5%. The dynamic model of a DMD separator developed in a previous publication by the authors was used in the NMPC simulations.

Keywords: coal beneficiation; dense medium drum; nonlinear model predictive control.

1. INTRODUCTION

Coal run-of-mine (ROM) is typically processed through dense medium separation (DMS) technology to selectively improve the overall coal quality such that it is saleable (England et al., 2002). Coal being lighter than gangue can be separated by using its difference in specific gravity (SG). A ferro-fluid medium is used to separate coal from gangue at specific relative densities.

In terms of applying automatic control to coal processing, a few publications in the early 1980s are available (Lyman et al., 1982, 1983). These simulations show the feasibility of applying control to the ash content of coal washed in dense medium cyclones using on-line ash gauges. The models used in Lyman et al. (1982) calculate the progress of coal, magnetite and water around the circuit on a second-to-second basis. The control of ash content is based on a linear regression model relating ash content to medium SG. A limitation with this approach was in the linear regression model, as it could not cater for wider SG ranges in medium. Given the linear regression model limitation, a nonlinear dynamic model and controller are used for simulations in this paper.

On-off control with pulse width modulation proportional to the difference between measured and desired heavy media SG values was developed by Cierpisz (1998) for a heavy media coal washing process. An expert algorithm was used to apply parameters for discrete control equations for each channel of the process. The simulation models made use of transfer functions to describe the heavy media process.

More recent work applying automatic control to coal processing is available from Zhang and Xia (2014) where model predictive control (MPC) is simulated on the control of product carbon content. This is achieved by manipulating the density of medium in real-time according to feedback of dense medium cyclone outputs. The models from Meyer and Craig (2010) were used in the MPC simulation. Zhang et al. (2015) illustrate how optimal control can be used to control a dense medium cyclone based on minimizing medium density to reduce energy costs while keeping the percentage of carbon content in the DMC product stable.

During the upgrading of ROM to either metallurgical coal or power station coal product, the objective of the DMS plant operation is to produce coal product within a minimum quality specification and maximum possible yield (England et al., 2002). Meyer and Craig (2010) highlight that coal DMS plants do not typically operate optimally from a process objective perspective. By utilising the time evolution of variables, it is possible to control the specific gravity of DMS such that the desired process objectives can be obtained.

Control systems can lead to improved plant performance in terms of stability and economics by utilising a high level of process understanding (Bauer and Craig, 2008). Plant upsets due to various process disturbances can be controlled by maintaining certain desired setpoints.

Meyer and Craig (2015) have developed a dynamic model of a dense medium drum (DMD) separator, a technology that can be used in DMS to beneficiate larger sized coal particles (typically greater than 25mm). This model was developed from first principals and was verified using production data from an actual coal industrial plant. The

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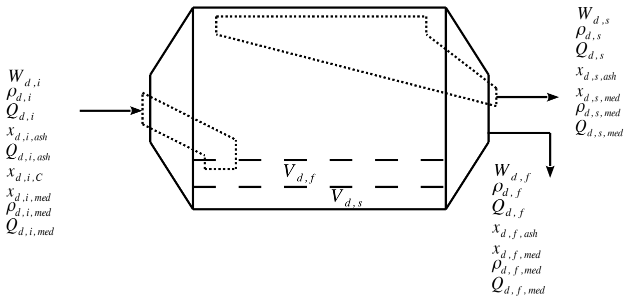

Fig. 1. Model representation of a DMD.

DMD dynamic model parameters were identified using the system identification principles described by Ljung (1987). By utilising a model-based controller based on the dynamic model developed by Meyer and Craig (2015), it is possible to simulate the control of a DMD.

In this paper, MPC will be used to perform the control simulations of a DMD. MPC uses a dynamic model to predict future outputs based on current and past inputs and outputs. By comparing the future process outputs to a reference trajectory, it is possible to calculate future errors. The best possible future control moves of the process can be calculated such that the future errors are optimised through a cost function and constraints.

Section 2 of this paper describes the DMD dynamic model developed by Meyer and Craig (2015) and the DMD industrial coal plant used with associated measurements and control variables. MPC and the development of an appropriate objective function for the DMD is given in Section 3. The MPC simulation results are shown in Section 4 with summary results and conclusion given in Section 5.

2. DENSE MEDIUM DRUM

This section describes the dynamic model of a DMD that is used from available literature. The dynamic model is required for the MPC simulations. Thereafter, the DMD process flow diagram and associated input and output variables are given.

2.1 Model description

The dynamic model of a DMD developed by Meyer and Craig (2015) is used in the MPC simulations for this paper. As a result, a brief description of the model, dynamic equations and model parameters are given. Further detail can be found in the original paper.

The dynamic model of the drum separator focusses on throughput equations by making use of the conservation of overall mass. Conservation of mass of components can be used to model the grade (i.e. ash percentage) of the drum coal product. A model representation of the drum separator can be found in Figure 1 while associated variables describing the model are given in Tables 1 and 2.

Table 1. Drum input variables

Variable	Description
$W_{d,i}$	Mass feed rate of the feed mix (kg/s)
$\rho_{d,i}$	Density of the feed mix (kg/m^3)
$V_d = V_{d,f} + V_{d,s}$	Volume of the material within the drum (m^3)
$x_{d,i,ash}$, $x_{d,i,C}$	Percentage ash and fixed carbon in the feed mix
$Q_{d,i,ash}$	Volumetric flow rate of the ash content in the feed mix (m^3/s)
$x_{d,i,med}$	Percentage magnetite medium in the feed mix
$\rho_{d,i,med}$	Density of the magnetite medium in the feed mix (kg/m^3)
$Q_{d,i,med}$	Volumetric flow rate of the magnetite medium in the feed mix (m^3/s)

Table 2. Drum output variables

Variable	Description
$W_{d,f}$	Mass flow rate of the floats (kg/s)
$\rho_{d,f}$	Density of the floats (kg/m^3)
$Q_{d,f}$	Volumetric flow rate of the floats (m^3/s)
$V_{d,f}$	Volume split of the floats within the drum (m^3)
$x_{d,f,ash}$	Percentage ash content in the floats
$x_{d,f,med}$	Percentage magnetite medium in the floats
$\rho_{d,f,med}$	Density of the magnetite medium in the floats (kg/m^3)
$Q_{d,f,med}$	Volumetric flow rate of the magnetite medium in the floats (m^3/s)
$W_{d,s}$	Mass flow rate of the sinks (kg/s)
$\rho_{d,s}$	Density of the sinks (kg/m^3)
$Q_{d,s}$	Volumetric flow rate of the sinks (m^3/s)
$V_{d,s}$	Volume split of the sinks within the drum (m^3)
$x_{d,s,ash}$	Percentage ash content in the sinks
$x_{d,s,med}$	Percentage magnetite medium in the sinks
$\rho_{d,s,med}$	Density of the magnetite medium in the sinks (kg/m^3)
$Q_{d,s,med}$	Volumetric flow rate of the magnetite medium in the sinks (m^3/s)

The model was simplified by assuming that the volumetric flow is at steady state (i.e. $Q_{d,i} = Q_{d,f} + Q_{d,s}$) and that the floats and sinks are volumetrically split by a proportion α_d. Similarly, it was assumed that the drum material volume V_d is separated according to the same split proportion α_d as in the volumetric feed flow (i.e. $V_{d,f} = \frac{\alpha_d V_d}{1+\alpha_d}$ and $V_{d,s} = \frac{V_d}{1+\alpha_d}$). By using the overall conservation of mass the following relationship describing the drum was developed:

$$V_{d,f}\frac{d\rho_{d,f}}{dt} + V_{d,s}\frac{d\rho_{d,s}}{dt} = W_{d,i} - Q_{d,f}\rho_{d,f} - Q_{d,s}\rho_{d,s}. \quad (1)$$

Gravity separation within the drum was used to model the effects of the dynamics of the density response for the drum. An additional factor was incorporated into the dynamic relationship allowing for the difference in ore density $[\rho_{d,i,ore} = W_{d,i}(1 - x_{d,i,med})/(Q_{d,i} - Q_{d,i,med})]$ to medium density ($\rho_{d,i,med}$) to facilitate further separation. The percentage of ash or carbon in the feed will also influence the dynamics of the drum. Proportionality constants for floats ($K_{d,f}$) and sinks ($K_{d,s}$) are used to relate the rates of change of density in floats ($\frac{d\rho_{d,f}}{dt}$) and sinks ($\frac{d\rho_{d,s}}{dt}$) to these factors and yields the following relationships: