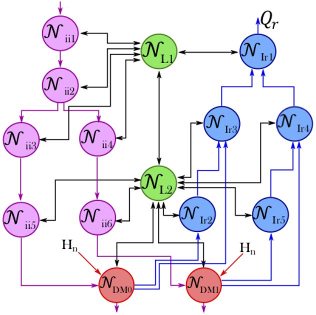
Controlling Thermal Effects in DoD Inkjet Printhead

Amritam Das

Control Systems Group, Eindhoven University of Technology



What is Inkjet Printing?

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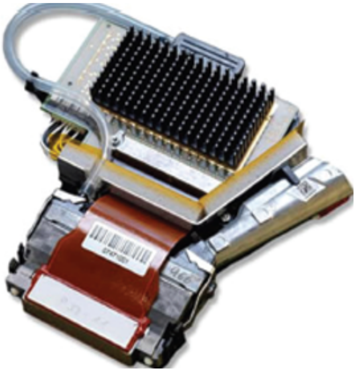
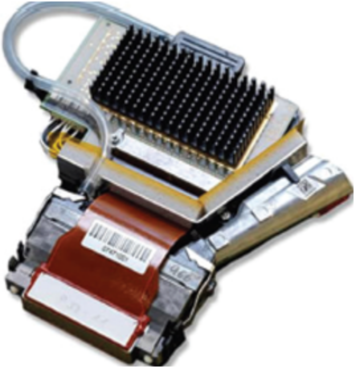
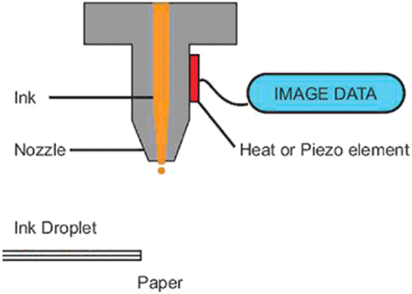


Piezoelectric-element DoD Inkjet Printing





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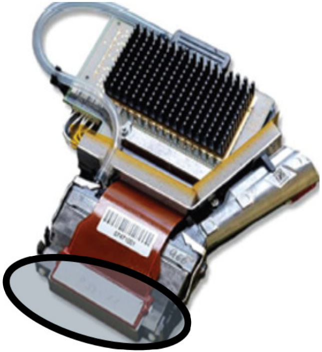

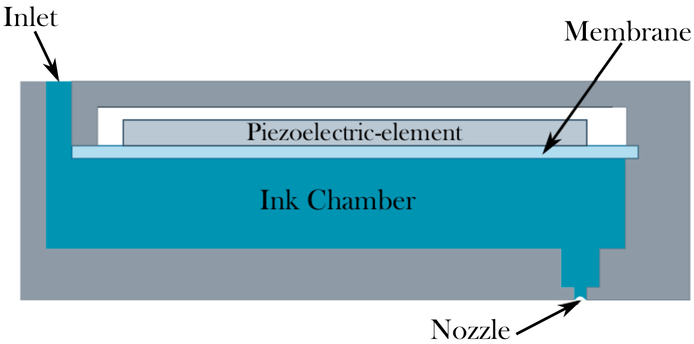

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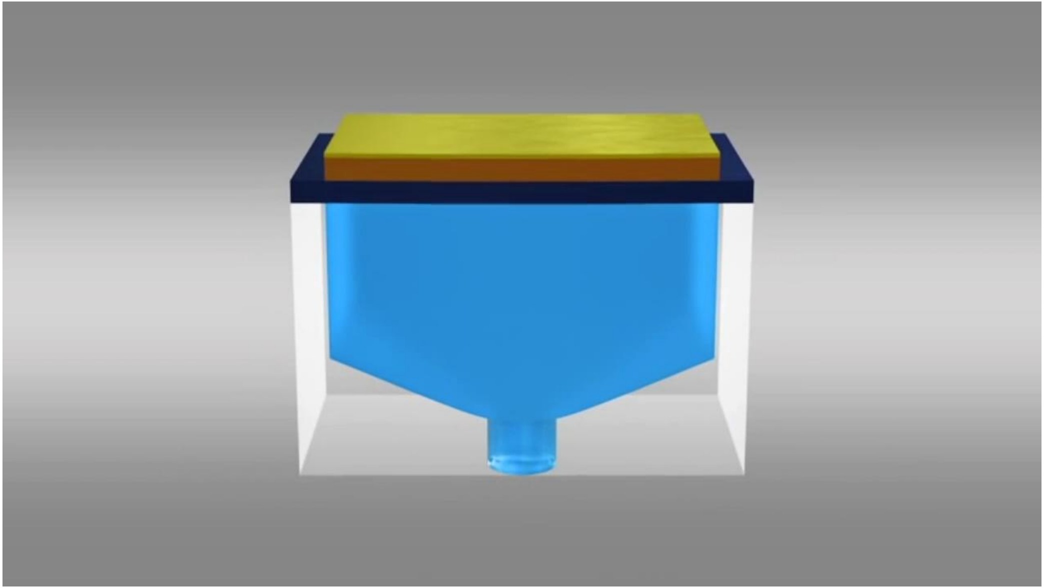
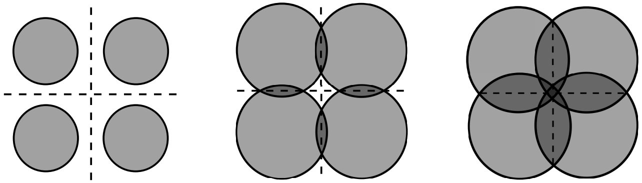


Requirements

- High quality
- High throughput
- Less cost



(a) Too small droplet volume (b) Favorable droplet volume (c) Too large droplet volume

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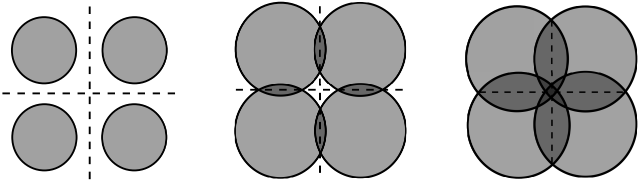


(d) Too small droplet volume

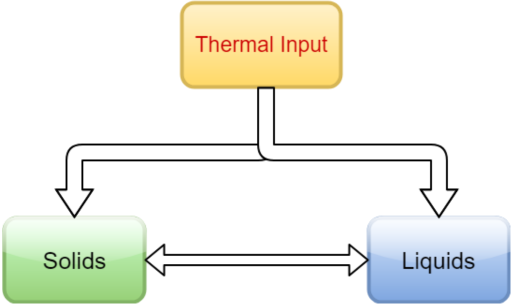
(e) Favorable droplet volume

(f) Too large droplet volume

Temperature consistency is vital !

Thermo-Fluidic Process

Interaction of solids and fluids under influence of Thermal Input



Objective

TU/e

Develop a virtual prototyping tool for controlling thermo-fluidic aspects in inkjet printhead.

- Thermo-fluidic model should be modular and adjustable.
- No additional actuator or sensor is allowed to use.

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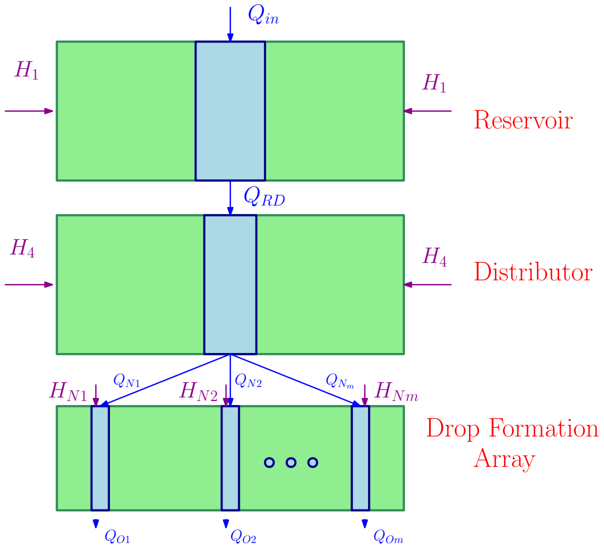
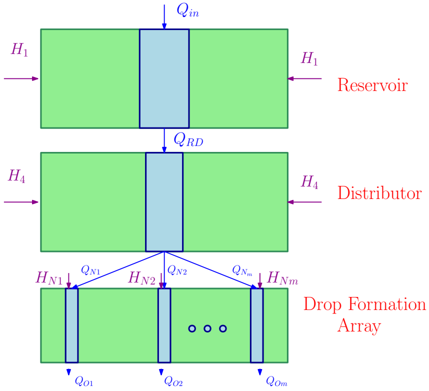


Thermo-Fluidic Process

The interaction of solids and liquids under influence of thermal dissipation.

Thermal Heat transfer

- Conduction
- Convection
- Advection



1. **The finite graph** $\mathcal{G}(\mathcal{N}(\Theta), \mathcal{E})$
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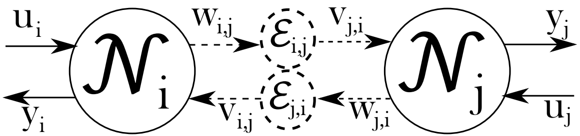
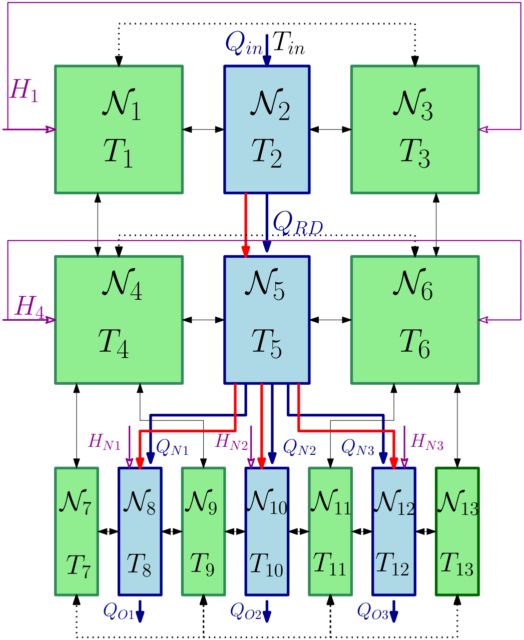
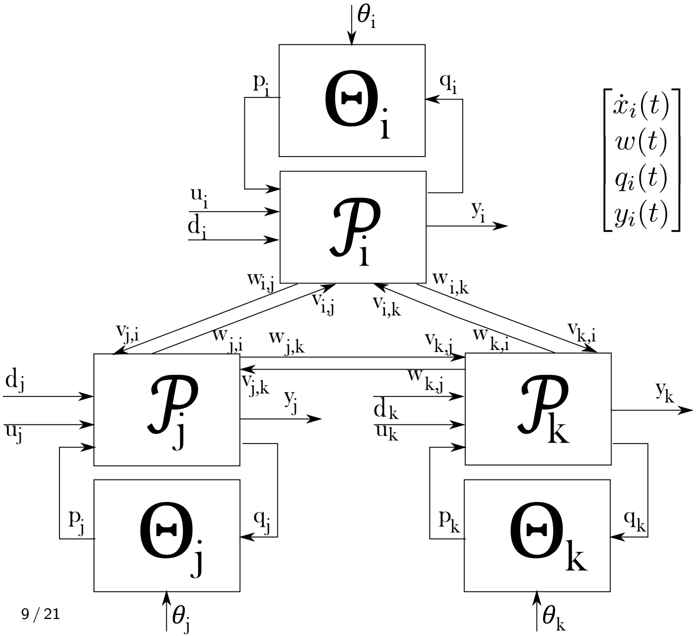
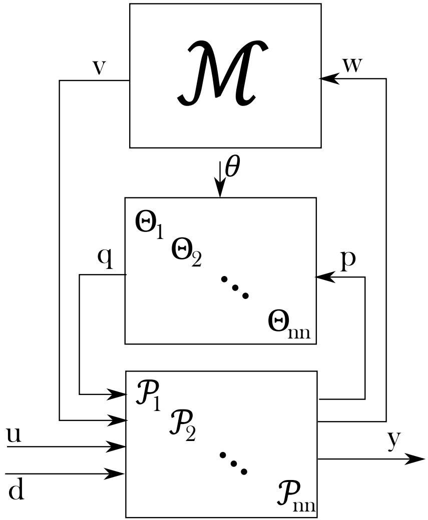


Modeling printhead as a spatially interconnected system



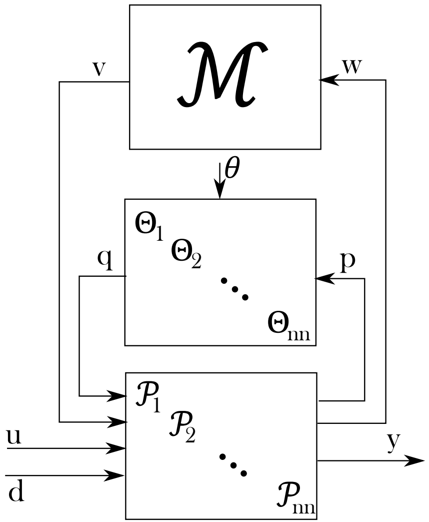


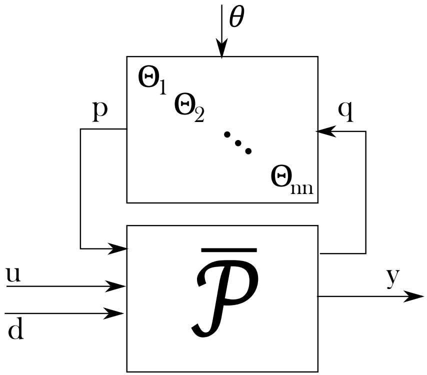
$$\begin{bmatrix} \dot{x}_i(t) \\ w(t) \\ q_i(t) \\ y_i(t) \end{bmatrix} = \underbrace{\begin{bmatrix} A^i_{xx} & B^i_{xv} & B^i_{xp} & B^i_{xu} & B^i_{xd} \\ C^i_{wx} & D^i_{wv} & D^i_{wp} & D^i_{wu} & D^i_{wd} \\ C^i_{qx} & D^i_{qv} & D^i_{qp} & D^i_{qu} & D^i_{qd} \\ C^i_{yx} & D^i_{yv} & D^i_{yp} & D^i_{yu} & D^i_{yd} \end{bmatrix}}_{\mathcal{P}_i} \begin{bmatrix} x_i(t) \\ v(t) \\ p_i(t) \\ u_i(t) \\ d_i(t) \end{bmatrix}$$



$\mathcal{M}$
v
w
θ
Θ_1
Θ_2
Θ_{nn}
q
p
$\mathcal{P}_1$
$\mathcal{P}_2$
$\mathcal{P}_{nn}$
u
d
y

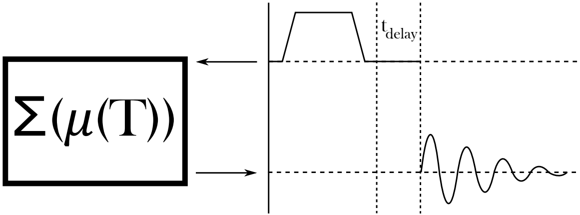
Various Representation of The Model

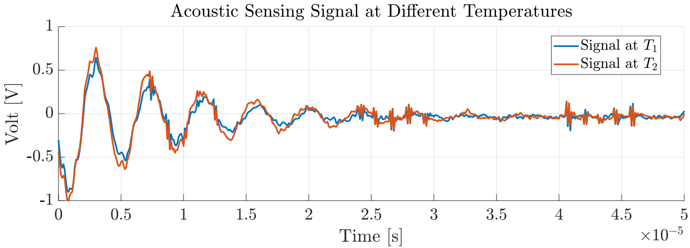




The model can be extended to arbitrary number of nozzles

Sensing Nozzle Temperature: Use Piezo as Soft Sensor





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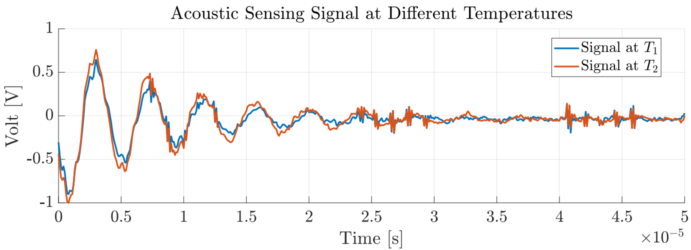

$$y(t) = \alpha(e^{-\zeta}\sin(\omega t + \phi)) + \gamma$$

- $\alpha \Rightarrow$ Amplitude [V]
- $\zeta \Rightarrow$ Damping [-]
- $\omega \Rightarrow$ Frequency [rad/s]
- $\phi \Rightarrow$ Phase shift [rad]
- $\gamma \Rightarrow$ Offset [V]
- $\varphi \Rightarrow$ Energy [J]

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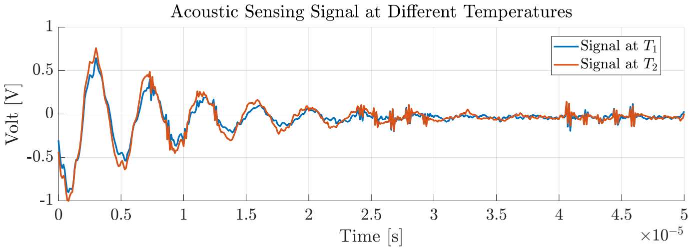

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Use the key parameters to estimate temperature

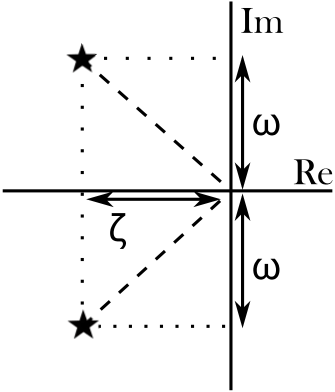
TU/e

Prametrizing Output response

$$y(k) = e^{Ak}x(0) = Z^k x(0)$$
$$Z = \overleftarrow{Y}^{\dagger} Y;$$

Construct the Hnakel matrix

$$Y = \begin{bmatrix} y_0 & \cdots & y_{L-2} & y_{L-1} \\ y_1 & \cdots & y_{L-1} & y_L \\ \vdots & \ddots & \vdots & \vdots \\ y_{N-L-1} & \cdots & y_{N-3} & y_{N-2} \end{bmatrix}, \overleftarrow{Y} = \begin{bmatrix} y_1 & \cdots & y_{L-1} & y_L \\ y_2 & \cdots & y_L & y_{L+2} \\ \vdots & \ddots & \vdots & \vdots \\ y_{N-L} & \cdots & y_{N-2} & y_{N-1} \end{bmatrix}$$

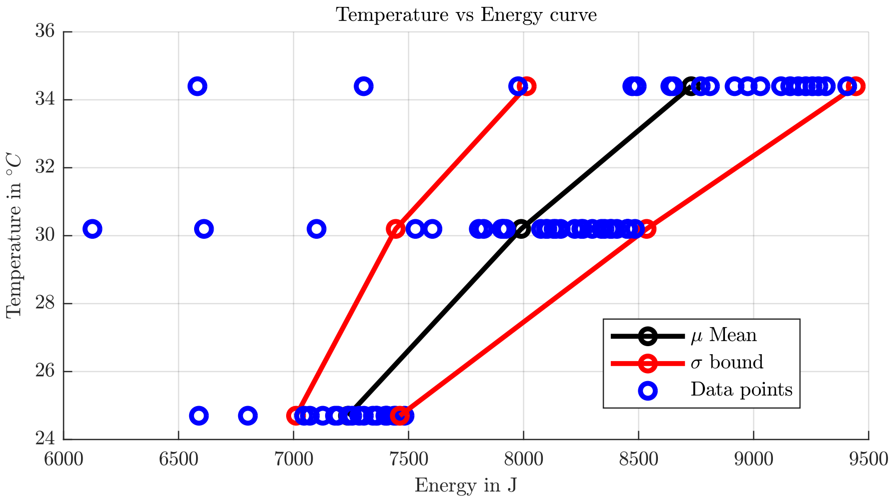


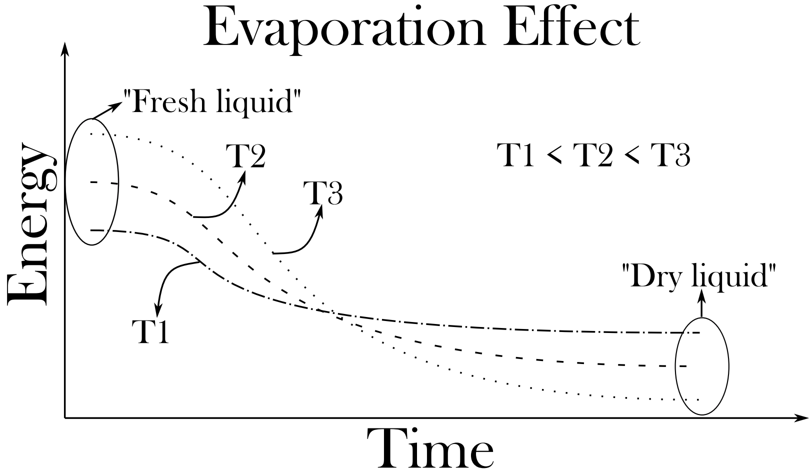
Find SVD of Z

$$Z = \overleftarrow{Y}^{\dagger} Y = \left[\sum_{k=1}^{2K} \frac{1}{\sigma_k} v_k u_k^{\top} \right] Y$$

Find the Poles $p = \ln\{\sigma(Z)\}$

Step 2: Use energy of the output response to estimate temperature




Evaporation Effect
"Fresh liquid"
T2
T3
T1 < T2 < T3
Energy
"Dry liquid"
T1
Time

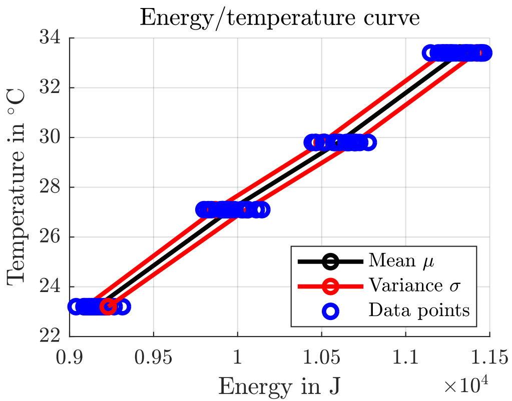


Figure: Variance plot of calibration III with 2000 jetting pulses

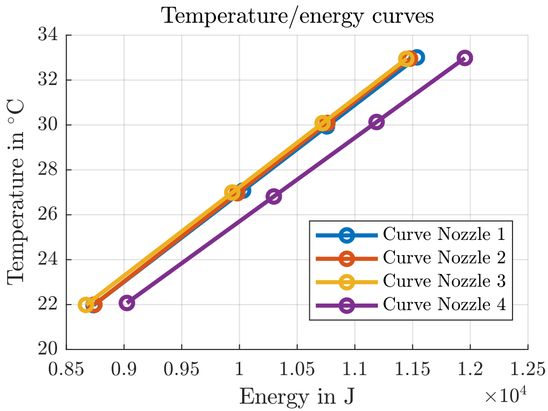
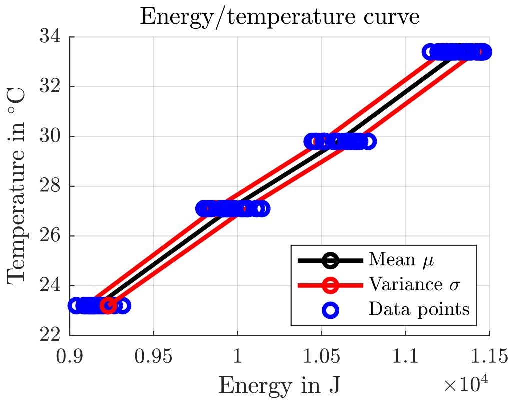


Figure: Temperature/energy curves of multiple nozzles

Soft sensor calibration to incorporate evaporation effect



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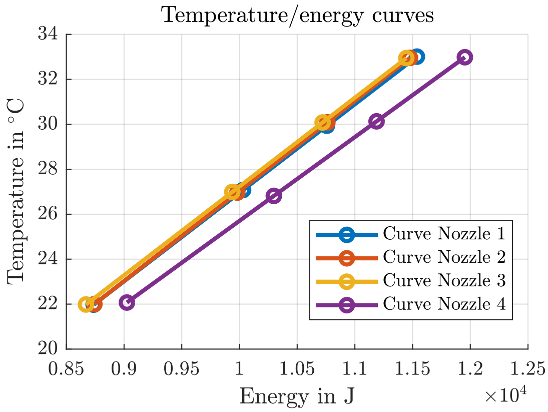

Figure: Temperature/energy curves of multiple nozzles

The soft sensor is accurate within 0.1 degree

Controller Requirement

Need to **anticipate** and **compensate** the temperature changes

Controller's Job

1. Utilise prior information of print-profile
2. Respect the constraints on states and inputs

Use the piezo as an heating actuator while no jetting

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Feedback Controller Synthesis

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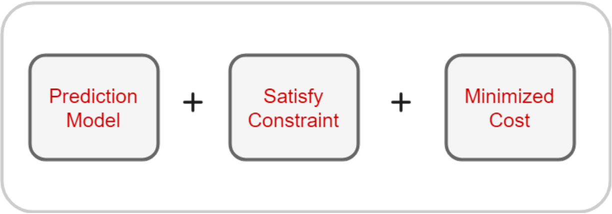

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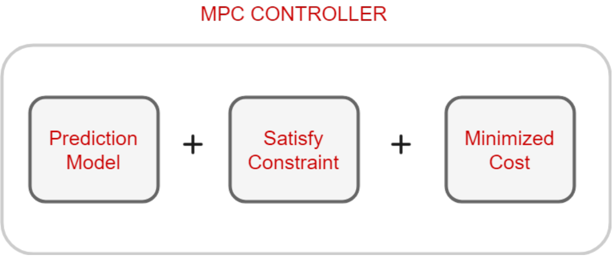

- **Prediction model** In discrete time

$$x_{i+1|k} = A_{i|k}x_{i|k} + B_{i|k}u_{i|k} + f_{i|k}, \qquad \forall i = 0, 1, \cdots, N-1$$

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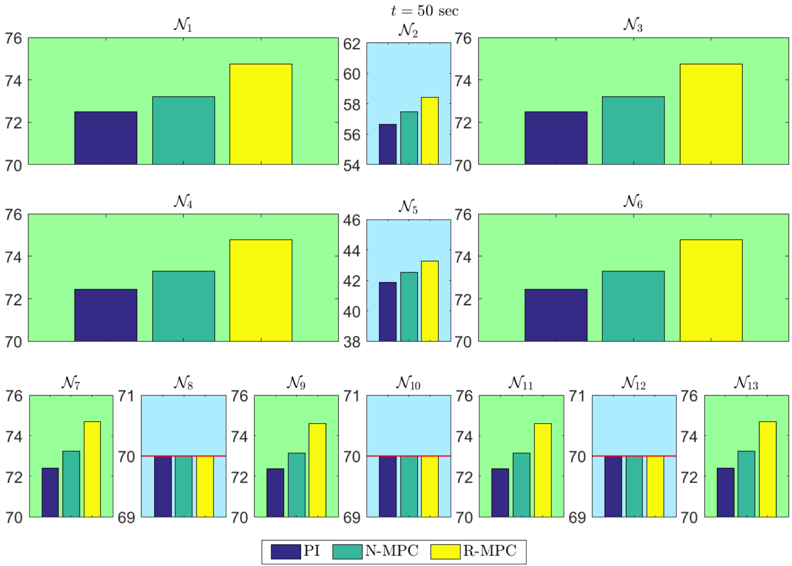
- **Optimization Problem:** Minimising the output and reference temperature

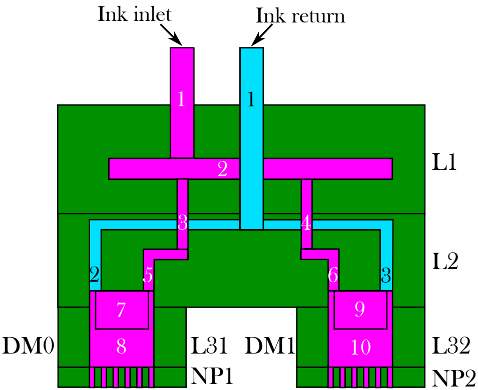
$$||x_{N|k} - x^{ss}_{N|k}||^2_{P_k} + \sum_{i=0}^{N-1} ||x_{i|k} - x^{ss}_{i|k}||^2_Q + ||u_{i|k} - u^{ss}_{i|k}||^2_R$$

subject to

$$u_{min} \leq u_{i|k} \leq u_{max};$$
$$x_{min} \leq x_{i|k} \leq x_{max}, \quad i = 0, \cdots, N$$

Closed-Loop Simulation of PID vs MPC for steady state tracking





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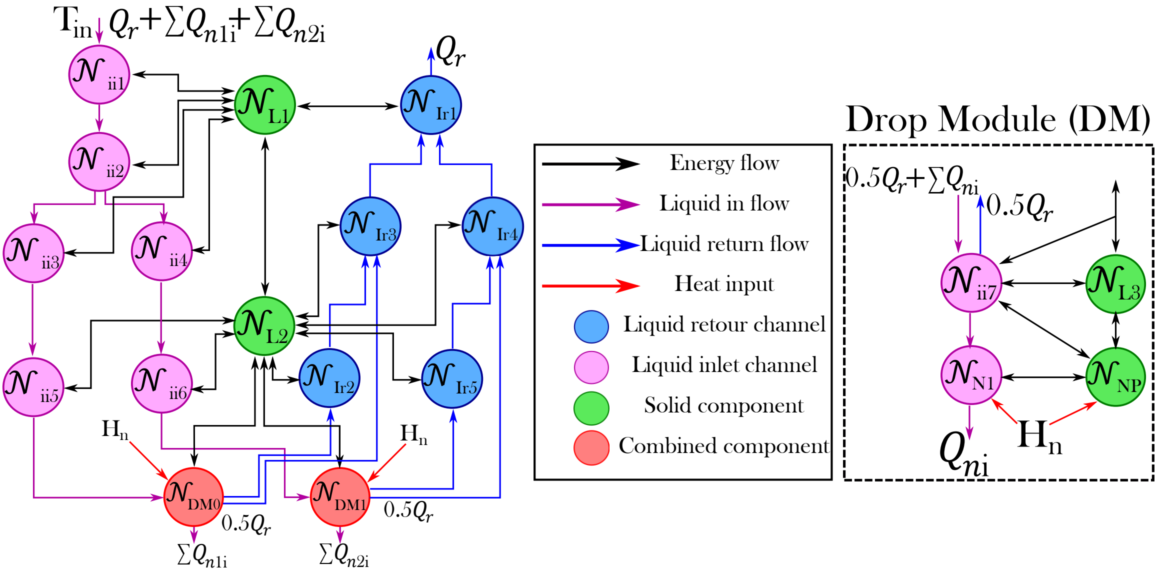
T_{in} $Q_r+\sum Q_{n1i}+\sum Q_{n2i}$
$\mathcal{N}_{ii1}$
$\mathcal{N}_{ii2}$
$\mathcal{N}_{ii3}$
$\mathcal{N}_{ii4}$
$\mathcal{N}_{ii5}$
$\mathcal{N}_{ii6}$
$\mathcal{N}_{L1}$
$\mathcal{N}_{L2}$
Q_r
$\mathcal{N}_{Ir1}$
$\mathcal{N}_{Ir2}$
$\mathcal{N}_{Ir3}$
$\mathcal{N}_{Ir4}$
$\mathcal{N}_{Ir5}$
H_n
H_n
$\mathcal{N}_{DM0}$
$\mathcal{N}_{DM1}$
$0.5Q_r$
$0.5Q_r$
$\sum Q_{n1i}$
$\sum Q_{n2i}$
Energy flow
Liquid in flow
Liquid return flow
Heat input
Liquid retour channel
Liquid inlet channel
Solid component
Combined component
Drop Module (DM)
$0.5Q_r+\sum Q_{ni}$
$0.5Q_r$
$\mathcal{N}_{ii7}$
$\mathcal{N}_{L3}$
$\mathcal{N}_{N1}$
$\mathcal{N}_{NP}$
Q_{ni}
H_n

MPC to minimize temperature gradient between adjacent nozzle

System-Level Thinking for Model-Based Control of Large Scale Models

Conclusion

- A modular, completely flexible modeling framework for thermal aspects in printhead.
- Fully automated software tools for simulation, design optimization and controller synthesis.
- Exploiting piezo as a self-sensing actuator; no need of additional sensors and heaters.

Future work

- Designing non-jetting pulse to generate control input for heating.
- Improve scalability of controller for implementation.
- Investigate new control architectures.

Thank You!