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Wireless Temperature Sensing Through Opaque Media and Enclosed Metal Vessels

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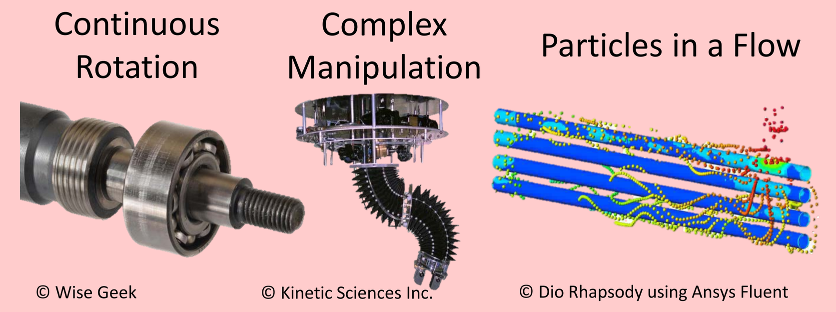
Problem

Compact and distributed temperature measurements are needed for sensing inside metal vessels or opaque media. Requirements include **no wire feedthroughs**, **no optical access**, and no extra power systems at the sensing points.

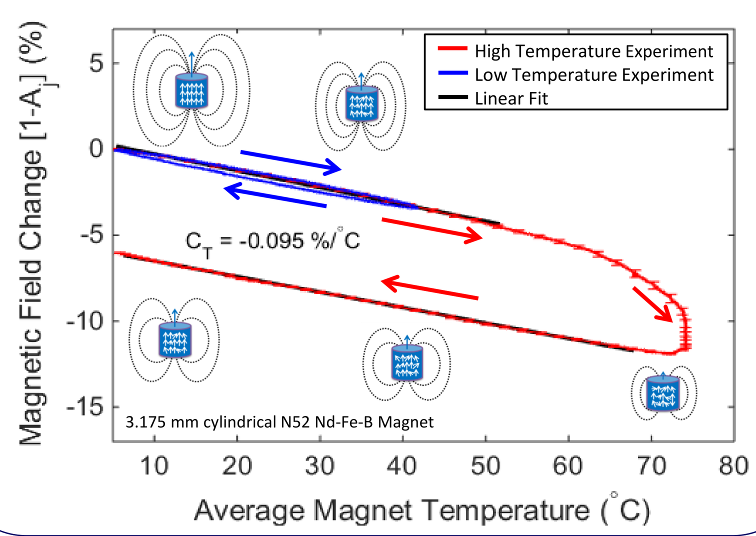
Sealed Opaque Vessels

Objects under Motions

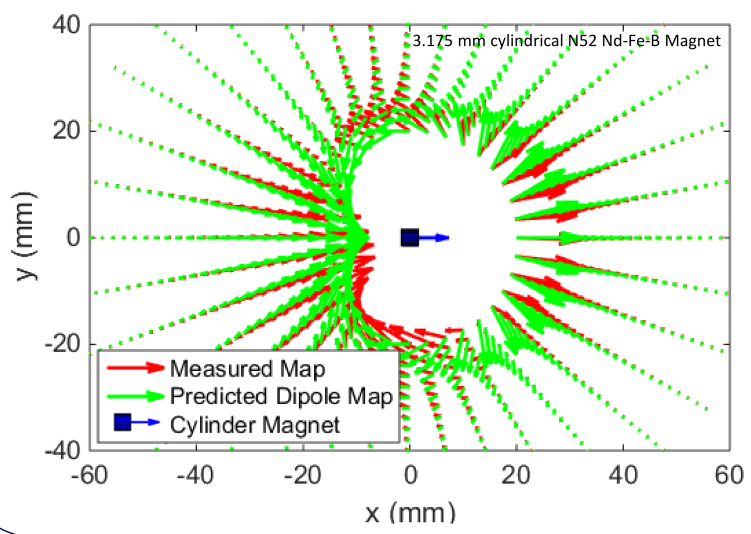


Hypotheses and Approach

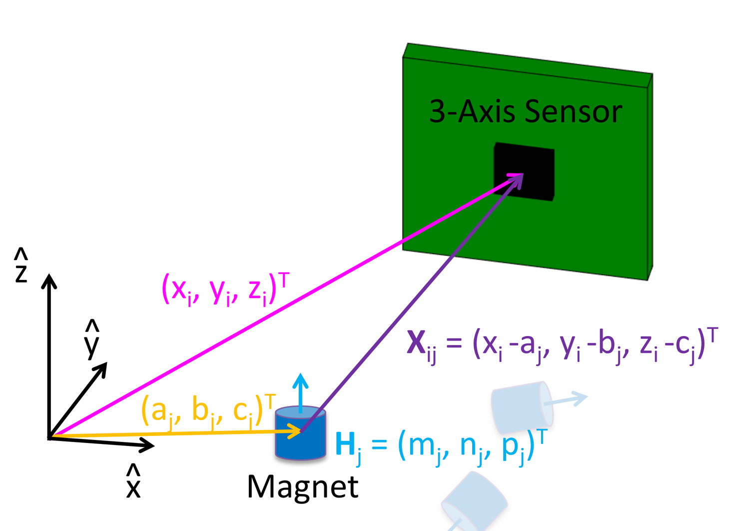
We hypothesize that the **temperature sensitivity of permanent magnets** can be used in their **linear recoverable regime** to measure temperature.



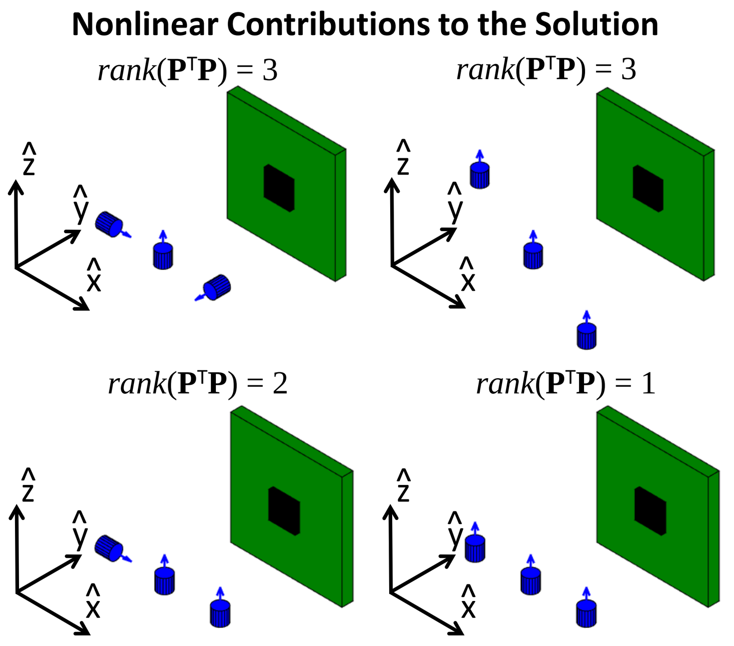
We hypothesize that the **three-dimensional nature of magnetic field in permanent magnets** can be utilized to separate the contributions of multiple closely-spaced points simultaneously.



Model and Solution



Nonlinear Contributions to the Solution



- The magnetic field sums linearly and permeability $\mu_r \approx 1$.
- Cylinder magnets behave like the dipole model,

$$\mathbf{B}_i = \sum_{j=1}^{J} B_{Tj}(T_j)\left(\frac{3(\mathbf{H}_j \cdot \mathbf{X}_{ij})\mathbf{X}_{ij}}{R_{ij}^5} - \frac{\mathbf{H}_j}{R_{ij}^3}\right),$$

$$\mathbf{B}_i = B_{ix}\hat{\mathbf{x}} + B_{iy}\hat{\mathbf{y}} + B_{iz}\hat{\mathbf{z}}.$$

- The system operates in the linear recoverable region and the field magnitude is isotropic with temperature,

$$B_{Tj}(T_j) = B_T(T_0)\left[1 - C_T\left(T_j - T_0\right)\right].$$

- We assume that position and orientation are fixed, known, or can be calibrated and then the system of equations becomes **linear**. The nonlinear content containing relative position and orientation information controls the inversion properties, such as matrix rank.
- With more magnets than sensor axes ($I \geq J$) we have,

$$\mathbf{Y} = \mathbf{P}\mathbf{A}.$$

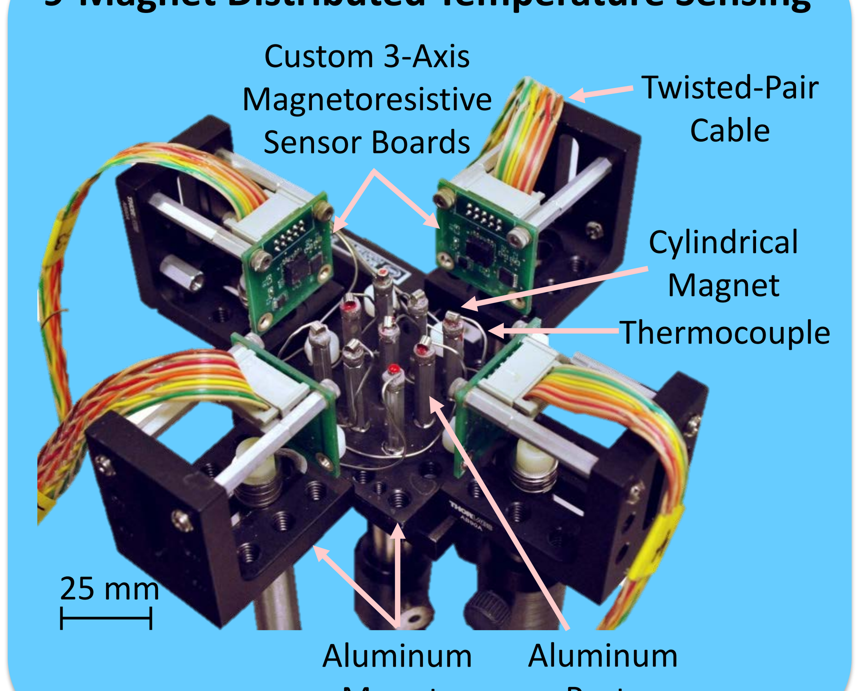
- The least squares solution is,

$$\mathbf{A} = (\mathbf{P}^T\mathbf{P})^{-1}\mathbf{P}^T\mathbf{Y},$$

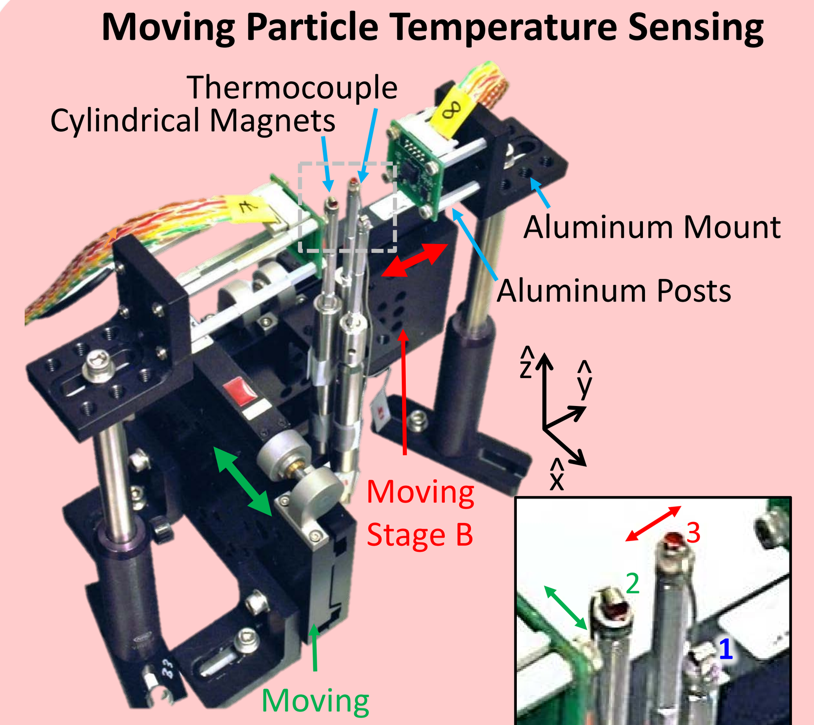
$$T_j = \frac{1}{C_T}\left(1 - A_j\right) + T_0.$$

Experimental Methods

9-Magnet Distributed Temperature Sensing

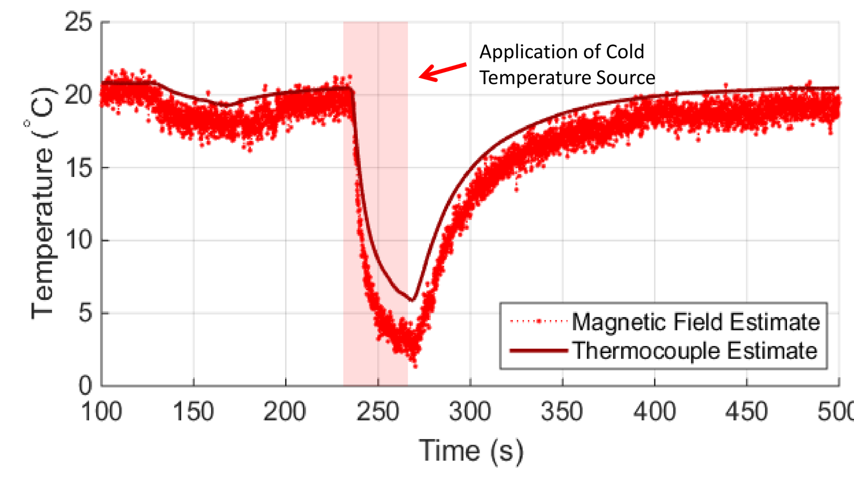


Moving Particle Temperature Sensing



- Custom 3-axis magnetic field sensor boards (HMC1053 , ±6 Gauss, 600 µG noise floor) are used.
- Initial experiments are conducted with 3.175 mm N52 grade Nd-Fe-B cylindrical magnets.
- Type K thermocouples are utilized for reference (not a perfect temperature match due to contact resistance).
- We calibrated the $\mathbf{P}$ matrix by placing or moving each magnet in the setup sequentially at T_0.

Results and Analysis



- Thermocouple and magnet temperature estimates are similar, showing that the approach works well. Thermal time constants of the magnet can be observed.
- We estimated matrix condition number $cond(\mathbf{P}^T\mathbf{P})$ to determine the configurations with the best inversion characteristics.
- We developed an *a priori* estimate for the temperature noise standard deviation on each magnet,

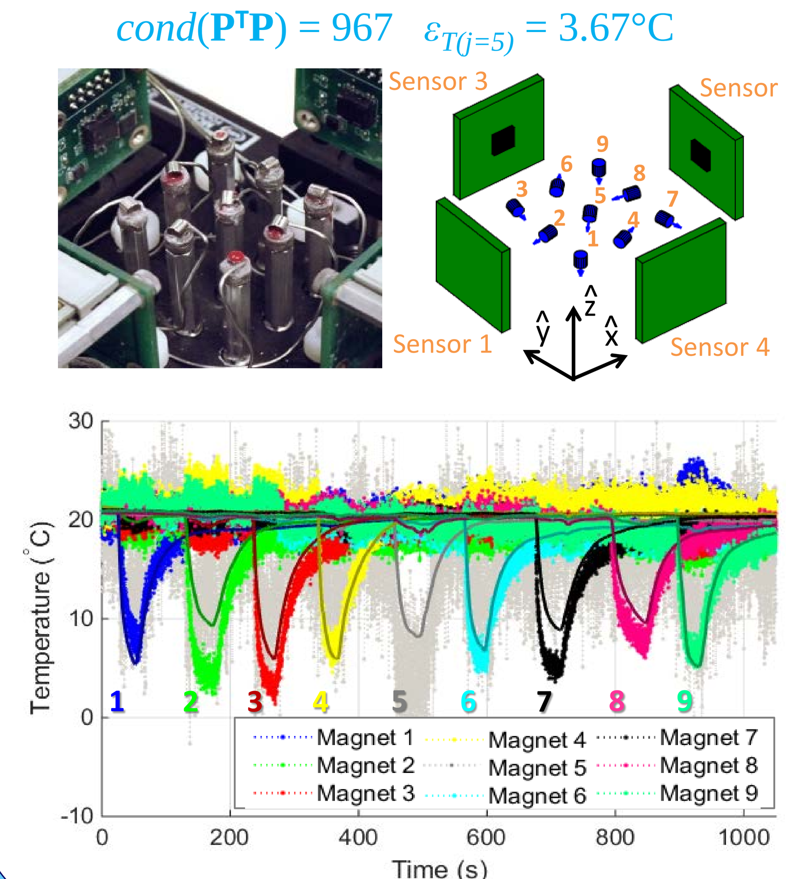
$$\hat{\epsilon}_{Tj} \approx \frac{\epsilon_B}{C_T}\sqrt{diag\left(\left(\mathbf{P}^T\mathbf{P}\right)^{-1}\right)_j}.$$

Model-Based Experimental Design Optimization to Minimize Noise

We created an algorithm which finds the optimal magnet and sensor placement and orientation via discrete global search in order to **minimize the estimated magnetic temperature noise and matrix condition number**. The optimized configuration places magnets that are the furthest away from the sensors (i.e. magnet 5) in unique orientations to maximize the signal magnitude and matrix contribution orthogonality.

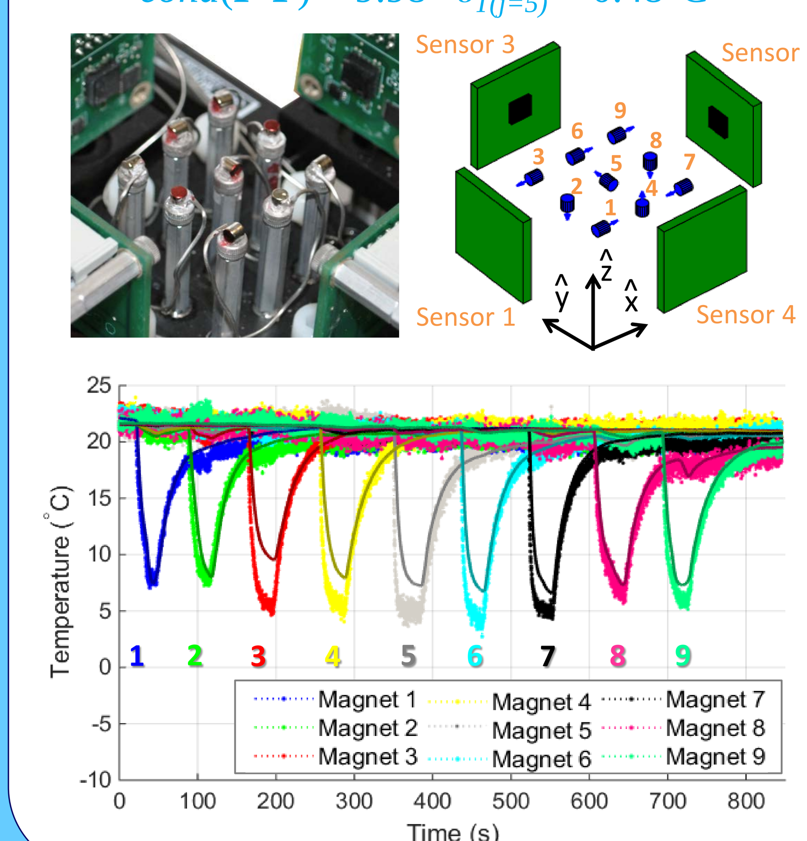
Magnets Oriented by Trial-and-Error

$cond(\mathbf{P}^T\mathbf{P}) = 967 \quad \epsilon_{T(j=5)} = 3.67°C$

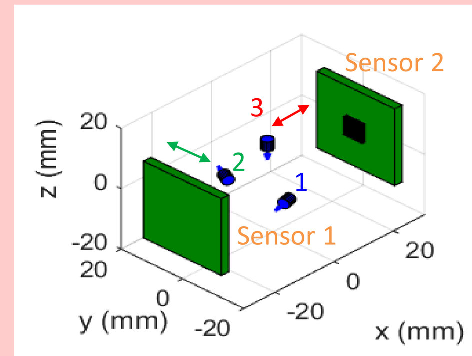


Magnets Oriented by Optimization Algorithm

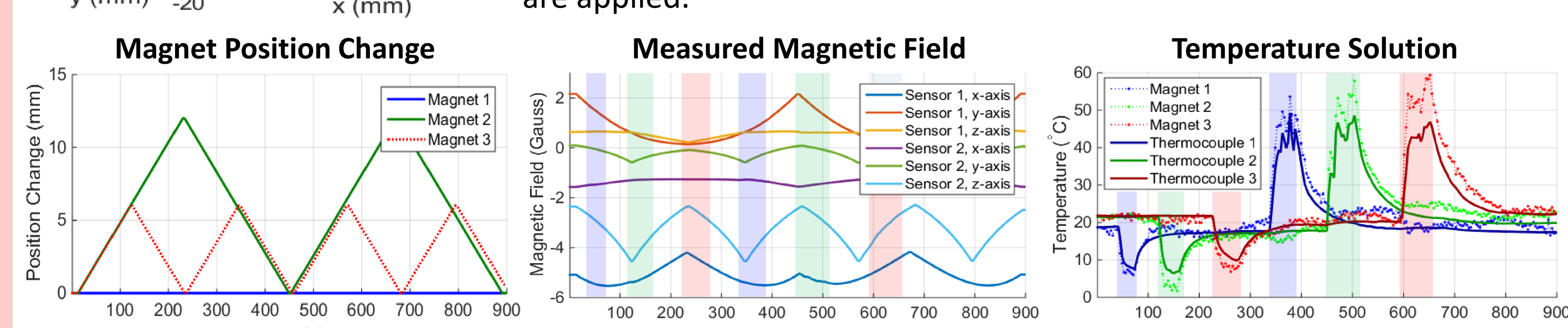
$cond(\mathbf{P}^T\mathbf{P}) = 9.98 \quad \epsilon_{T(j=5)} = 0.48°C$



Sensing Points Moving In Repeatable Motions

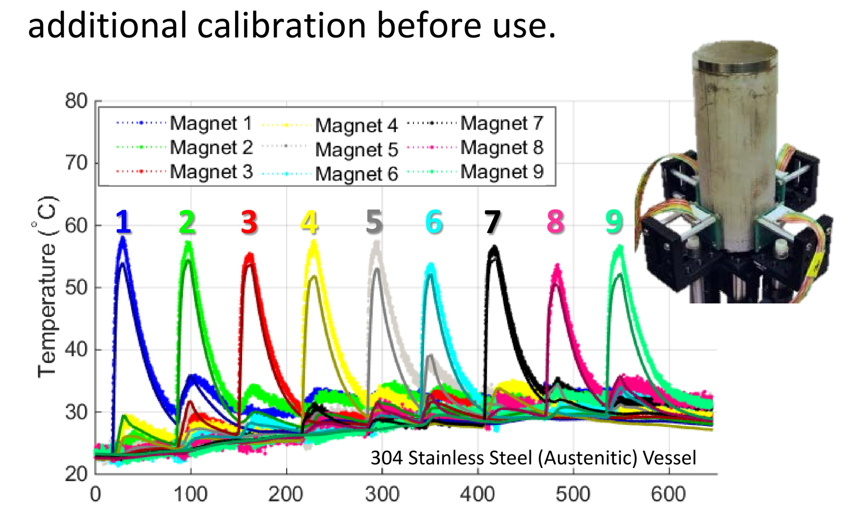


- Calibrations are created for the positions of each magnet (not each combination of magnet positions since the system is linear).
- The magnetic field signal level due to position change is orders of magnitude greater than the signal levels due to temperature change.
- We are able to successfully **recover the temperature of the magnets accurately while the sensing points are moving** as cold and hot sources are applied.

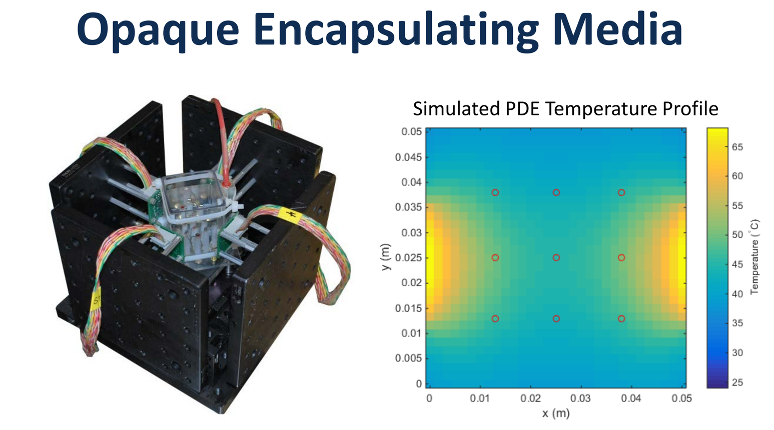


Enclosed Metal Vessel

Measurements were successfully obtained inside metal vessels. Austenitic (μ_r=1) stainless steels do not alter the magnetic field. Martensitic and ferritic stainless steels do alter the field and require additional calibration before use.

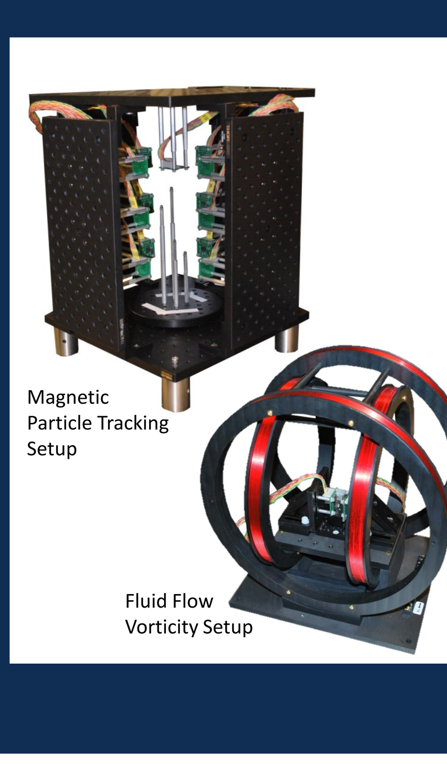


Opaque Encapsulating Media



Measurements are made in silicone and foam (self-heating) encapsulation with external heaters in order to control the temperature profiles while curing. PDE constrained optimization can be used to solve for **temperature source terms (hot spots) and material properties**. Model-based and underactuated control algorithm strategies are used to **modulate the temperature profiles** inside the encapsulating media.

Conclusions



- We validated our hypotheses and were able to measure temperatures wirelessly with magnets and were also able to separate the contributions of different magnets using the three-dimensional nature of the magnetic field.
- We developed a method, model, and instrumentation for measuring multiple closely-spaced stationary or moving temperature points wirelessly in sealed metal vessels and opaque media using permanent magnets.
- A design optimization algorithm to minimize estimation noise was created.
- These techniques can be applied to measure a variety of properties wirelessly.
- Current work includes magnetic particle tracking, vibration tracking, and fluid flow vorticity measurements.

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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References:

[1] Y. Chen, O. Guba, C. F. Brooks, C. C. Roberts, B. G. van Bloemen Waanders, and M. B. Nemer, "Remote Temperature Distribution Sensing Using Permanent Magnets," IEEE Trans. Magn., 2016, [in press].

[2] Y. Chen, O. Guba, C. F. Brooks, C. C. Roberts, B. G. van Bloemen Waanders, and M. B. Nemer, "Wireless temperature sensing using permanent magnets for multiple points undergoing repeatable motions," in Proc. of the ASME 2016 Dynamic Systems and Control Conf., 2016, pp. 1–10, DSCC2016-9663.

[3] L. A. Gupta and D. Peroulis, "Wireless temperature sensor operating in complete metallic environment using permanent magnets," IEEE Trans. Magn., vol. 48, no. 11, pp. 4413–4416, 2012.

[4] D. D. Reigosa, F. Briz, M. W. Degner, P. Garc´ıa, and J. M. Guerrero, "Magnet temperature estimation in surface PM machines during six-step operation," IEEE Trans. Ind. Appl., vol. 48, no. 6, pp. 2353–2358, 2012.