TECHNOLOGICAL PAPERS

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Know-How in Process Control

Optimization-based AFC Automatic Flatness Control in Cold Tandem Rolling

An integrated flatness optimization approach for the whole tandem mill.

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Cold tandem mills have the purpose of reducing the thickness of flat steel by means of consecutive rolling stands. This type of process is widely deployed in order to supply a wide variety of industries, from food processing to automotive manufacturing.
In the recent years, the production of steel (and other metals, like copper and aluminium as well) by cold rolling has been subject of research efforts to reach ultra-thin gauges and to advance the production performance together with the quality of the material.

The automation behind this process resorts to complex control technologies and advanced hardware solutions that are often organized in two hierarchical layers. The PLC automation level (Level 1 automation) regulates the thickness and flatness in a closed-loop by means of real-time operating systems. Meanwhile, the Level 2 automation optimizes the so-called set-up that defines, in particular, the reduction to be performed by each rolling stand; the prediction of the rolling force applied by each stand; the target flatness to be realized by an intermediate rolling stand; and, finally, the best initial configuration of the flatness actuators.
The control tasks realized in the Level 1 automation of cold tandem mills mainly concern the thickness (gauge) (AGC - Automatic Gauge Control) and the flatness (AFC - Automatic Flatness Control).
It is worthwhile to point out that both AGC and AFC rationales can change significantly from installation to installation, according to the mechanical solution considered and the sensors availability.
For a strip subject to cold rolling, the flatness can be defined as the amount of internal stress difference along the width of the material. The strip's internal stresses (the so-called shape) can be measured during coiling by suitable sensors named shapemeters or stressometers that, until now, represent a significant investment. Due to the cost of these sensors it is rare for a plant to be equipped with more than one flatness sensor, i.e. the shapemeter installed at the exit of the mill.
Despite the fact that a cold tandem mill generally is constituted of several rolling stands with effective flatness actuators, the AFC task is usually performed by installing the flatness actuators in a closed loop at the last stand only, since it is the nearest to the shapemeter and it has the most immediate and predictable effect on the coil's final flatness.
In this paper an extension of the traditional AFC task is presented in order to exploit the compensation properties of other stands; and three control techniques based on online optimization and delay compensation are proposed. Both a centralized control scheme, where a single controller computes the input signals for all the actuators, and a decentralized solution, where each stand of the mill is optimized locally to lower the computational burden, are investigated.
Including more than one stand in the control loop could lead to non-negligible advantages. For instance, for ultra-thin gauges (under 0.2 mm), the flatness at exit of some preliminary stands must be controlled, in order to avoid roll kissing in those stands where this phenomenon could potentially happen, so as to reduce the risk of cobbles and improve the final quality of both thickness and flatness.
As a benchmark example to evaluate the performance of the presented control approaches, we consider a cold tandem mill

1 **Tandem Mill Z-High at Avesta Polarit RAP5, Finland**

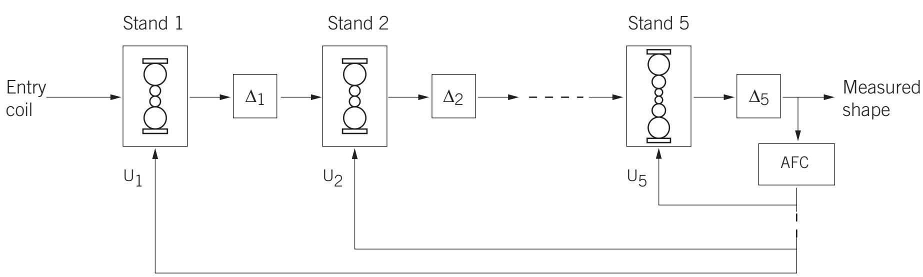
equipped by only one shapemeter and constituted of five stands, where the last one is of six-high type.
In the following part of this paper a novel AFC technique is introduced, which makes it possible to compensate measured flatness defects during rolling, on the basis of the measurements provided by a shapemeter.
In the AFC task of a tandem mill that will be discussed in the following paper, these points need to be taken into account:

> Each actuator is subject to a dynamical response.
> The actuators' commands are bounded. When a saturation limit is reached in a given stand, it is possible to use alternative flatness actuators in the same stand (for instance, IRC can be used to recover WRB/IRB from saturation), or to modify the configuration of other stands that are far from saturation in order to recover the saturation in the considered stand.
> Each stand presents a different transport delay from the shape sensor, since this is placed at the exit side of the tandem mill, i.e. after the last stand. These delays need to be suitably compensated in order to guarantee closed-loop stability, see Figure 1.

Control Algorithms

We start by giving some preliminaries on Model Predictive Control (MPC), a technology diffused in the general field of control of sheet and film processes.
MPC is widely used in the industry to control highly complex, multivariable processes under constraints on input and state variables.

2 **Structure of a five-stand tandem mill with 4-high stands, and a 6-high stand as last stand.**



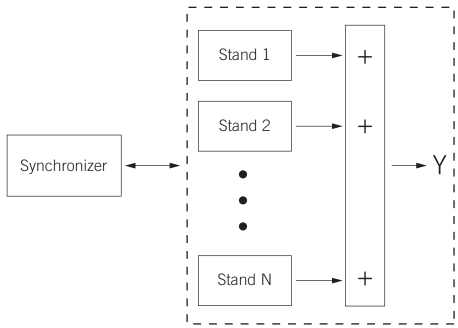
The idea behind MPC is to solve an open-loop finite-horizon optimal control problem at each sampling time point, based on a given prediction model of the process, by taking the current state of the process as the initial state. Only the first sample of the sequence of future optimal control moves is applied to the process. At the next time step, the remaining moves are discarded and a new optimal control problem based on new measurements is solved over a shifted prediction horizon.
When the prediction model and the constraints are linear, and the control objective is expressed through a quadratic function, the computation of the control action requires the solution of a quadratic programming (QP) problem.
An alternative approach to evaluate the MPC law was proposed rather than solving the QP problem on line for the current state vector, by employing techniques of multiparametric QP, the problem is solved offline for all state vectors within a given range, providing the explicit dependence of the control input on the state and reference, which is piecewise affine and continuous.
The straightforward application of the basic MPC algorithm to the whole tandem mill dynamic model is not viable because of the excessive computational demands.
Neither is the decentralized MPC approach recently proposed in literature realizable, owing to the presence of delays between stands. Henceforth, relying on a model of different solutions for control of tandem mills based on quadratic optimization and delay compensation are examined.
The three alternative QP-based control schemes presented in the following will be referred to as Global QP Controller - Figure 3, Decentralized QP Controller “Optimize & Push” - Figure 4, Decentralized QP Controller “Pull & Optimize”- Figure 5.

Global QP Controller

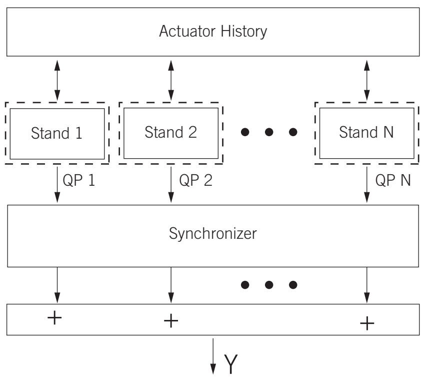
The Global QP control algorithm considers a single QP problem for the whole tandem mill, see Figure 3. The idea is to have a central unit solving the following optimization problem at each time step. In order to take into account the relevant delays in the system, a Synchronizer block supplies each actuation command at the right time. Once the input for stand   has been calculated, it is placed into a buffer with a delay.
The drawback of the Global QP control approach is the amount of computation involved in solving the centralized problem, especially when a large number of stands and actuators is involved. Decentralized, computationally simpler approaches are therefore explored in the next sections.

Decentralized QP controller “Optimize & Push”

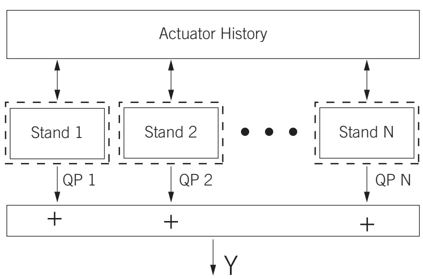
The first solution consists of a simpler QP controller placed at every stand, working in parallel with the others. The principle is the same as the global one because each QP optimizes a delay-free system and send its data to the Synchronizer, see Figure 4.



3 Virtual delay-free model for Global QP Controller.



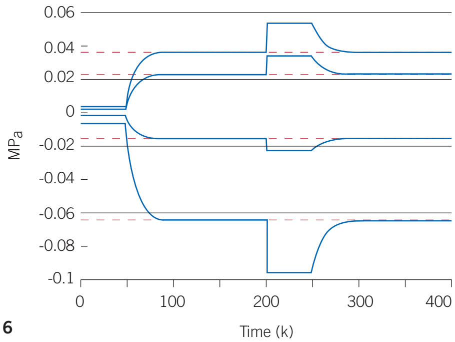
4 Virtual delay-free model for Decentralized QP Controller “Optimize & Push”.



5 Virtual model for Decentralized QP Controller “Pull & Optimize”.

As no information exchange among QP controllers happens during the decentralized computation at time, every QP controller operates under the assumption that at time the other QP controllers maintain their applied values, which have been previously calculated at time, therefore leading to sub-optimal solutions. Note that, while communication among stands takes place, no exchange of information happens during the optimization of each stand.
A variation of the above scheme leading to an improved overall closed-loop response includes the dynamics of the WRB actuator in the optimization of the first stand.
This is achieved by considering the input values obtained from the static QP minimization as setpoints to an explicit MPC controller based on the actuator dynamics of the first stand.
The MPC problem is formulated using the Model Predictive Control Toolbox.
The MPC controller is converted to its explicit form by using the Hybrid Toolbox, resulting in a piecewise affine control law.

Decentralized QP Controller
"Pull & Optimize"
A rather different control approach that still maintains the desired low computational effort of the decentralized QP solution presented above consists of getting rid of the global Synchronizer block. After an input vector computed by a QP is calculated, it is applied to the stand without buffering. The basic idea is to formulate the optimization problems so that the i -th QP is responsible for computing the command inputs to be actuated with no delay, considering the effects that other stands have had or will have on the same section of the strip that is currently being processed at the i -th stand. Hence, a global delay-free model is no longer employed, see Figure 5.
As a consequence, the optimization of a generic stand #i at time k only requires the information about what the QPs at the previous stands 1,...i-1 have applied on its current strip section in the past (which in general is different from the actuators values at the previous time step k-1), and a prediction of what the following stands i+1,...,N will apply to it.
In principle, as for the ``Optimize & Push'' approach, an explicit MPC controller could be added to generate the actual actuator signals from the input values computed by the QP.



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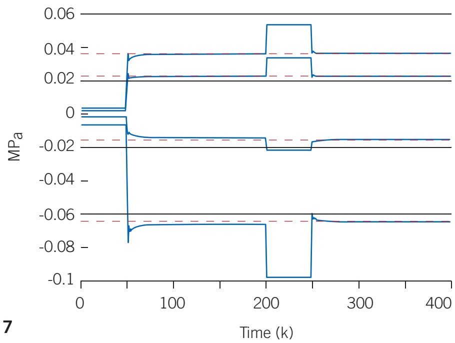
6 Global QP control action, output shape of zones 1, 15, 20 and 25. Solid line: output, dashed line: target.



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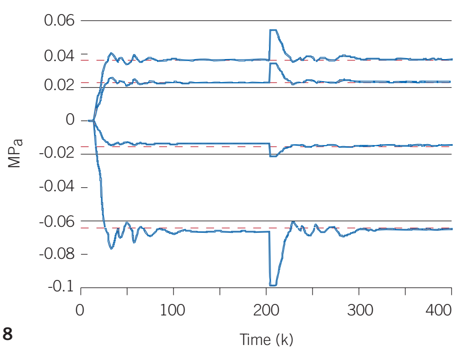
7 Decentralized QP "Optimize & Push" control action, output shape of zones 1, 15, 20 and 25. Solid line: output, dashed line: target.



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8 Decentralized QP "Pull & Optimize" control action, output shape of zones 1, 15, 20 and 25. Solid line: output, dashed line: target.

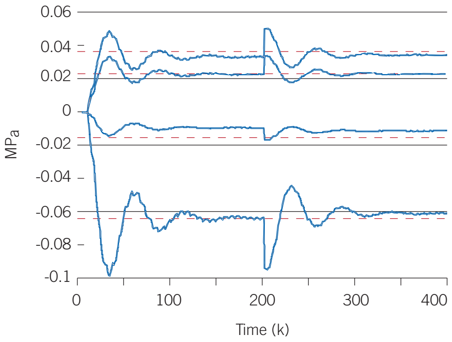
Numerical Results

The control algorithms described in the previous section have been tested on a nonlinear simulator exploiting the same flatness models used in a real automation system, with N=5 stands and the following actuators configuration: stands 1-4 are of four-high type and are equipped with WRB only, while the fifth stand is of six-high type and it is equipped with WRB, IRB and IRC. The resulting delay vector is given by Δ=[15,11,9,7,6].

The strip shape is desired to assume a constant profile.
The nonlinear simulation model includes the roll thermal crown dynamics, which affect the work rolls on all the stands of the mill.
This disturbance is due to the thermal expansion of the rolls, which heat up during the rolling process, and produce an increased roll bending action.
To take into account other disturbances than roll thermal crown, a unmeasured disturbance that can be considered as a sudden material variation during weld transition in a continuous tandem rolling mill.
Both the Global QP and the Decentralized QP ``Optimize & Push''+MPC approaches, whose performances are respectively depicted in Figures 6 and 7, show a smooth behavior with no output oscillations, thanks to the coordinated action between stands.
Their delayed reaction to the disturbance is due to the delay-free model employed for the static QP optimization.
The decentralized solution shows a much better rising time with respect to the global control thanks to the MPC action, which exploits partial knowledge of the process dynamics.
On the other hand, the Decentralized QP “Pull & Optimize” exhibits a faster reaction to the disturbance.
The independence of the stands allows them to react more promptly to the disturbance.
Such an increased autonomy is paid in terms of larger settling time and higher output oscillations, due to local models mismatches.
Moreover, we compared the proposed control schemes with a traditional LMS-based controller where only the WRB and IRB actuators equipped on the last stand are optimized online, and where no information on the actuator dynamics is exploited.
Closed-loop behavior of this control approach is shown in Figure 9.
Table 1 reports comparative numerical results for T_{sim}=1000 simulation steps, where performances have been evaluated using the cumulated norm of the tracking error.

Table 1: Simulation results

Controller	Perf. index *J*
LMS-based controller	17.89
Global QP controller	16.35
Dec. QP “Optimize & Push”	16.59
Dec. QP “Pull & Optimize”	8.39



9 LMS-based control action, output shape of zones 1, 15, 20 and 25. Solid line: output, dashed line: target.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