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

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Overview

- **Setpoint options**
- **Human-Machine Interface**
- **Setpoint Generator**
- **MAN/MACHINE SUPERVISORY LOOP**
- **Controller**
  - Separate PID controller for each spray zone
- **Automatic Control Loop**
  - Shell thickness and surface temperature estimation
- **Controller**
  - 2-D transient thermal model (200 moving 1-D slices)
  - \( \rho c_p \frac{dT}{dt} + \frac{\partial}{\partial x} (k \frac{dT}{dx}) \)
- **Software Sensor**
- **Caster**
- **Surface temperature setpoint**
- **Spray water flow rates**
- **Caster data**
Computer Architecture

Windows Computers

CononlineMonitor

Caster Automation

Current control logic

CommClient

Controller Computer

(Slackware Linux)

ActiveXServer

CommServer

CONCONTROLLE

shared memory

CommServer

Model Computer

(CentOS Linux)

CommClient

CONSENSOR

Legend:

TCP/IP connection

Shared memory connection

Consensor Overview: CON1D

• Fundamentally based transient finite-difference model:

\[ \rho \cdot C_p \cdot \frac{\partial T}{\partial t} = k \cdot \frac{\partial^2 T}{\partial x^2} + \frac{\partial}{\partial T} \left( \frac{\partial T}{\partial x} \right)^2 \]

• 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

- Zone 1
- Zone 2
- Zone 3
- Zone 4
- Zone 5 (Inner/Outer)
- Zone 6 (Inner/Outer)
- Zone 7 (Inner/Outer)

4 x 1 + 3 x 2 = 10 controllers
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:
        \[ \Delta T_j(t) = \frac{\int T'(z,t) - \tilde{T}(z,t) \, dz}{L_j} \]
     ii. Use \( T_{err} \) to compute the water flow rate command:
        \[ u_j(t) = k_j \Delta T_j(t) + \int k_j \Delta T_j(t) \, dt \]
  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

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Monitor Overview: Profile Screen

![Profile Screen Diagram](image1)

Monitor Overview: Parameter Screen

![Parameter Screen Diagram](image2)
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
Spray table control

PI Control: speed-based 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
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
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  - GOALI DMI 05-00453 (Completed July 29, 2009)
  - GOALI CMMI-0900138 (Received July 14, 2009)
- Other CCC grad students
  - Sami Vapalahti, Xiaoxu Zhou