Spatial Mapping of Soil Saturation Levels Using UAV Deployable Smart Penetrometers

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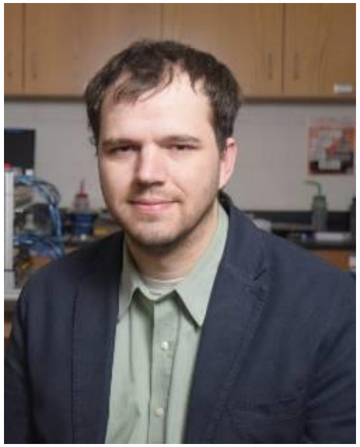
Meet Your Instructor

- This work was developed at the Adoptive Real-Time Systems (ARTS)-Lab at the University of South Carolina in Collaboration with Jackson State University.
- The ARTS-Lab is an interdisciplinarity lab focused on real-time data processing on embedded system.
- This work is presented by Austin Downey.



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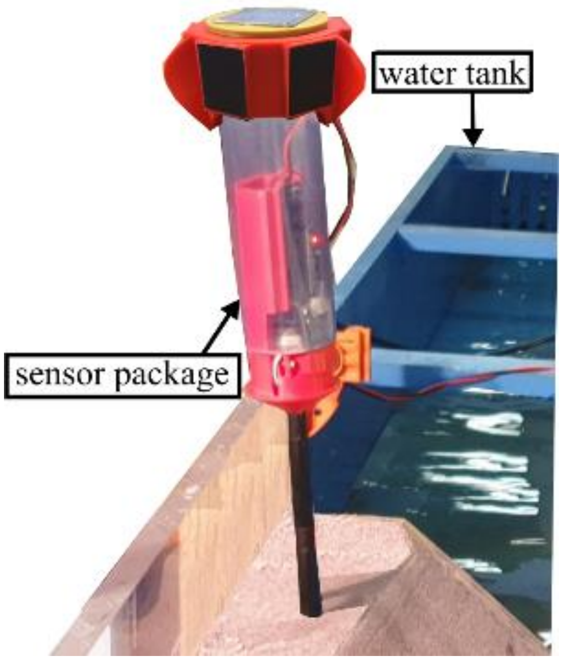
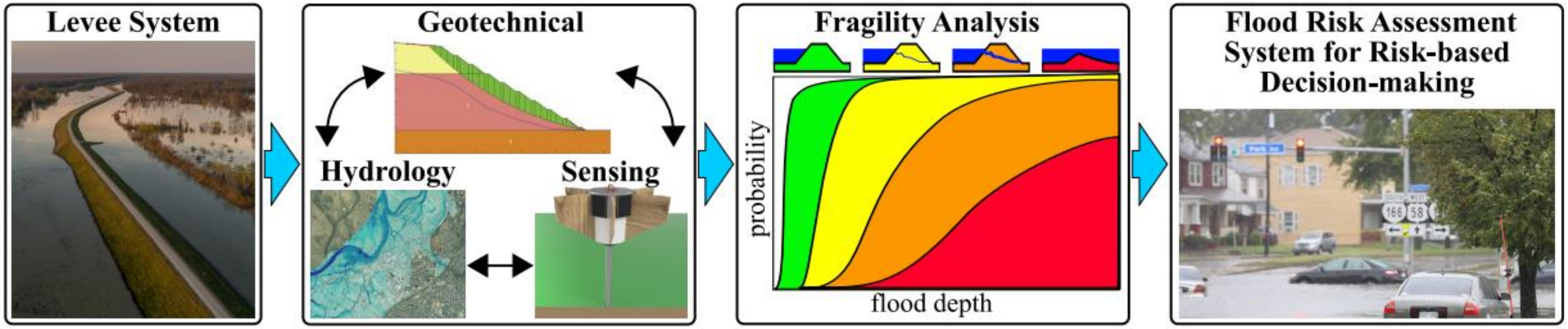
Risk Assessment of Levee Breach

- This work is part of a larger effort to develop a data-driven fragility framework for risk assessment of levee breach.
- This presentation will focus on preliminary results obtained using a hand/UAV-deployable sensor package for monitoring levees.
- This work in being done in close collaboration with experts in data-driven risk assessment, geo-technical, and hydrology.





Levee

- A dry levee works by absorbing and slowing down the water until river level drops.
- Levees are made mostly of
  - compacted dirt,
  - not concrete or metal,
  - are permeable.
- Water will seep through or under a levee given enough time.

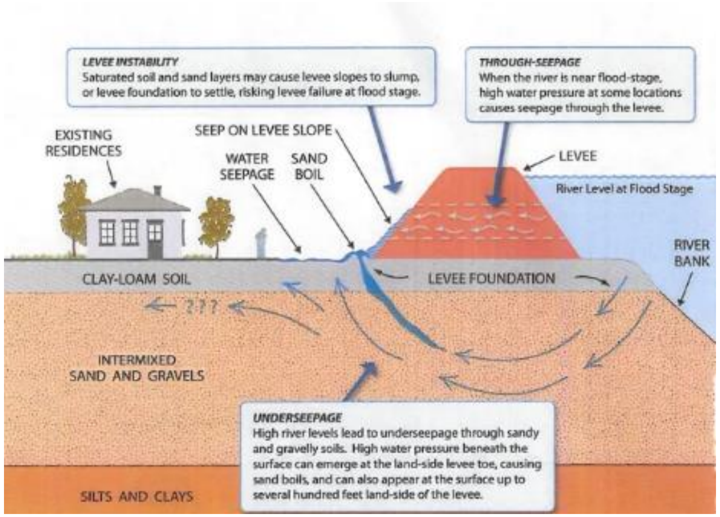
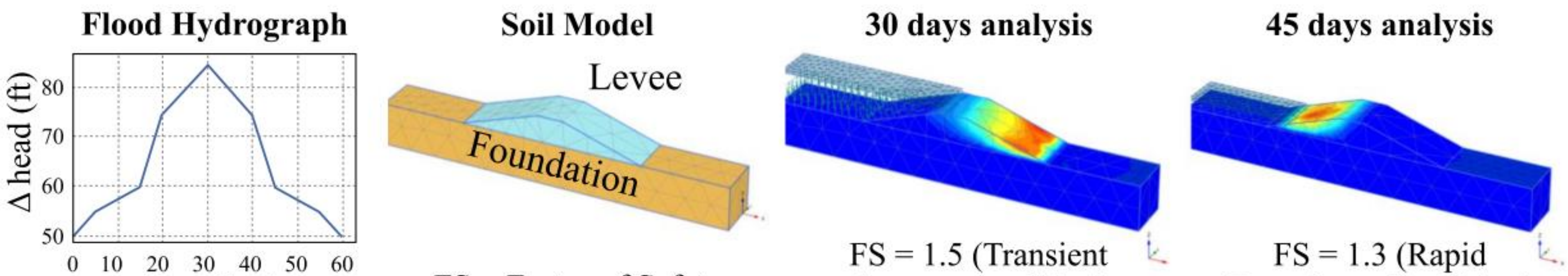


Image courtesy of SAFCA 2007, NLIP Landside Improvements Project DEIR.



FS = Factor of Safety

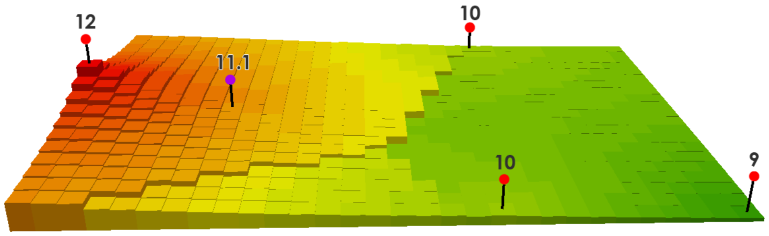
FS = 1.5 (Transient Seepage condition)

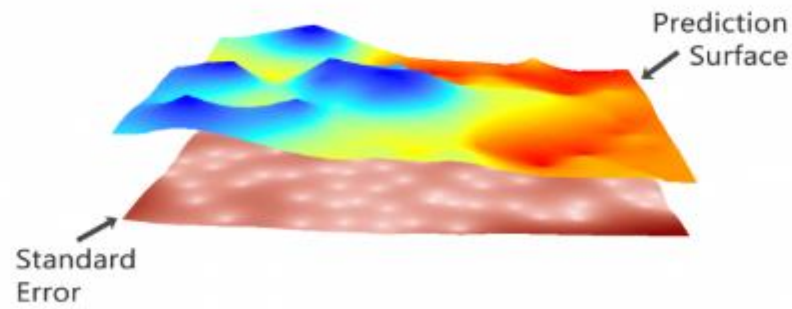
FS = 1.3 (Rapid Drawdown Condition)

Measuring Soil Moisture

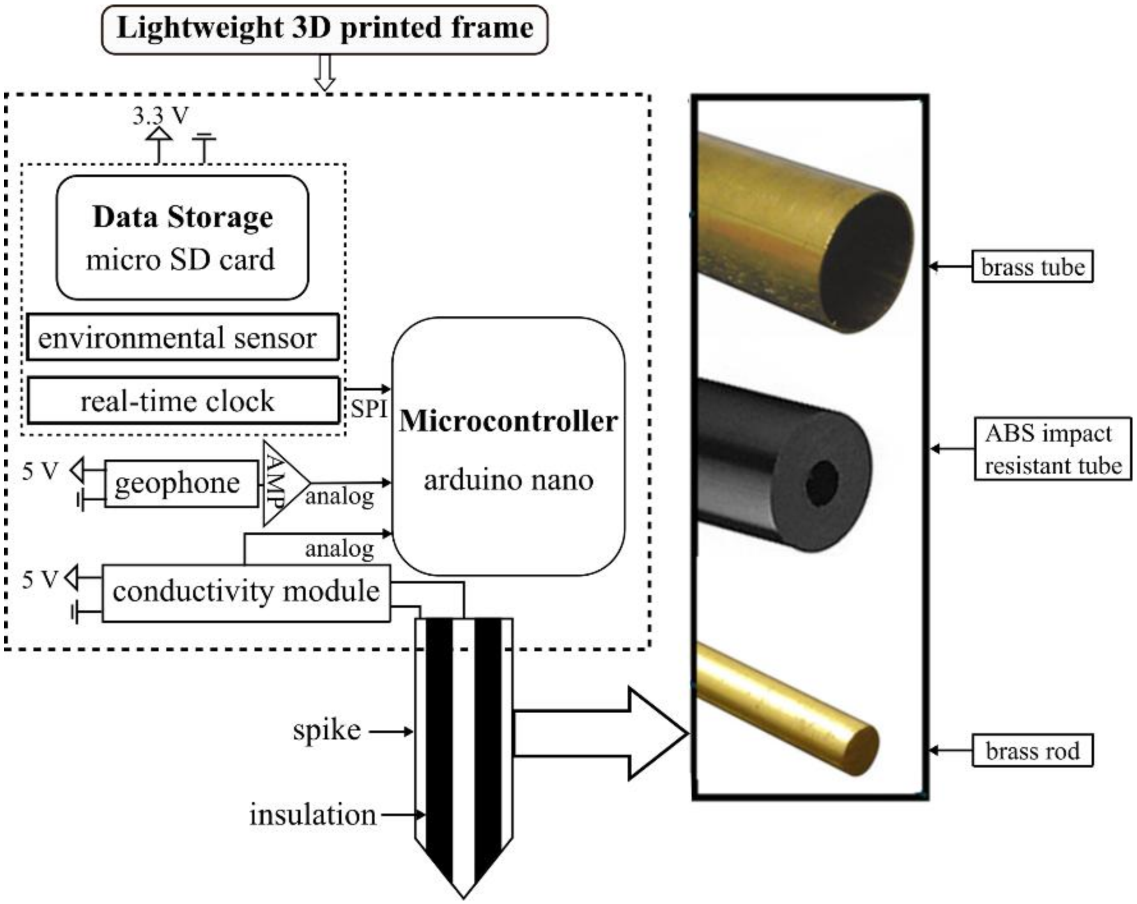
- Deterministic:
  - uses predefined function

- Kriging:
  - Probabilistic
  - Measure of confidence
  - Provides prediction surface and the error surface.
  - distances between spikes
    - $d_{ij} = |x_i - x_j|$
  - raw values of the variogram
    - $\frac{\left(t(x_i) - t(x_j)\right)^2}{2}$
  - The gaussian covariance
    - $C_{ij} = be^{-\frac{d_{ij}^2}{2a^2}}$
  - The variogram
    - $\gamma_{ij} = b\left(1 - e^{-\frac{d_{ij}^2}{2a^2}}\right)$





Open-Source Sensor Package



Sensor Package Levee Test

Spikes for Soil Moisture Test And Sensor Package for Levee Test

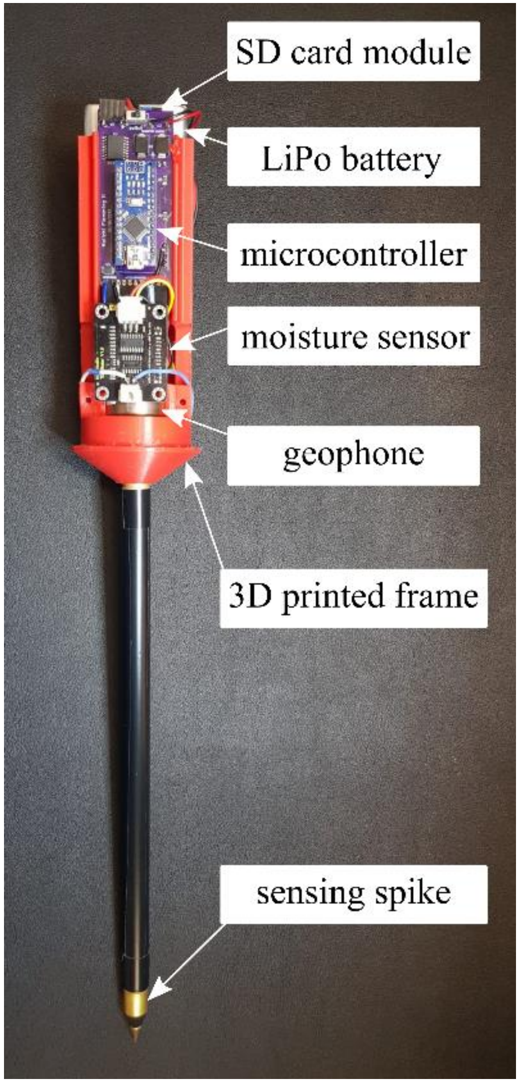
Raw material to final product

raw material

spike

back side

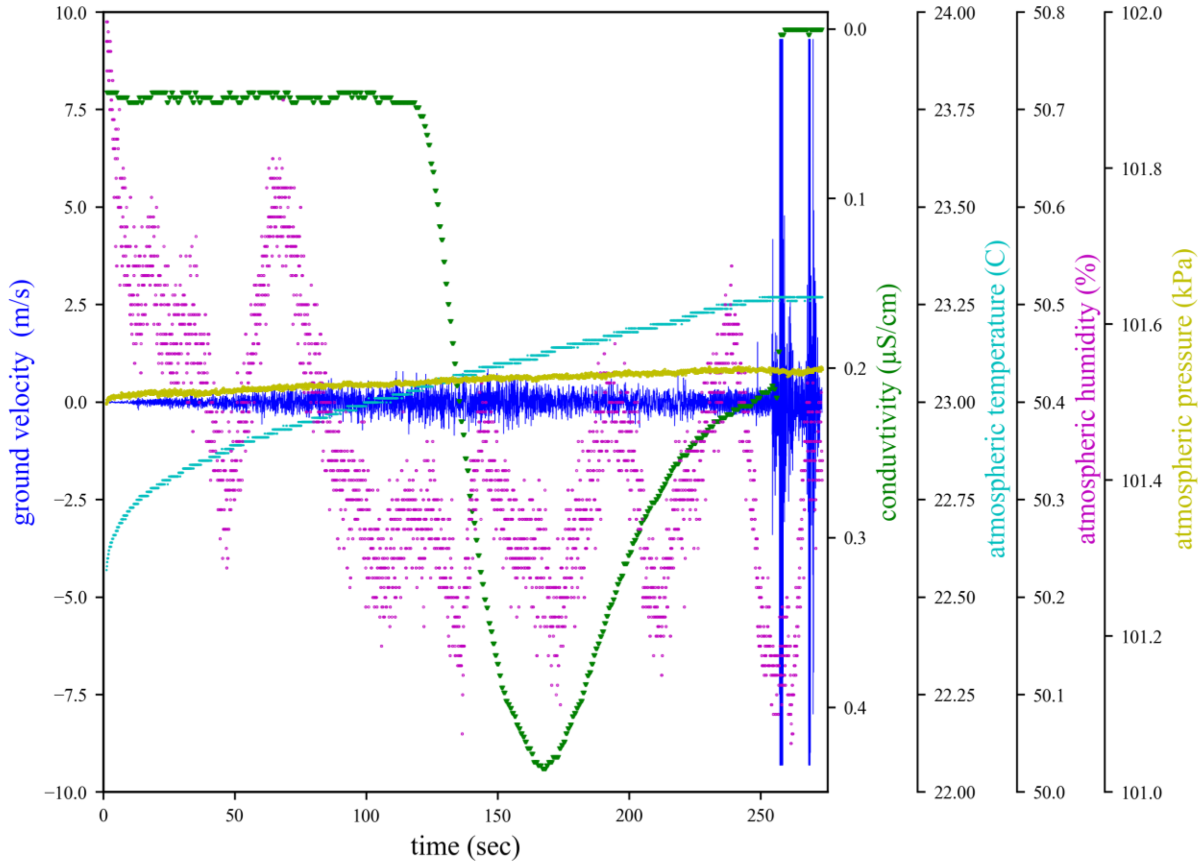
different layer



Sensor package

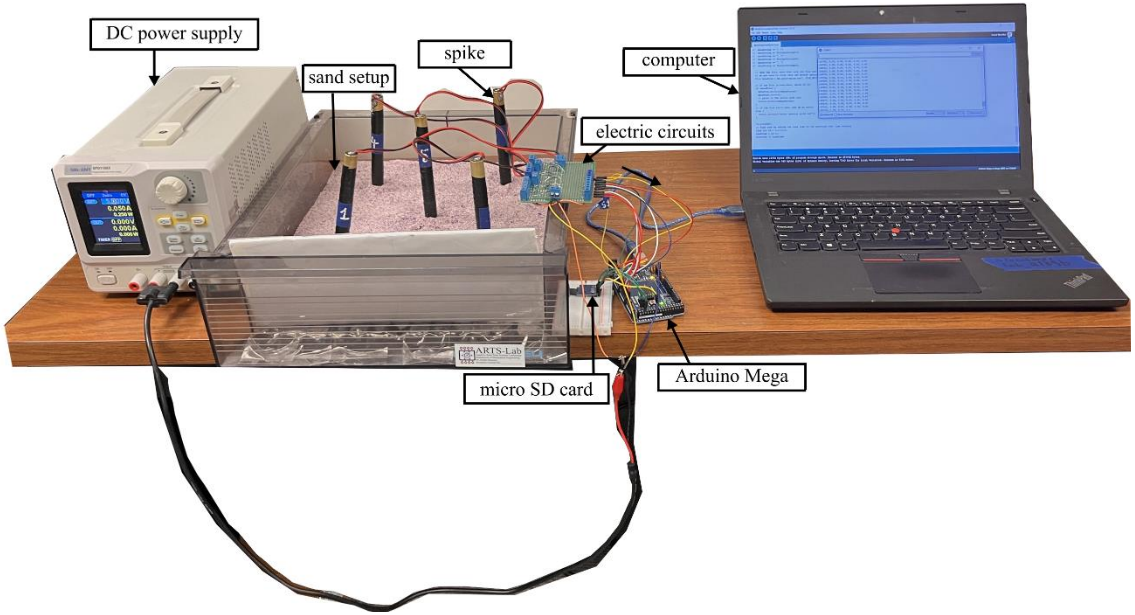
Sensor Package Levee Test

Levee test



Moisture Test Experimental Setup

- Sensor package for Levee test.
- Smart sensing nodes for soil moisture test.



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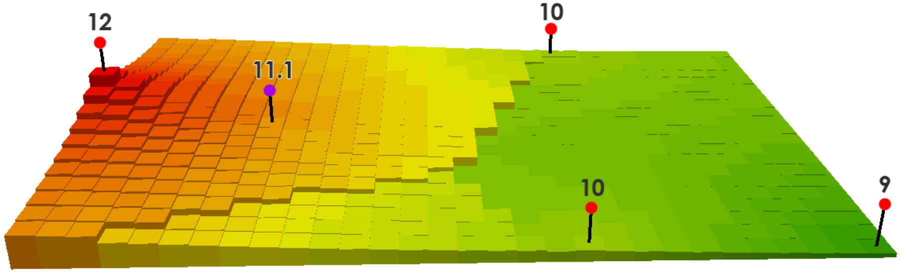
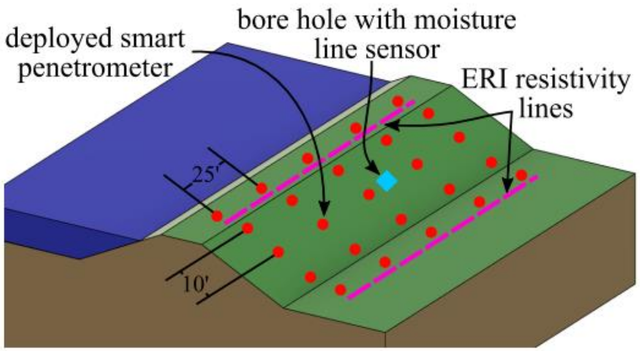
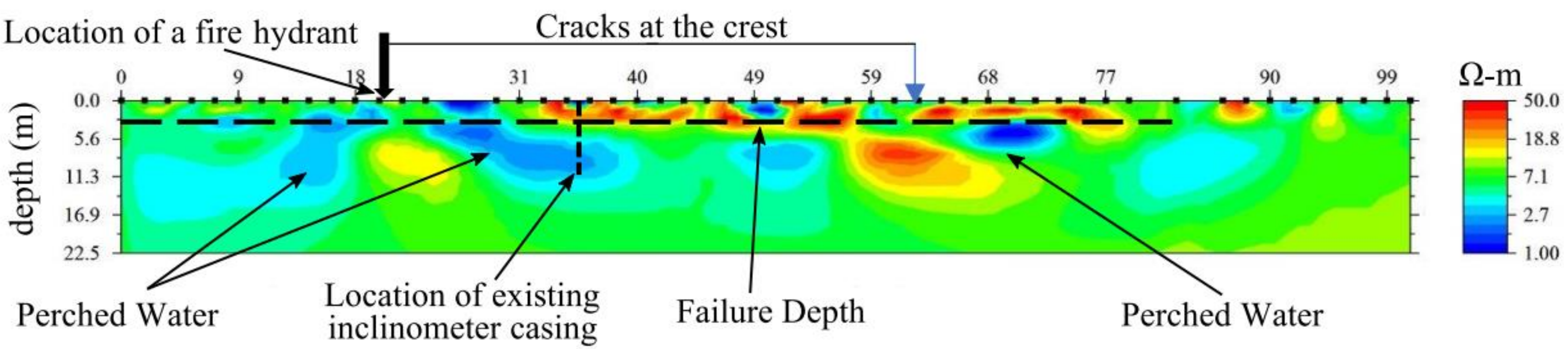
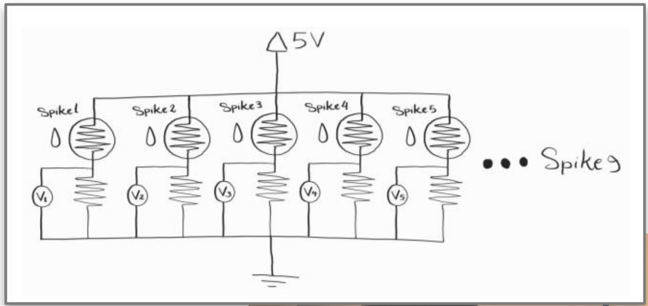
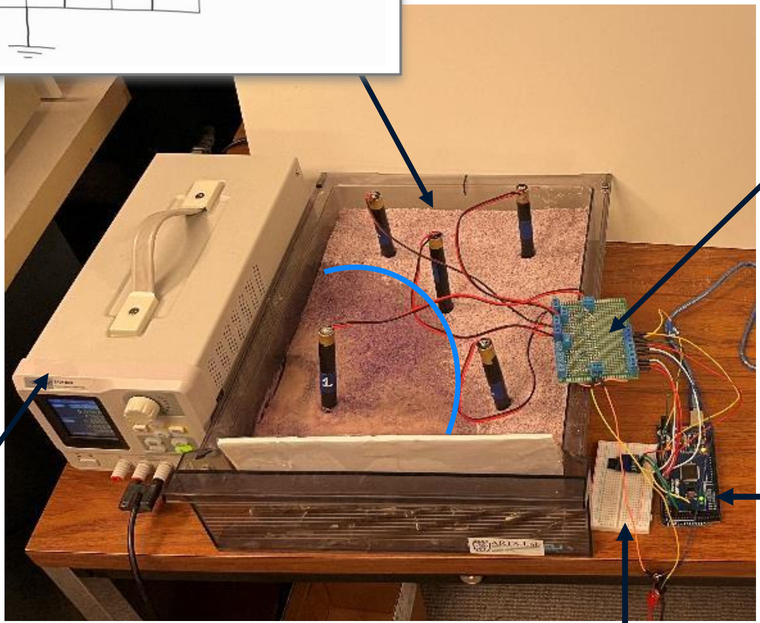






Electrical Circuit Explanation





Perfboard :

- Used for prototyping with electric circuits.

DC power supply :

- Powered the spikes at 5 V and 0.001 Amps.

Arduino Mega :

- Used this to convert the data to a digital number.

White breadboard :

- Connect the micro-SD card

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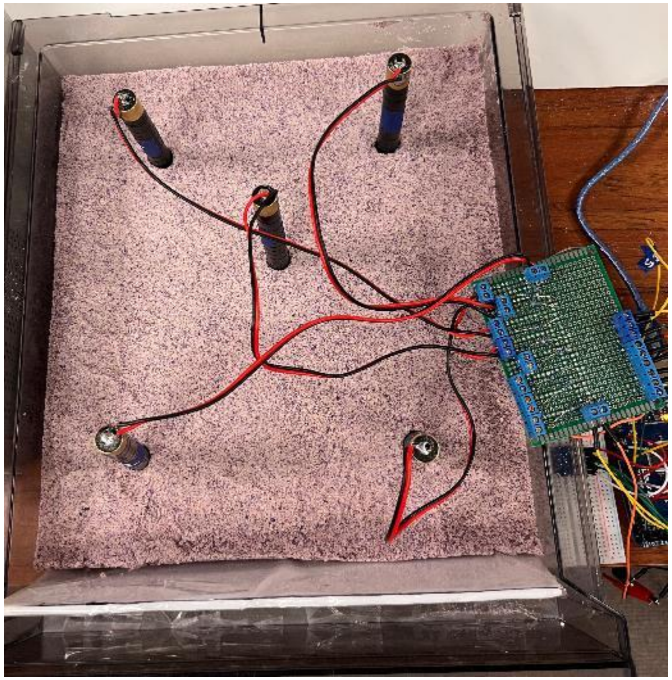
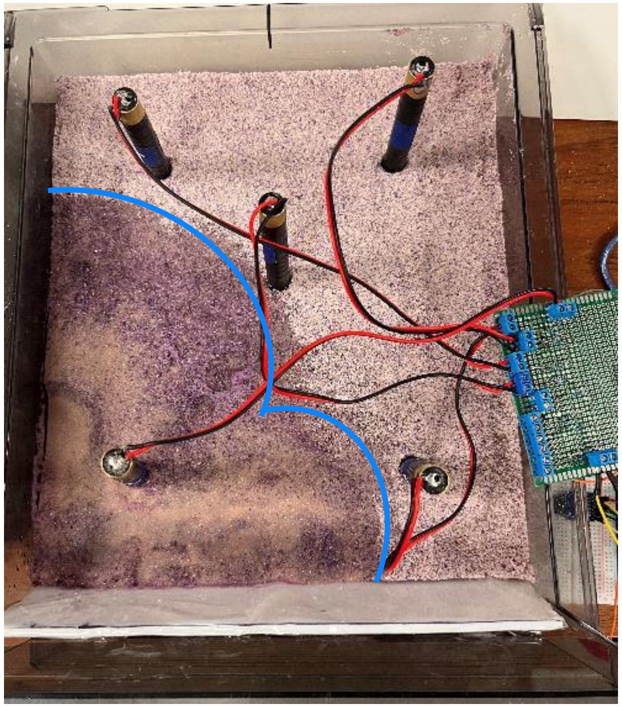
Moisture Test



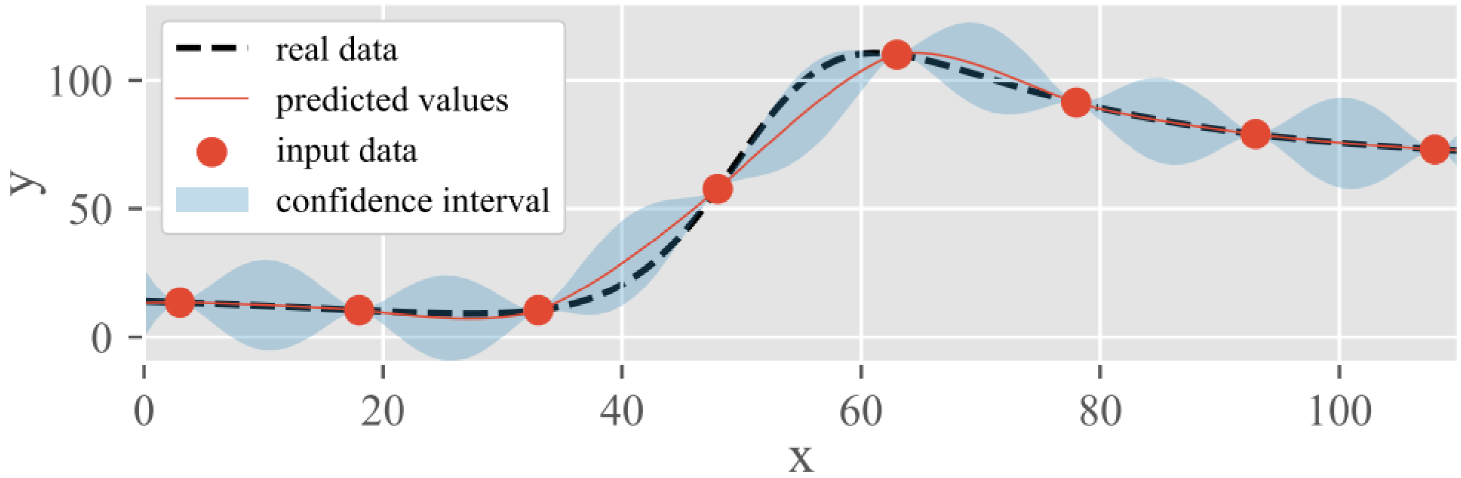
Dry sand



Moisture propagating through sand

Spatial Interpolation (Kriging)

- Selecting kriging as the spatial interpolation method used in this work.



- Other spatial interpolations could have been used, including:
  - Radial Bias Functions (RBF).
  - Spline
  - Trend (polynomial fitting a least-square regression fit)
  - Inverse Distance Weighted (IDW).

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Kriging

- **Kriging** is a spatial interpolation method with a few key types or models.

- **Simple kriging** assumes the model : $Z(x) = \mu + \epsilon(x)$
  - where Z is the kriging predicted value at x
  - where μ is a known constant
  - where ϵ is error (small scale variation) at x
  - simple and not really used in practice

- **Ordinary kriging** assumes the model: $Z(x) = \mu + \epsilon(x)$
  - where μ is an unknown constant
  - assumption of a constant mean is unreasonable for this case

- **Universal kriging** assumes the model: $Z(x) = \mu(x) + \epsilon(x)$
  - where $\mu(x)$ is a deterministic function.
  - also called kriging with external drift or regression kriging

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Universal Kriging

- **Universal kriging (UK)** is used in cases where the prediction mean $\mu(x)$ varies smoothly.
- A spatially continuous process Z at a location x represented as:

$$z(x) = \mu(x) + \epsilon(x)$$

- In matrix notation, the estimated value $\hat{z}(x_0)$ can be solved for as:

$$\hat{z}(x_0) = q_0^T \cdot \hat{\beta} + \lambda_0^T \cdot e$$

where

- q_0 is a vector of the predictors at x_0.
- $\hat{\beta}$ is a vector that contains the estimated drift term coefficients.
- λ_0 is a vector of n kriging weights determined by the covariance function.
- e is a vector that contains all the regression residuals (solved iteratively).

Universal Kriging

- $\hat{\beta}$, can be solved for by generalized least squares:

$$\hat{\beta} = (q^T \cdot C^{-1} \cdot q)^{-1} \cdot q^T \cdot C^{-1} \cdot z$$

where

- **z** is the sampled observations
- q is the matrix of the predictors at all observed locations.
- C is the covariance matrix of residuals.

$$C = \begin{bmatrix} C(x_1, x_2) & \cdots & C(x_1, x_n) \\ \vdots & \ddots & \vdots \\ C(x_n, x_1) & \cdots & C(x_n, x_n) \end{bmatrix}$$

Universal Kriging

- The power variogram model, $s \cdot d^{\alpha} + n$, forms the piecewise semivariance function $\gamma(d)$:

$$\gamma(d) = \begin{cases} 0 & d = 0 \\ s \cdot d^{\alpha} + n & 0 \leq d \end{cases}$$

where

- *s* is a scaling factor
- *d* is the distance between point covariance pairs $C(x_i, x_j)$
- *α* is the exponent (between 1 and 1.99)
- *n* is the nugget term

when $\gamma(d) = n - C(x_i, x_j)$. Given:

$$\mathbf{e} = \mathbf{z} - \mathbf{q} \cdot \widehat{\boldsymbol{\beta}}$$

$\hat{z}(x_0)$ can be iteratively solved for.

Universal Kriging

- After solving for the residuals, the predicted value can be obtained:

$$\hat{z}(x_0) = q_0^T \cdot \hat{\beta} + \lambda_0^T \cdot \left(z - q \cdot \hat{\beta}\right)$$

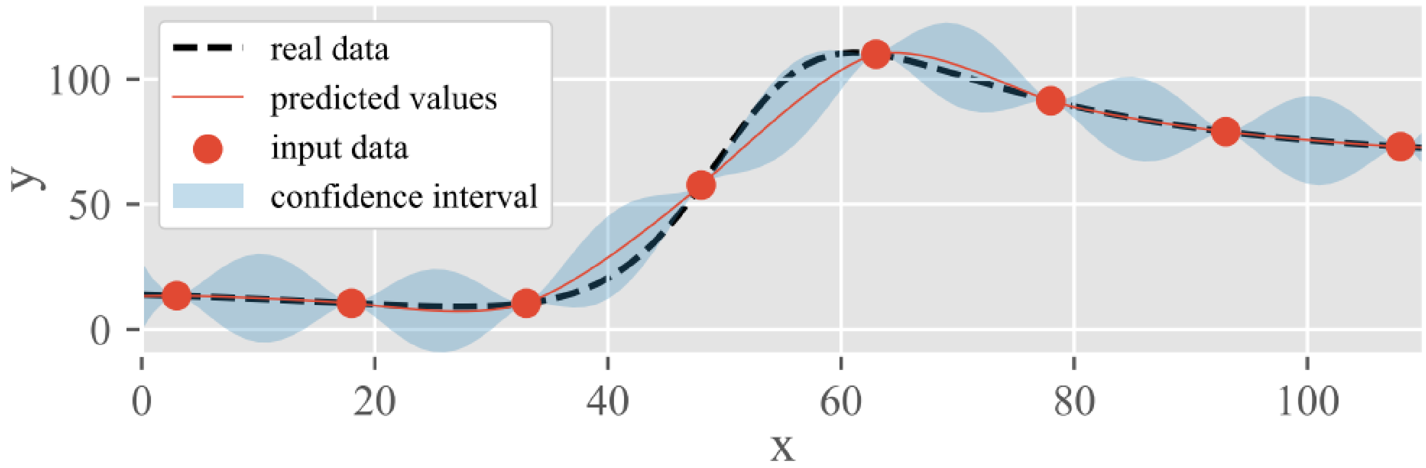
- As can the variance of the predicted value:

$$\sigma^2(x_0) = n - c_0^T \cdot C^{-1} \cdot c_0 + (q_0 - q^T \cdot C^{-1} \cdot c_0)^T . (q^T \cdot C^{-1} \cdot q)^{-1} \cdot (q_o - q^T \cdot C^{-1} \cdot c_o)$$

- A more compact way of expressing universal kriging (UK) is:

$$[\hat{z}(x_0), \sigma^2(x_0)] = UK((x_0)|D = \{(x, z)\})$$

Universal Kriging

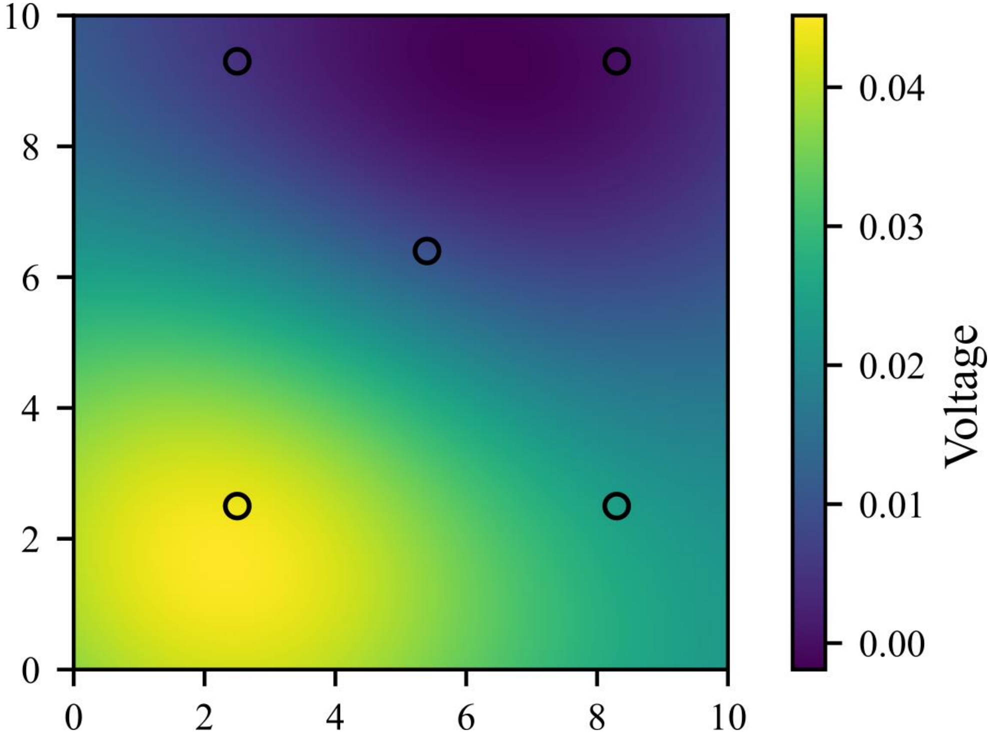


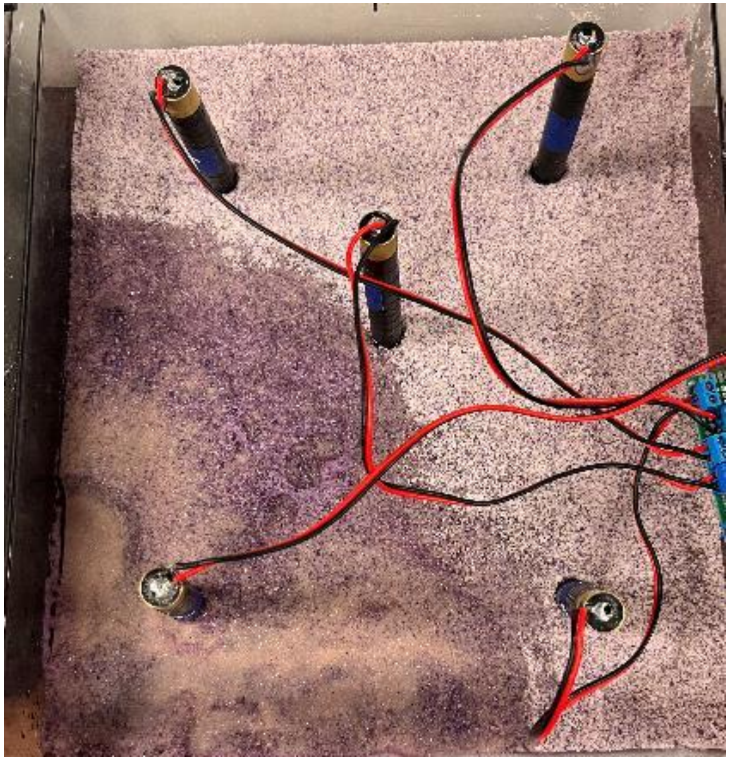
Key attributes of universal kriging:

- At each site, solves for the mean and variance.
- The solutions are precise (the prediction equals the training data at training locations).
- A variogram model is required; in this case, a power model is utilized.
- A drift term equation is required, and liner regional drift is employed here.

Spatial Kriging

- Spatial kriging for single timestamp.





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Data Processing

Data processing :

- Experimental data is in bits.
- Time is in millisecond.
- Convert it into seconds.
- 10-Bit to voltage conversion used equation is given below.

- $y = \frac{5x}{1024}$

	ID	Nom	xcord	ycord	zcord
0	1	spike_1	2.5	2.5	1.69
1	2	spike_2	8.3	2.5	1.69
2	3	spike_3	8.3	9.3	1.69
3	4	spike_4	2.5	9.3	1.69
4	5	spike_5	5.4	6.4	1.69

Processed data (coordinate)

	time(ms)	spike_1(bit)	spike_2(bit)	spike_3(bit)	spike_4(bit)	spike_5(bit)	time(s)	spike_1(v)	spike_2(v)	spike_3(v)	spike_4(v)	spike_5(v)
0	0	9.0	5.0	0.0	1.0	2.0	0.000	0.043988	0.024438	0.0	0.004888	0.009775
1	1070	9.0	5.0	0.0	1.0	2.0	1.070	0.043988	0.024438	0.0	0.004888	0.009775
2	2096	8.0	5.0	0.0	1.0	2.0	2.096	0.039101	0.024438	0.0	0.004888	0.009775
3	3123	8.0	5.0	0.0	1.0	2.0	3.123	0.039101	0.024438	0.0	0.004888	0.009775
4	4149	8.0	5.0	0.0	1.0	2.0	4.149	0.039101	0.024438	0.0	0.004888	0.009775

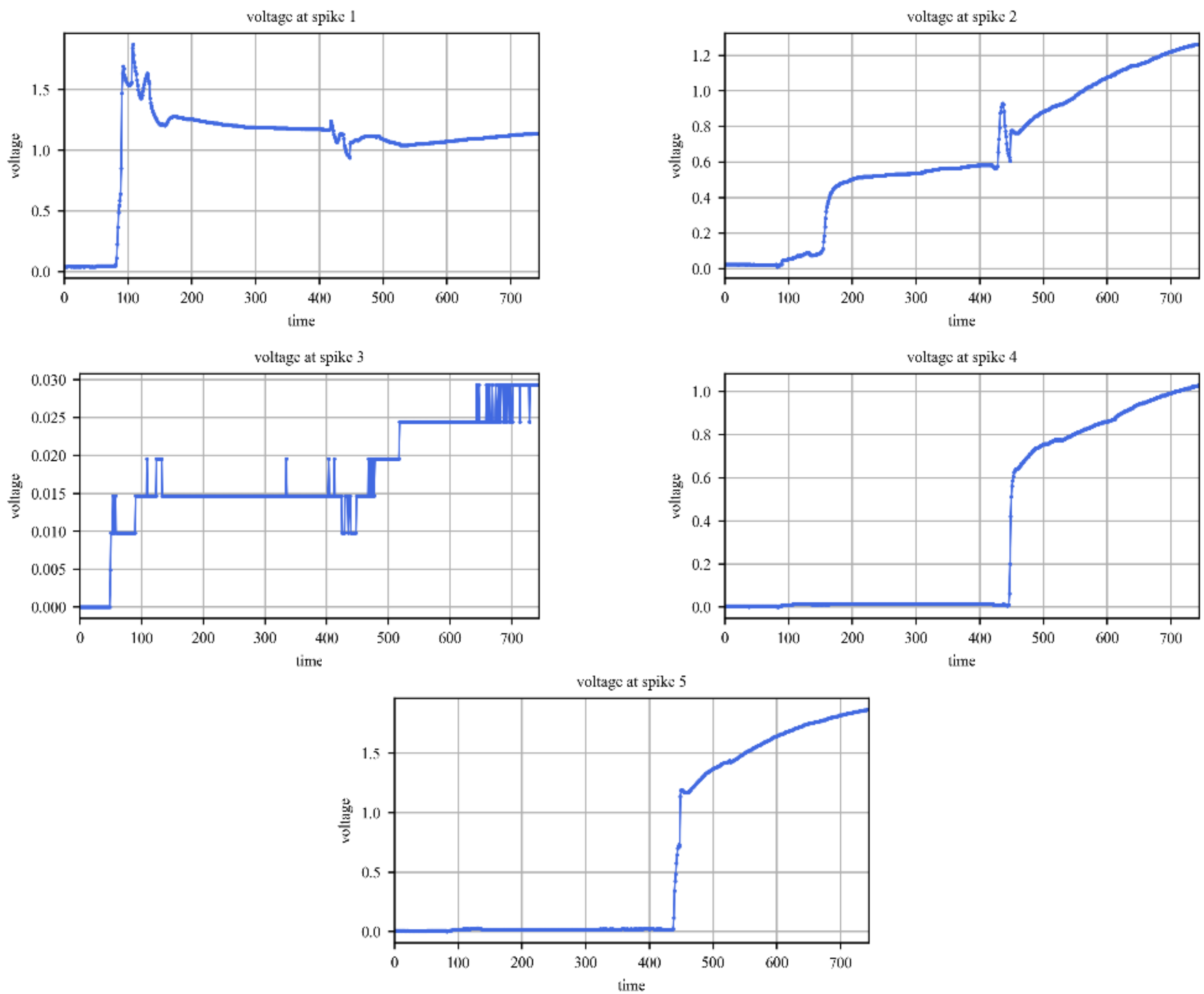
Processed data (voltage)

Approaches:

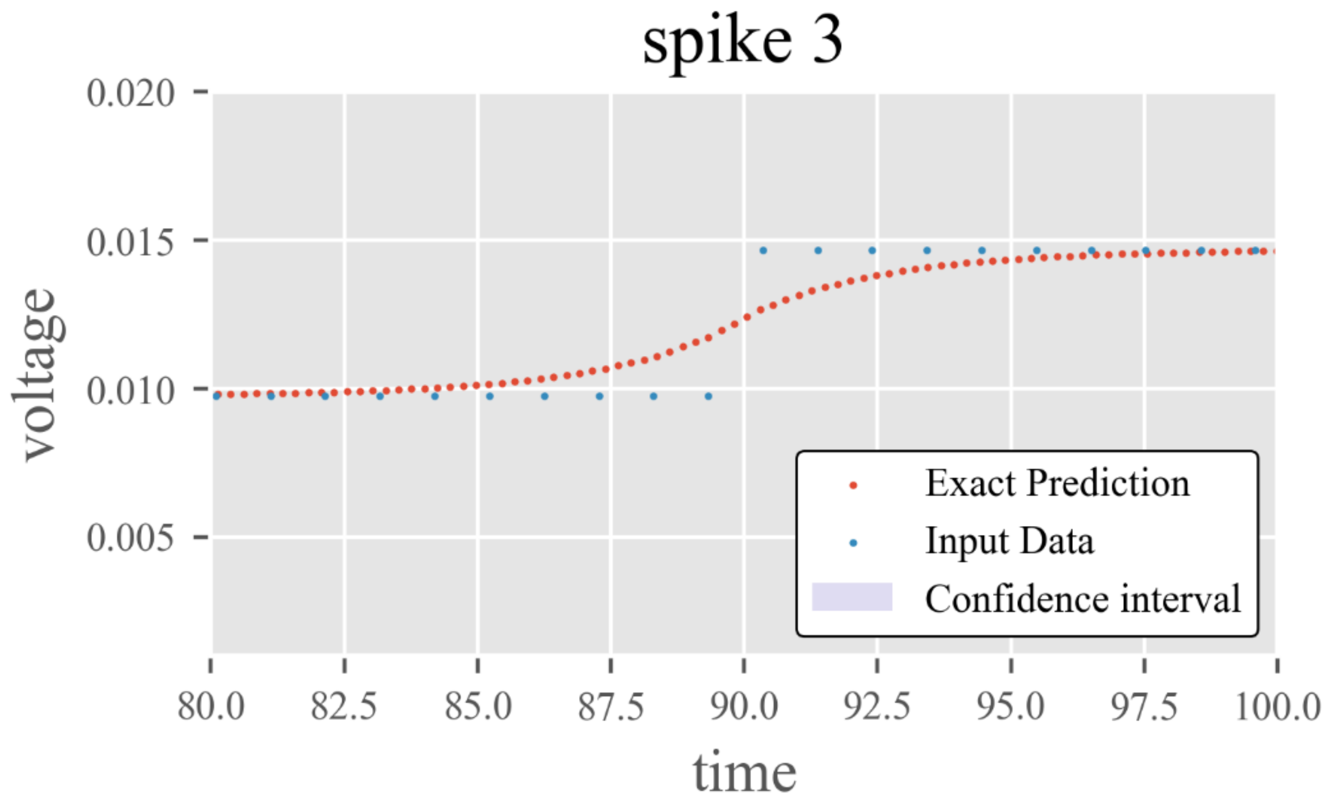
- Temporal kriging for each spike.
- Spatial kriging for one timestamp.
- Data: Need complete mesh grid data.

Low Resolution Time Series Data

Original data from spikes



Temporal Kriging



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Conclusion

- Developed an open-source sensing platform for geotechnical monitoring.
- Demonstrated the sensing platform in lab-scale testing.
- Demonstrated soil conductivity mapping using a network of sensors.
- Kriging model used to infer soil conductivity between sensors.

Open-Source Hardware Designs

CC BY SA

https://github.com/ARTS-Laboratory/Smart-Penetrometers-with-Edge-Computing-and-Intelligent-Embedded-Systems

Thanks!

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