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Online Control of Spray Cooling Using Cononline

Bryan Petrus

BG Thomas

Joseph Bentsman

Department of Mechanical Science and Engineering

University of Illinois at Urbana-Champaign

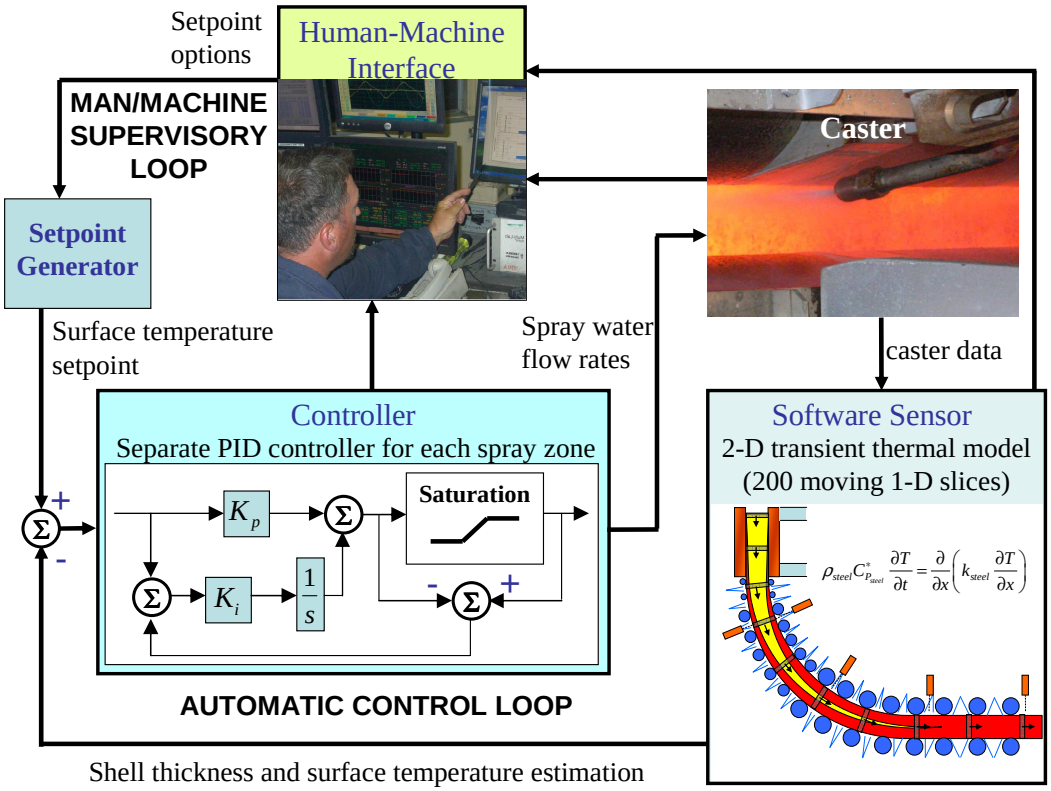
Overview

- Cononline Overview
  - Consensor: “software sensor”
  - Concontroller: PI controller bank
  - Monitor
- Controller performance comparison
- Future research

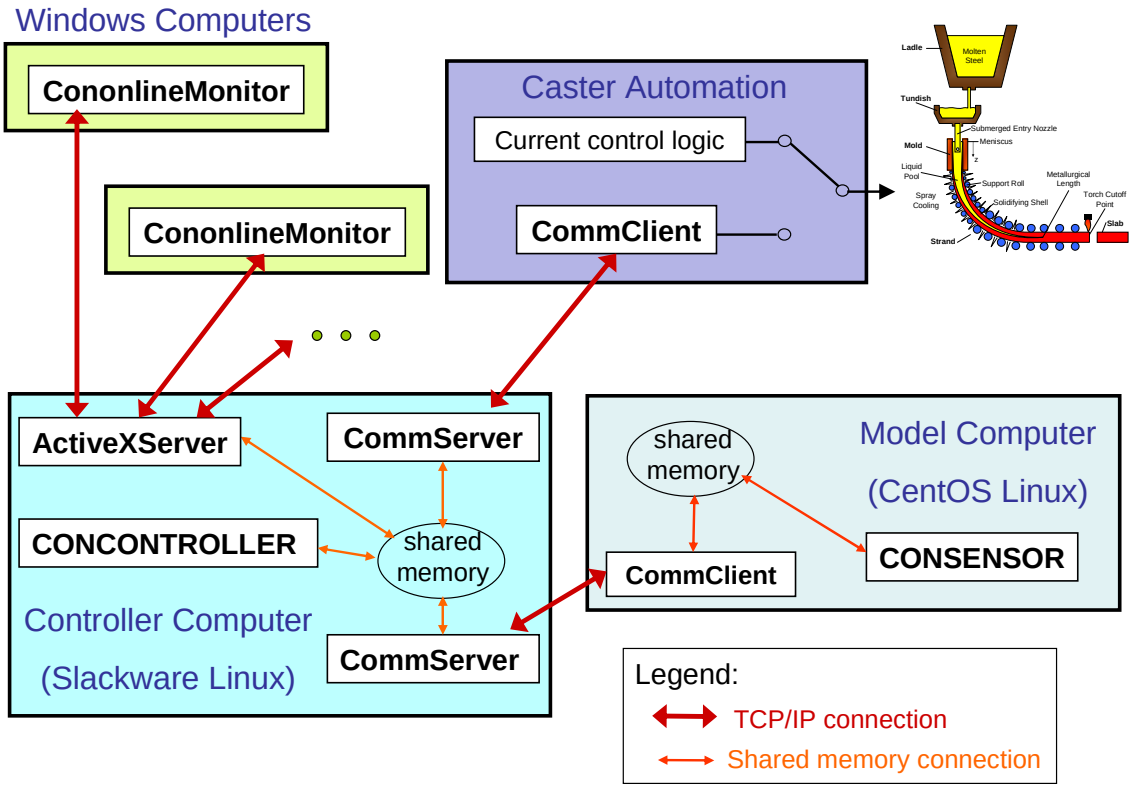
Project Motivation: Approaches to Cooling Spray Control

1) **Manual control:**
   - Operator sets of water flow rates
   - Difficult at high casting speeds when response times must be short
2) **Casting-speed-based control:**
   - Set water flow rates according to casting speed
   - Results in non-optimal cooling during transient conditions
3) **Conventional feedback control:**
   - Limited measurement opportunities
   - Pyrometers etc. can be unreliable in spray zones
4) **Software-sensor-based control:**
   - Create "software sensor," an accurate, real-time computational model to base control on

Overview



Computer Architecture

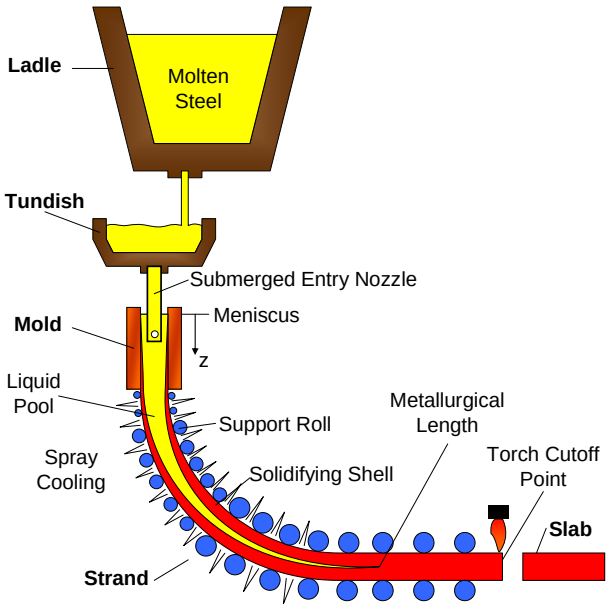


Consensor Overview: CON1D

- Fundamentally based transient finite-difference model:

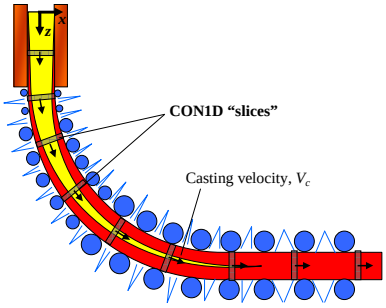
$$\rho_{steel} Cp^*_{steel} \frac{\partial T}{\partial t} = k_{steel} \frac{\partial^2 T}{\partial x^2} + \frac{\partial k_{steel}}{\partial T} \left(\frac{\partial T}{\partial x} \right)^2$$

- CON1D predicts:
  - shell thickness
  - temperature distribution
  - heat flux profiles
- Suitable for real-time model
  - Can simulate entire caster in < 1 second
  - "Restart mode": Can stop simulation at arbitrary point, continue later

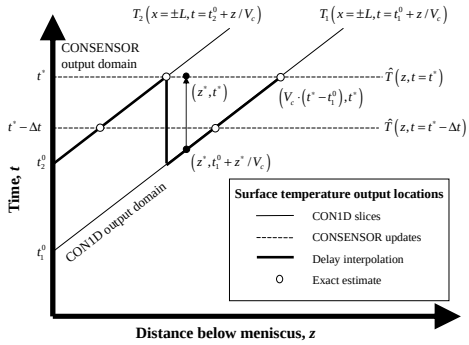


Consensor Overview

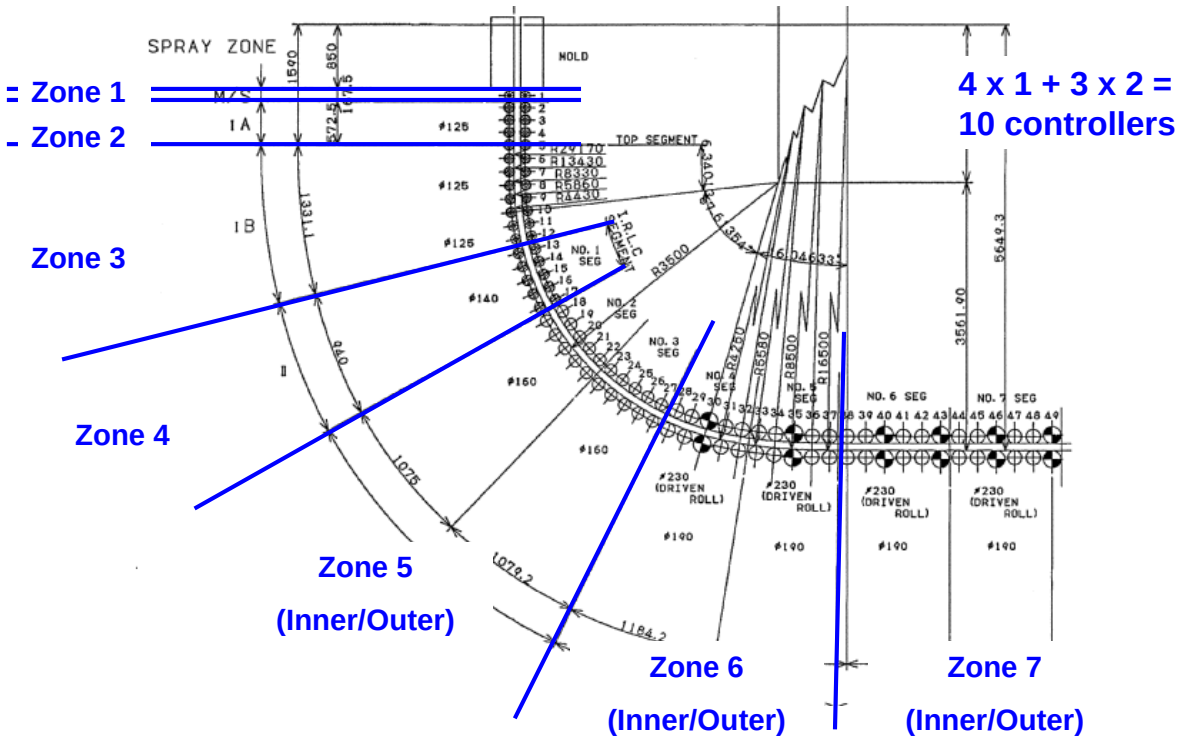
- Multiple "slices"
  - Each second, simulate each slice for 1 second
  - 200 slice simulation for 1 second each takes ~ same time as 1 slice through entire caster: < 0.5 seconds



- Consensor
  - stores and manages 200 CON1D slices
  - Interpolates between slices to estimate full shell & temperature profile



Concontroller Overview: Spray Zones



Concontroller Overview

- Zone-based PI control: 10 individual PI controllers, one for each spray zone

- **Controller Algorithm:** At each second of time:
  1. Obtain surface temperature profile from CONONLINE.
  2. For all 10 zones:
     i. Compute the zone-based average surface temperature error for current zone:

$$\Delta T_j(t) = \frac{\int_{\text{zone } j} \left[T^s(z,t) - \hat{T}(z,t) \right] dz}{L_j}$$

     ii. Use T_{err} to compute the water flow rate command:

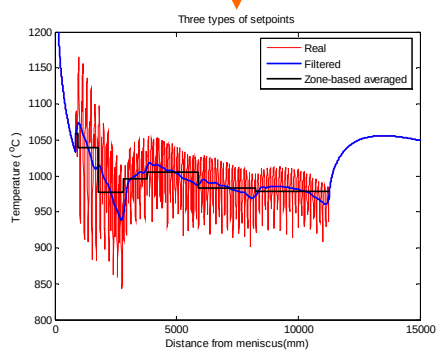
$$u_j(t) = k_j^P \Delta T_j(t) + \int_0^t k_j^I \Delta T_j(t)\, dt$$

  3. Send all water flow rate commands to Consensor, caster automation, and Monitor

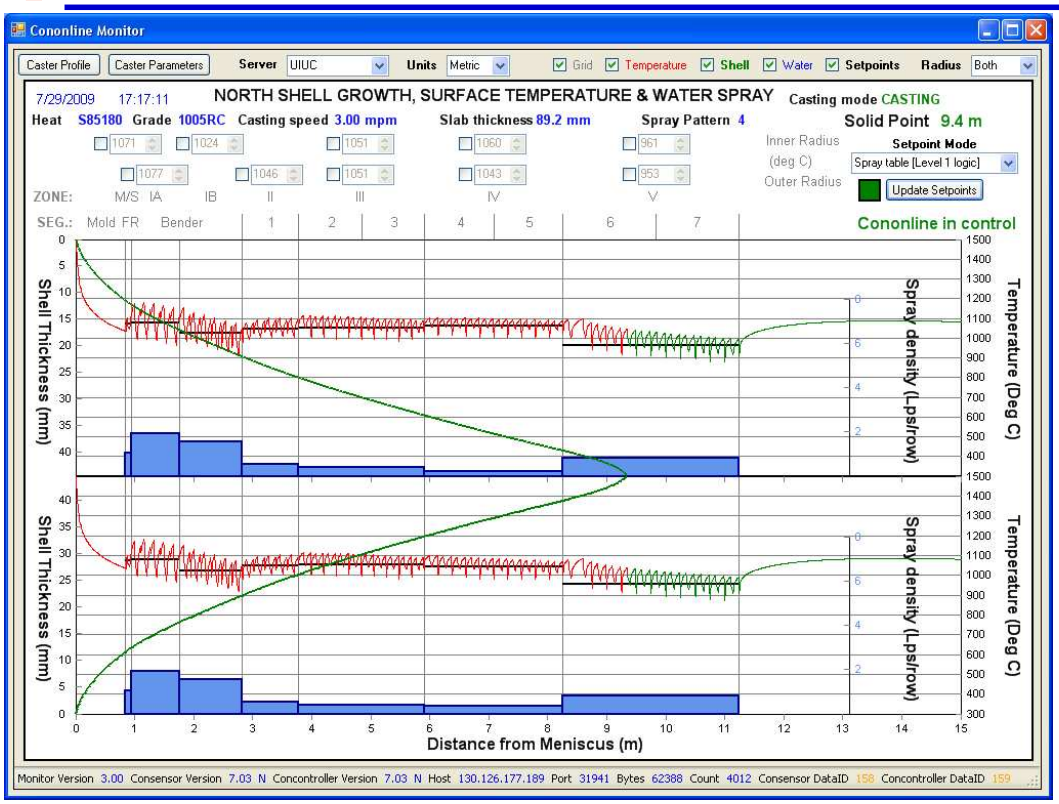
Setpoint Methodologies

1. Speed-based spray flow setpoints – current Nucor spray practices
2. Temperature setpoints (zone-averages) based on steady states for flows in (1)
3. Vary (2) based on casting conditions
   - Casting speed
   - Mold exit temperature (mold heat flux, superheat)
4. Operator chosen

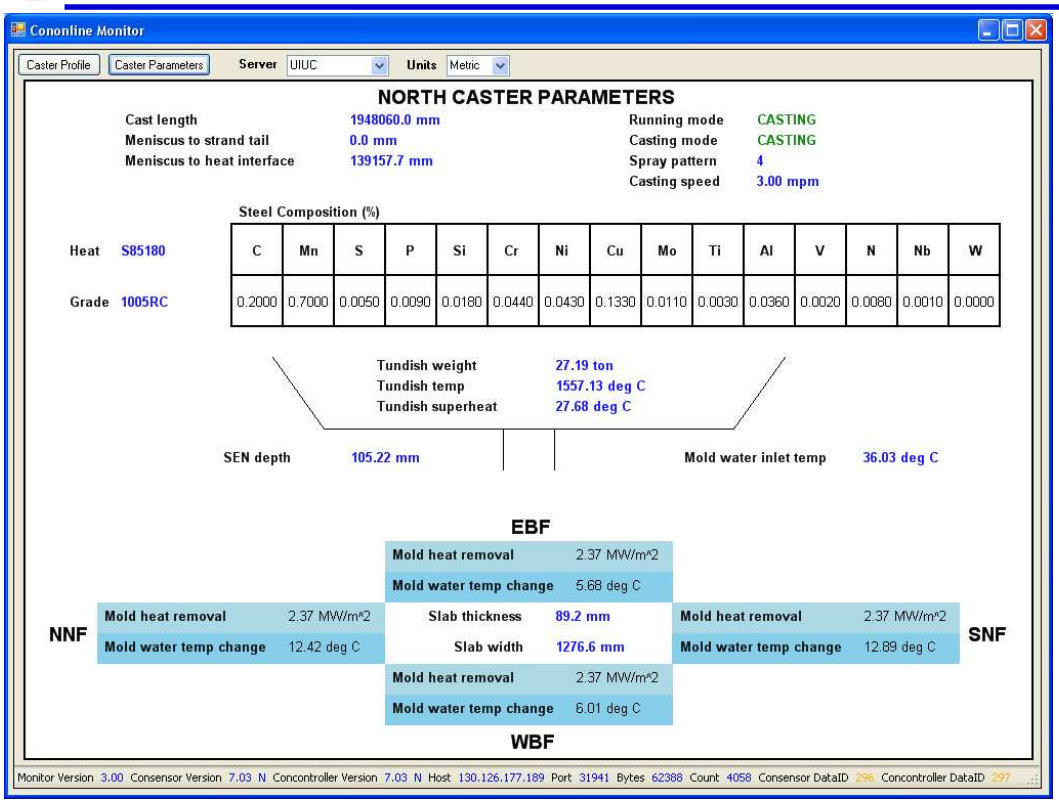
	Pattern 1	Pattern 2	Pattern 3	Pattern 4
	(i/min)	(in/min)	(in/min)	(in/min)
	(gal/min)	(gal/min)	(gal/min)	(gal/min)
Zone 1, Speed 1	0	0	0	0
Zone 1, Flow Rate 1	0	0	0	0
Zone 1, Speed 2	15.7	15.7	15.7	15.7
Zone 1, Flow Rate 2	26	24	26	23
Zone 1, Speed 3	31.5	31.5	31.5	31.5
Zone 1, Flow Rate 3	26	24	26	23



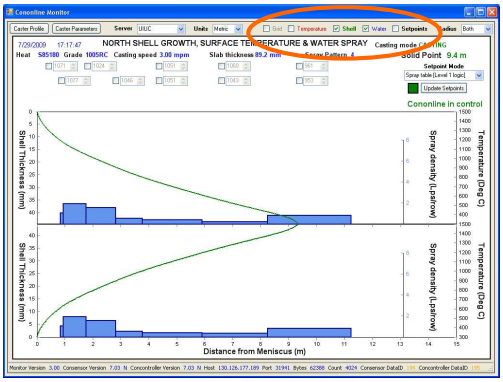
Monitor Overview: Profile Screen

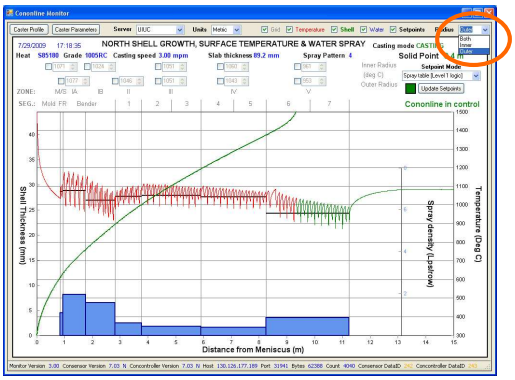


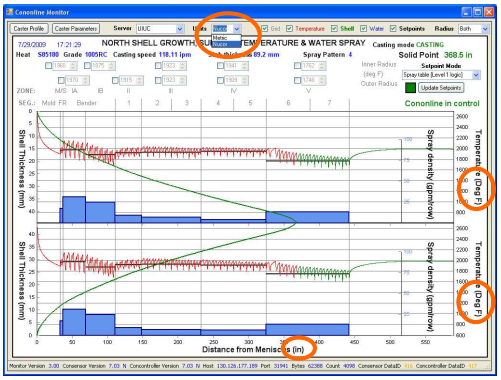
Monitor Overview: Parameter Screen

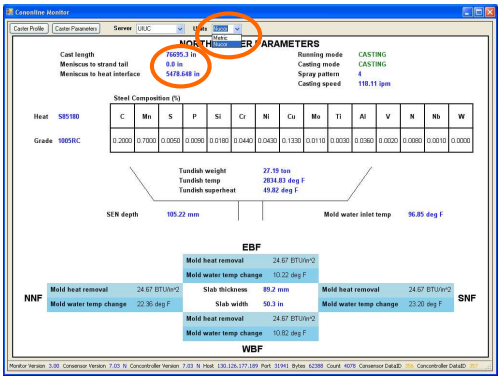


Monitor Overview









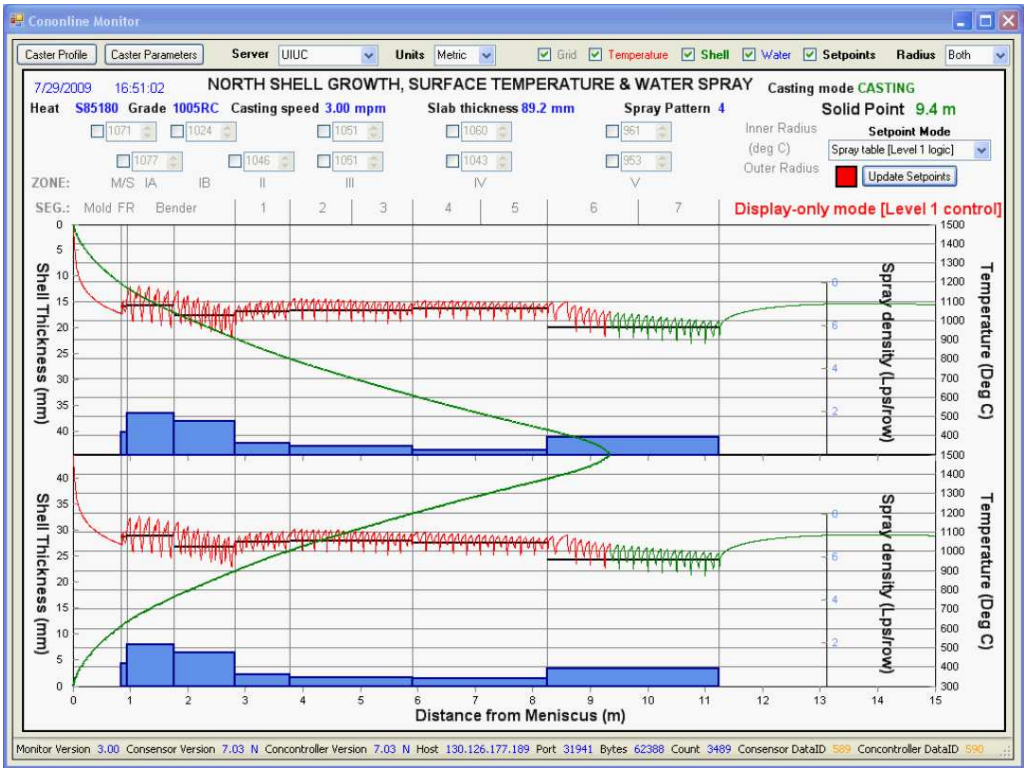
Ongoing work on Cononline

- Adding new features to Monitor (for plant operation)
  - "Passive" mode that displays without allowing changes to setpoints
  - Automatic resize window from 1024x768 up
  - Options (servers, mode) set in configuration file
- Changing to production versions of software
  - Programs run as Linux "daemons"
  - Program log files can be used for debugging
- Fixing stability issues
- Multi-threading Consensor for faster running

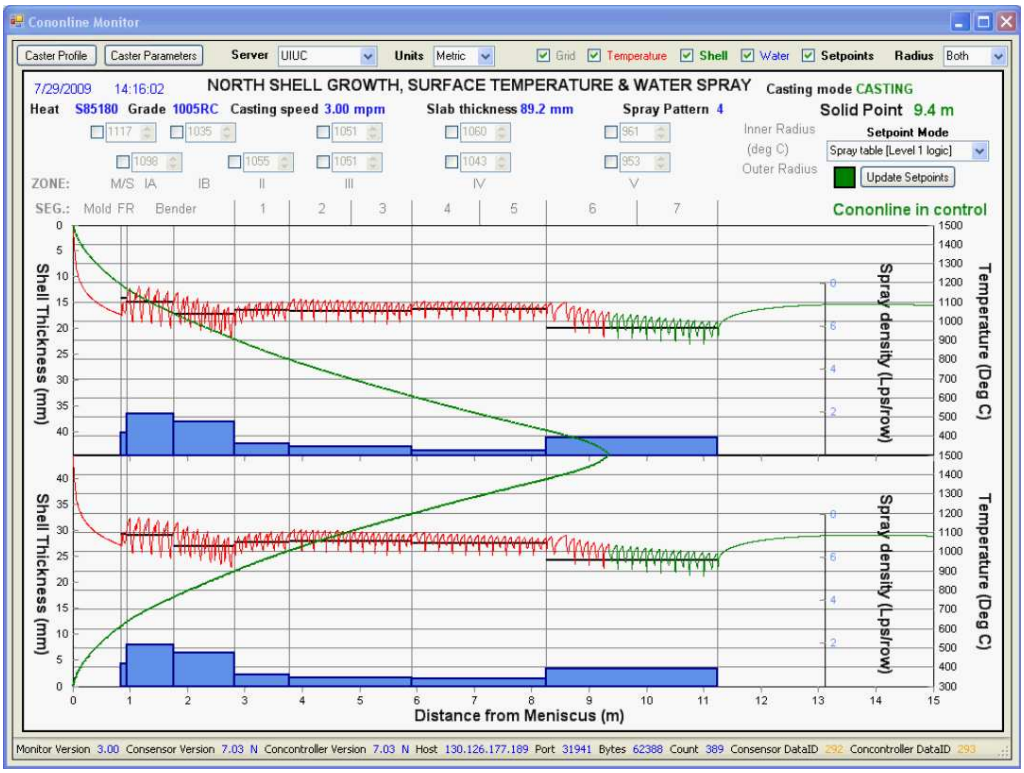
Controller Performance Comparison

- Based on caster data recorded at Nucor Decatur
  - thanks to Terri Morris, Rob Oldroyd, and Alan Hable
- Simulations run in real-time at UIUC
  - HP servers, Intel Xeon processors
- Test situation: sudden slowdown
  - Casting speed drops from 3.0 m/min to 2.5 m/min 30 seconds into simulation
- Comparing four different control methodologies
  - No control (constant spray rates)
  - Spray-table based control
  - PI control with speed-based setpoints
  - PI control with mold-exit-temperature-based setpoints (“fixed setpoints”)
- All videos are recorded at 6x playback speed

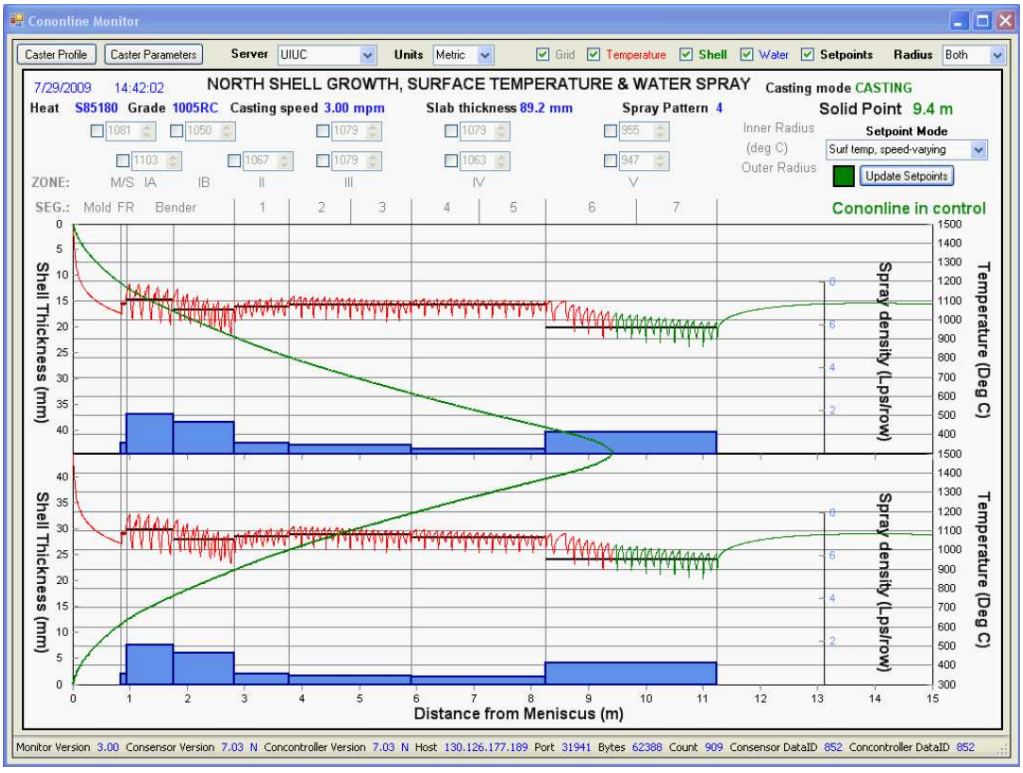
No Control (fixed spray rates)



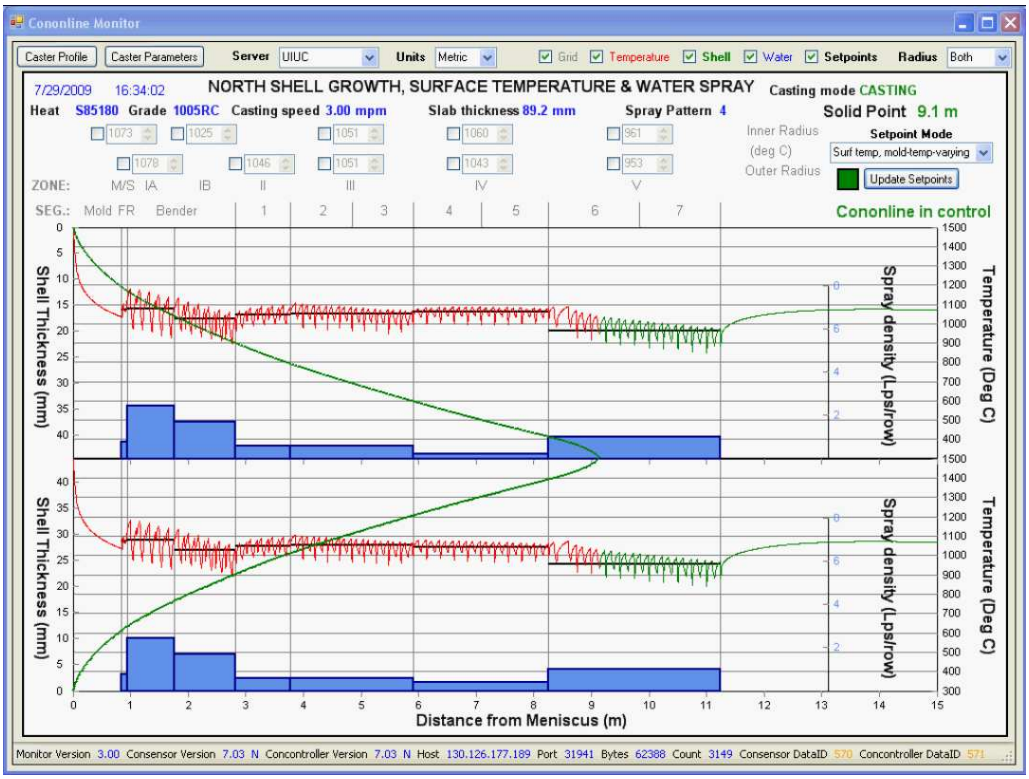
Spray table control



PI Control: speed-based setpoints



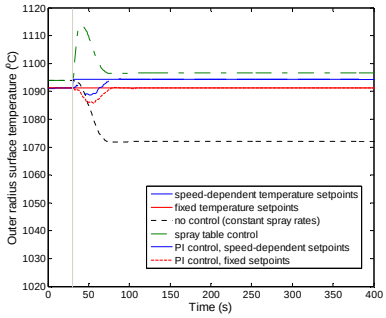
PI Control: fixed setpoints



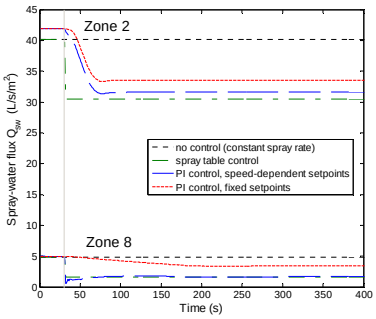
Controller Performance Comparison

- Spray-table control displays temperature overshoot during slowdown
- PI control with speed-varying setpoints reacts quickly at all points throughout caster
- PI control with fixed setpoints reduces sprays more gradually in zones further down the caster

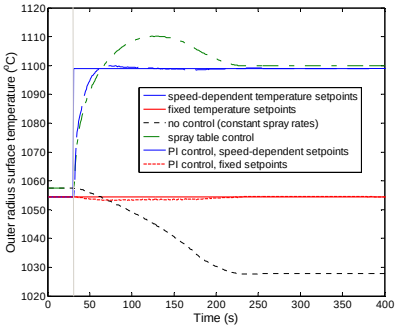
Zone 2 (outer radius) average surface temperature



Spray rates

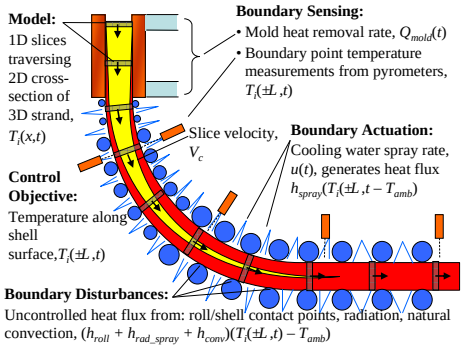


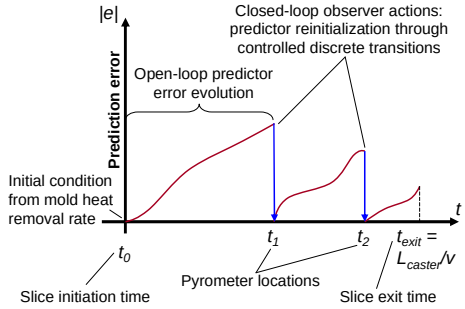
Zone 8 average surface temperature



Future Research: Advanced Control Development

- Surface temperature control does not guarantee metallurgical length control
  - Develop control algorithm for centerline temperature
  - Switch between objectives?
    - solidification front (prevent whales)
    - surface temperature (steel quality)?
- New NSF grant: "Hybrid Control of Continuous Casting for Whale and Crack Prevention"
  - Closed-loop measurements are very spatially localized (discrete)
    - Mold heat removal rate
    - Pyrometer readings
  - Need temperatures between measurements (continuous)





Future Research: Model Development

- Make model robust to casting conditions and data errors
- Improve accuracy of model by adding physical behavior
  - More accurate heat transfer coefficients (Sami, Xiaoxu's research)
  - Possible hysteresis effects during spray changes

Thank you!

- Continuous Casting Consortium Members
- Nucor Decatur
  - Terri Morris, Rob Oldroyd, Kris Sledge, Ron O'Malley
- National Science Foundation
  - GOALI DMI 05-00453 (Completed July 29, 2009)
  - GOALI CMMI-0900138 (Received July 14, 2009)
- Other CCC grad students
  - Sami Vapalahti, Xiaoxu Zhou