MPC Feed-Forward for Constraint Handling

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Abstract— **In a mineral concentrator, ore is milled and later separated into concentrate and tailing by a process called flotation. When a milling line abruptly stops, a significant inflow disturbance to the downstream flotation series is often observed. To avoid de-tuning the flotation level controller to handle the worst case scenario, we introduce a feed-forward model predictive controller (MPC) that considers the closed loop system in its design. This addition to the control structure gives constraint handling properties to the existing well-functioning level controller.**

I. INTRODUCTION

When producing metals, ore from the mine is first processed in a concentrator plant where valuable minerals are separated from waste rock. The resulting mineral concentrate is transported to a smelter where it is smelted into pure metals. At the mining site Aitik, located near Gällivare in Sweden, copper ore is mined and concentrated. In this concentrator, there are two milling lines that mill the ore to a fine sand that is mixed with water to form a slurry. The slurry is, through a distribution box, divided equally between two downstream rougher flotation lines, each consisting off a buffer tank and 13 flotation cells connected in series.

The mineral separation takes place in the flotation cells. Chemical reagents are added to make the desired minerals water repellent. Air bubbles generated at the bottom of the cells collect the minerals as they rise to the surface to form a mineral froth. The froth is collected as it flows over the rim of the cell, making good level control a foundation to receiving good recovery.

For each flotation line, including the upstream buffer tank, the level control is governed by an LQ-controller. The LQ-controllers reduce the propagation of disturbances along the series compared to the previous cascade coupled PI-controller structure.

Due to different types of disturbances in the milling lines, the mill may come to an unexpected halt. When this happens, the inflow to the flotation lines is reduced to half. The size, shape and duration of the resulting inflow disturbance will depend on what happened in the milling line, and hence, the levels in the flotation cells will be affected to different extent. Fast level fluctuations may damage the froth layer, disrupting the yield until the froth has reformed. Fluctuations may also result in slurry flooding the cell, causing waste rock to end up in the next process step.

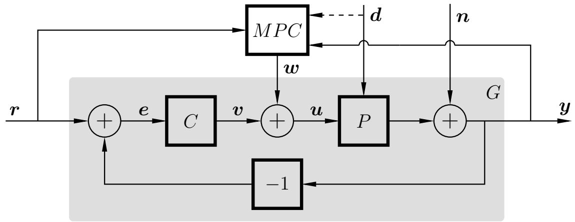

Fig. 1: Block diagram illustrating a feedback MIMO loop with LQ-controller C, process P, reference $\boldsymbol{r}$, process load disturbance $\boldsymbol{d}$ and measurement noise $\boldsymbol{n}$. The process input $\boldsymbol{u} = \boldsymbol{v} + \boldsymbol{w}$ consists of the LQ control signal $\boldsymbol{v}$ and the MPC control signal $\boldsymbol{w}$. The closed-loop system in the gray box, denoted G, is the process considered in the MPC design. Note that the LQ-controller is an internal component to G.

The majority of the inflow disturbances are handled successfully by the LQ-controllers that use the buffer tank volume to allow for a slower change in inflow to the flotation series. For some extreme cases however, the buffer tank volume is not big enough. This results in that the level in the buffer tank goes below the allowed operating range. Outside of the allowed range, safety features that protect the equipment will be triggered, causing the pumps between the buffer tank and the flotation line to be shut down. This requires manual restart and hence lost production time. These disturbances are problematic since an LQ-controller (or a PI controller) lacks constraint handling properties to honor these level constraints.

It can be addressed by de-tuning the LQ-controller to keep the level in the buffer tank tighter to its reference. However, this is not desirable since maximising the usage of the buffer volume is beneficial for level control of the downstream flotation cells. Instead of tuning the LQ-controller to handle the worst case, it is tuned to handle the majority of the disturbances. To stay within the bounds in the extreme cases, a feed-forward logic can be used. Traditionally, a static feed-forward logic has been used in the plant, but when it is triggered, it also introduces abrupt changes in the flow between the buffer tank and the flotation cells.

II. MODEL-BASED FEED-FORWARD BY MPC

When the LQ-controller was introduced, a process model was developed and this model can be used to design a more adaptive feed-forward logic using MPC. The control structure is described in Figure 1.

Here P is the process, i.e the buffer tank and the downstream flotation cells, and C is the LQ-controller. The levels and the level references are $\boldsymbol{y}$ and $\boldsymbol{r}$ respectively. Measurement noise is represented by $\boldsymbol{n}$, and $\boldsymbol{d}$ represents load disturbances, such as inflow disturbances. With the setup in Figure 1, the total control signal, $\boldsymbol{u}$, entering the process is the sum of the control signal from the LQ-controller, $\boldsymbol{v}$, and

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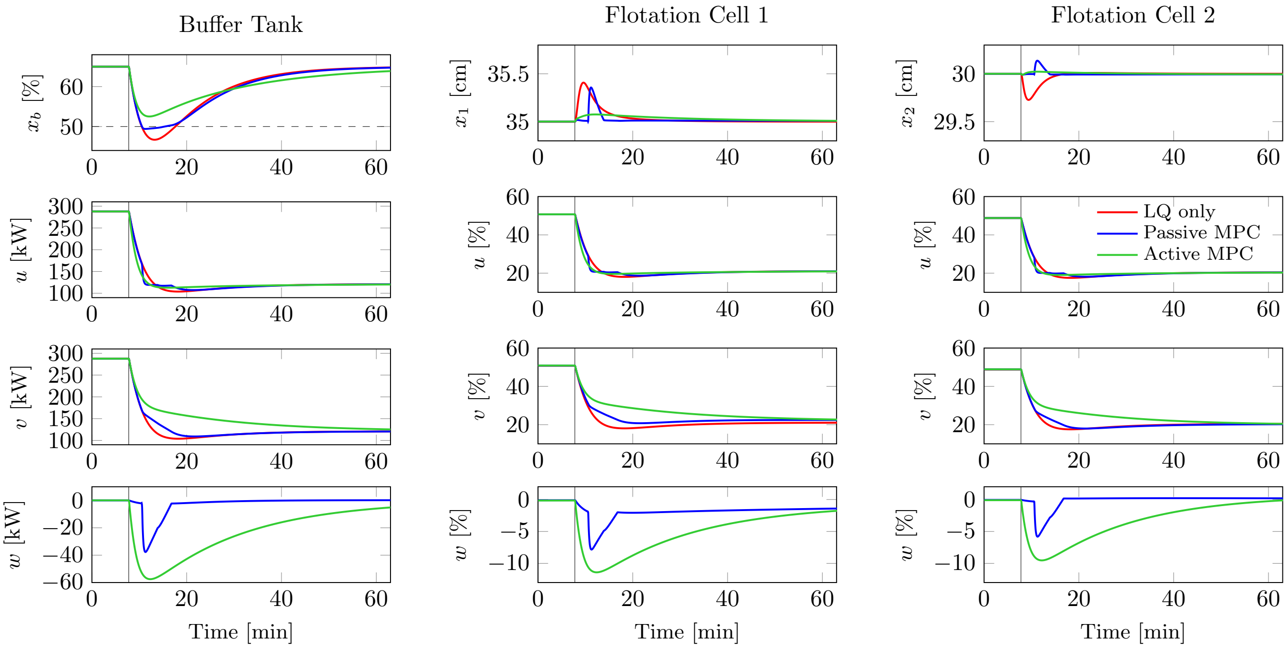

Fig. 2: Level deviations in the buffer tank and the two first flotation cells, caused by an abrupt milling line stop causing the inflow to the buffer tank to decrees to half at the vertical black line marked in the figures. The horizontal dashed line in the sub-figure in the top left corner indicates a level constraint.

the feed-forward control signal from the MPC-controller, $\boldsymbol{w}$. When designing the MPC-controller, the system considered is the closed loop system, G, marked with the gray box in Figure 1. This way, the MPC-controller has knowledge of how the LQ-controller affects the process and can account for that in its optimization. The control signal from the MPC-controller is determined by

$$\begin{aligned} \underset{\boldsymbol{w}}{\text{minimize}} \quad & \sum_{t=0}^{h} \boldsymbol{x}^T Q_1 \boldsymbol{x} + \boldsymbol{w}^T Q_2 \boldsymbol{w}, \\ \text{subject to} \quad & G, \;\; x_b \geq 50. \end{aligned} \tag{1}$$

Where h is the prediction horizon, and the state vector $\boldsymbol{x} = [x_b \; x_1 \; ... \; x_{13}]$ contains the levels of the buffer tank and the flotation cells. The diagonal weight matrices Q_1 and Q_2 parameterize the controller and the relative size of the weights determines the controller behavior. One MPC-controller that is active to control the buffer tank level, and one that is more passive in this regard, were designed by altering the Q_1-weight corresponding to the buffer tank. In Figure 2, the responses in the buffer tank and the first two flotation cells to an inflow disturbance are shown for the two different MPC-extensions and the LQ-controller alone.

In the top left sub-figure, the buffer tank level constraint is violated when it is controlled by the LQ alone. For the active MPC-tuning, represented in green, the MPC starts acting as soon as the disturbance enters and it is active to bring the level back to its reference in the buffer tank. For this tuning, the effects on the levels in the flotation cells are extremely small and the MPC-contribution is active in the flotation cells when it is active in the buffer tank. For the passive MPC-tuning, represented in blue, the MPC-controller is barely active until the constraint is violated. When it is, the constraint handling properties of the MPC-controller comes in to play and $\boldsymbol{w}$ acts to bring the level in the buffer tank back into the allowed range, while keeping the levels in the cells close to their reference.

The level deviations in the flotation cells are small for all controllers. For reference, process noise in the real process with an amplitude smaller then 1 cm is normal and unproblematic, meaning that the small deviations in the cells are insignificant. However, the deviation in the first flotation cell as a result of a milling line stop for the LQ-controller usually is 2 cm in the real process. This corresponds to the red curve in the central sub-figure at the top in Figure 2, which is below 0.5 cm in the simulation.

The MPC-controllers have different advantages and drawbacks. In this simulation, the active MPC handles the disturbance excellent. However, the MPC-controller is more sensible to model errors than the LQ-controller, this was one of the main reasons for choosing the LQ-controller over the MPC for level control in the first place. Therefore, having an active MPC-tuning might introduce errors due to model errors in the real process. The active MPC will also act on smaller deviations than these, meaning that if it has issues with model errors, these will affect the over all controller performance. The passive MPC-controller will not act unless the constraint is violated, and hence contribute to $\boldsymbol{u}$ in fewer cases than the active MPC. This is an advantage if model errors turn out to be a problem for the MPC. For the passive MPC, the abrupt change in $\boldsymbol{w}$ when hitting the constraint may, however cause a disturbance in the flotation cells.

Which strategy that works best in production will be determined by fine tuning once the solution is deployed in the Aitik concentrator.