Iterative Learning Control for Time-Delayed and Time-Varying Systems

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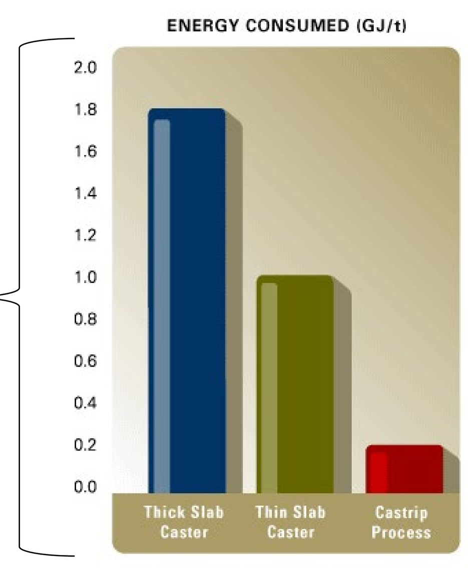
Sponsor: Castrip, LLC

Problem Statement

Twin Roll v. Traditional Casting [1]

Twin roll casting is used to produce thin steel strips by pouring steel directly onto rollers that compress the steel to near final gauge, whereas traditional casting uses a mold to form a steel slab that is later rolled to the desired thickness.

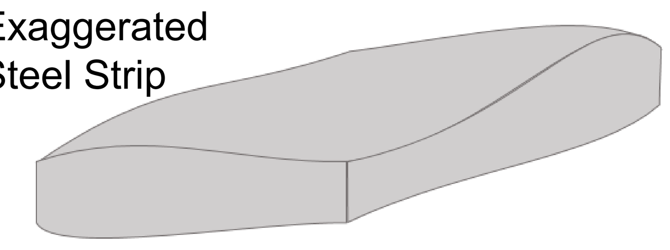
Twin roll casting consumes 9x less energy than thick slab casting



Parameter	Castrip	Thin Slab	Thick Slab
Cast Thickness (mm)	1.6	50	220
Casting Speed (m/min)	80	6	2
Ave. Mold Heat Flux (MW/m²)	14	2.5	1.0
Total Solidification Time (s)	0.15	45	1070
Ave. Shell Cooling Rate (°C/s)	1700	50	12

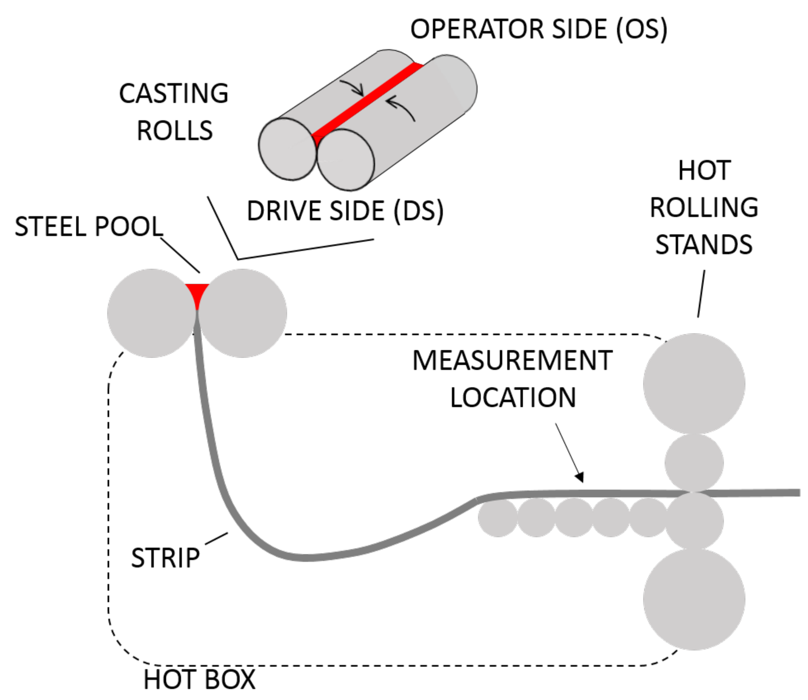
Twin roll casting has 7000x less solidification time and 14x more heat flux than thick slab casting.

Exaggerated Steel Strip



This rotational motion produces periodic disturbances in the thickness profile due to angular variations in the shape and thermodynamic characteristics of the rolls.

Large measurement delays make feedback control practically infeasible.



Research Goals:

- **Design an iterative learning control (ILC) algorithm for time-delayed and time-varying systems**
- **Apply ILC to twin roll strip casting process to minimize the effect of periodic disturbances**

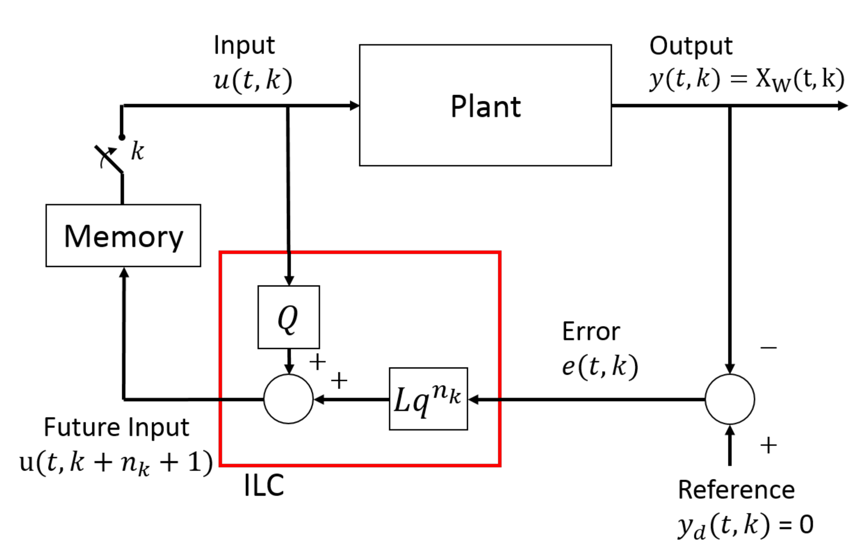
Approach

Iterative Learning Control [2]

The rotational nature of twin roll strip casting makes iterative learning control (ILC) an attractive control methodology for reducing the effect of the periodic disturbances.

$$u(t,k+n_k+1)=Qu(t,k)+Lq^{n_k}e(t,k)$$

An identified plant model assists in tuning and analyzing the ILC algorithm.



To facilitate the use of ILC for twin roll strip casting, we have made theoretical control contributions that:

1. Provide criteria for asymptotic convergence in the presence of time delay estimation error
2. Provide criteria for asymptotic stability of a coupled ILC and time delay estimation problem

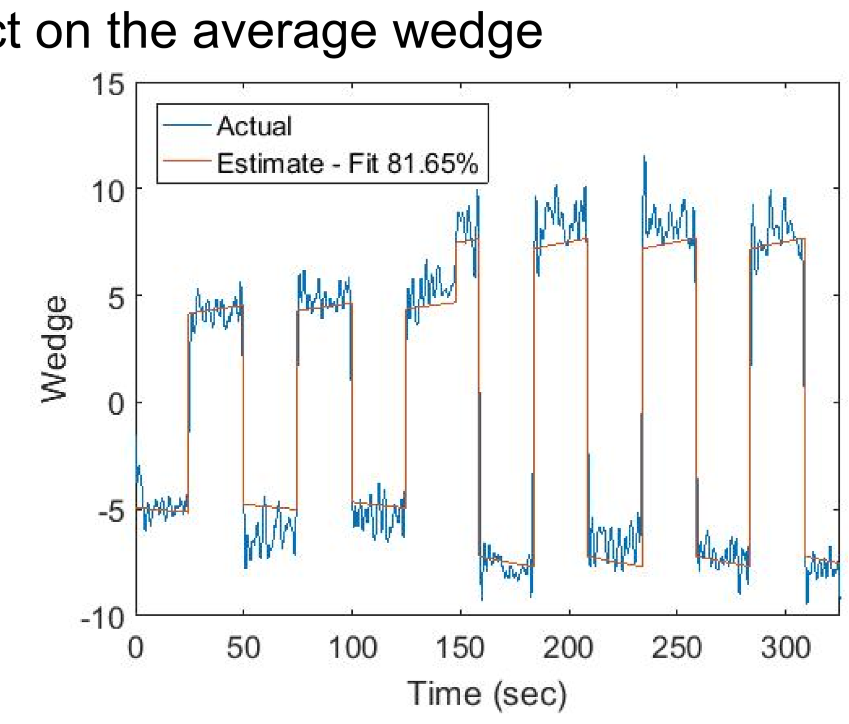
Plant Model

The effect that the casting rolls' tilt (DS position – OS position) has on the strip profile is modeled by applying a step signal to one of the casting rolls and measuring its effect on the average wedge measurement.

An ARX model of the form

$$A(z)y(z)=B(z)u(z)$$

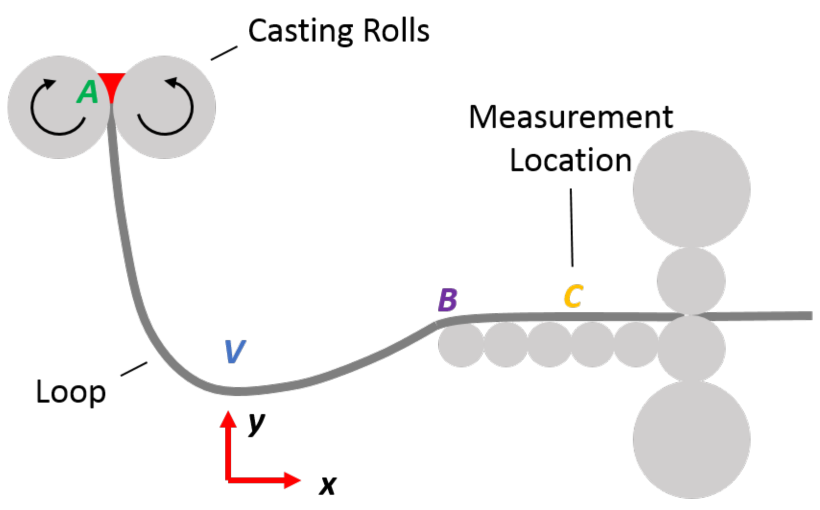
achieves a 81.65% goodness of fit for the filtered wedge signal.



Time Delay Estimation [3]

A time delay estimation (TDE) algorithm is necessary to ensure convergence in the ILC algorithm.

We divide the delay estimate into two components: an n_k component that estimates how many iterations occur in the delay, and a τ component that estimates the residual of $\Delta T - n_k T_R$.



$$\Delta T = n_k T_R + \tau$$

Control law with estimated delay:

$$u(t,k+\bar{n}_k+1)=Qu(t,k)+Le(t+\hat{\tau},k+\hat{n}_k)$$

Results

ILC Algorithm Development [3]

Theorem: The ILC system with the time delay estimation scheme described above is asymptotically stable if there exists $Q>0$ and $L>0$ such that

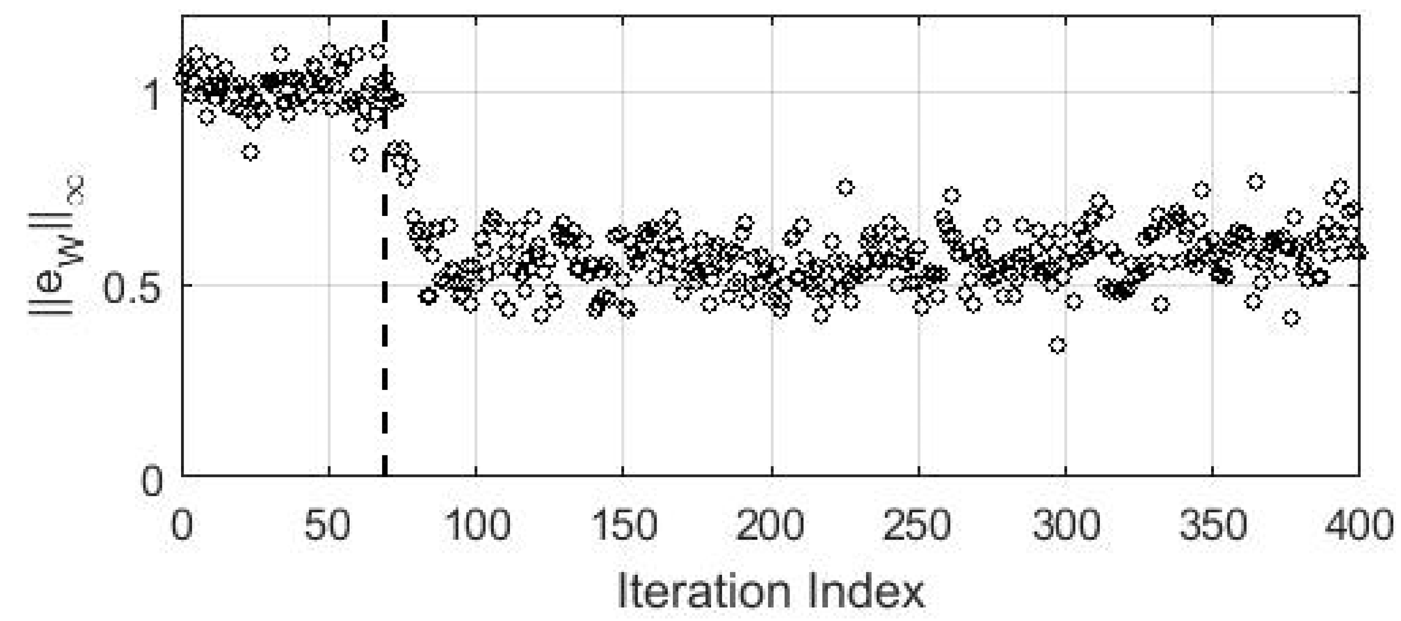
$$\left\|Q-LGp^{\hat{\tau}-\tau}q^{\hat{n}_k-n_k}\right\|_\infty<1.$$

See proof in [3].

Controller Testing

In coordination with Castrip and Nucor, we tested our algorithms at their plant in Crawfordsville, Indiana.

The combined ILC and TDE algorithms consistently **reduced the error by approximately 50%** across multiple casts.



Future Work

1. Improve the robustness of the TDE algorithm to disturbances in the casting process.
2. Adapt the ILC algorithm to compensate for uncertainty in the plant and time-delay estimates.

Potential Impact of Research

This research has **improved the quality of the steel produced by the twin roll casting process** and generated one patent: US20190091761.

Additionally, the research results can be translated to other manufacturing technologies that have periodic processes with large time delays and/or time-varying dynamics.

Acknowledgements

We would like to thank Brad Rees and the other engineers at Castrip.

Some images and figures in the problem statement section are from:

[1] Castrip.com, 'The Castrip Process', 2014. Available: http://www.castrip.com/Process/process.html

Cited Papers:

[2] F. Browne, G. Chiu and N. Jain, "Iterative Learning Control For Periodic Disturbances in Twin-Roll Strip Casting with Measurement Delay," 2018 Annual American Control Conference (ACC), Milwaukee, WI, 2018, pp. 4458-4463.

[3] F. Browne, B. Rees, G. Chiu, and N. Jain. "ILC With Time-Varying Delay Estimation: A Case Study On Twin Roll Strip Casting". 2018 Dynamic Systems and Control Conference, Atlanta, GA, 2018.