Structures, Sensing, and Computing

— the Pursuit of Digital Twins

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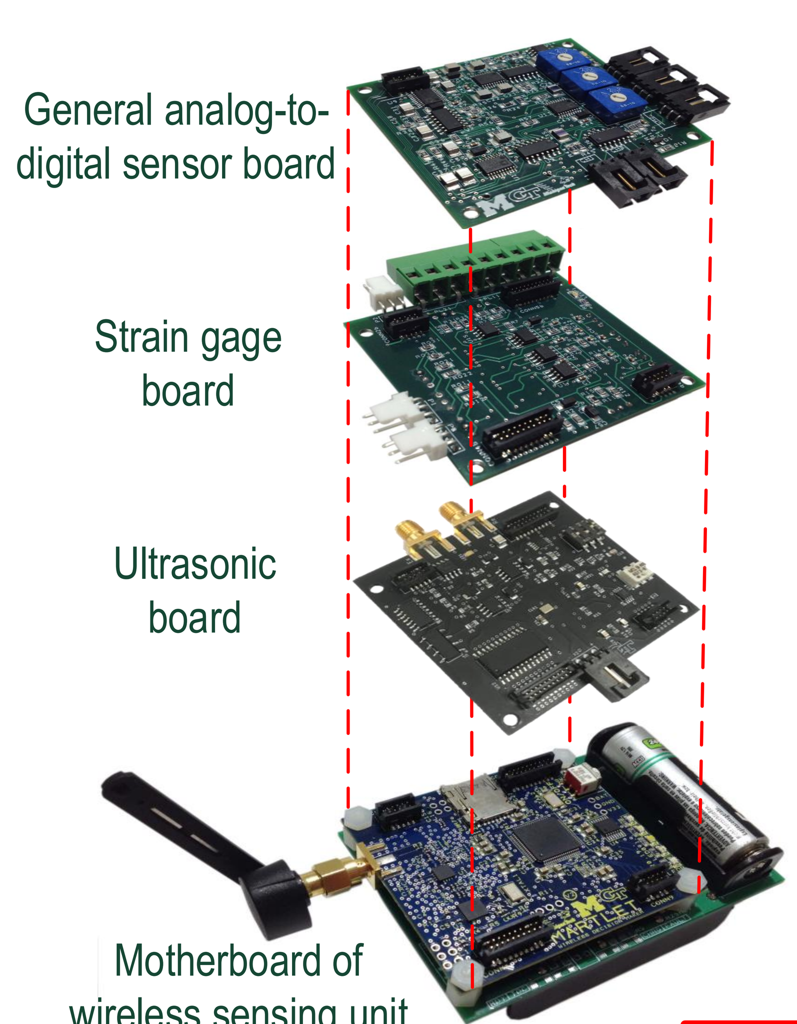
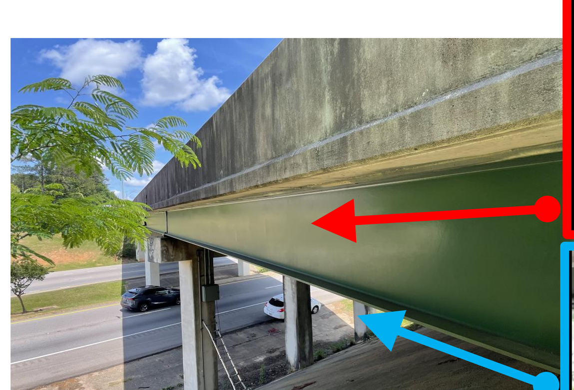
Background

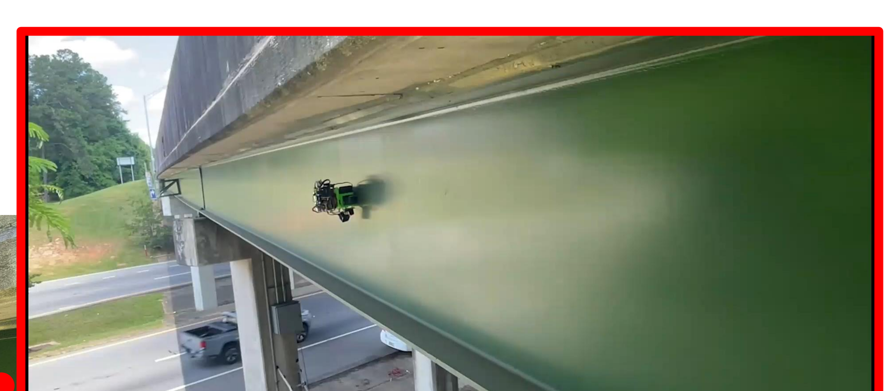
Despite decades of success in structural modeling and simulation, in-situ sensor measurements from an as-built structure often considerably differ from the behavior simulated by a computer model. This discrepancy between model and reality poses substantial difficulty for the development of digital twins, which refer to computer models that rely on real-time sensor measurements to constantly update themselves in order to mirror the changes in an as-built structure. To this end, recent advances in sensor technologies have enabled growingly large amount of field measurements from as-built structures, providing us highly detailed and quantified recording of in-situ structural behaviors.

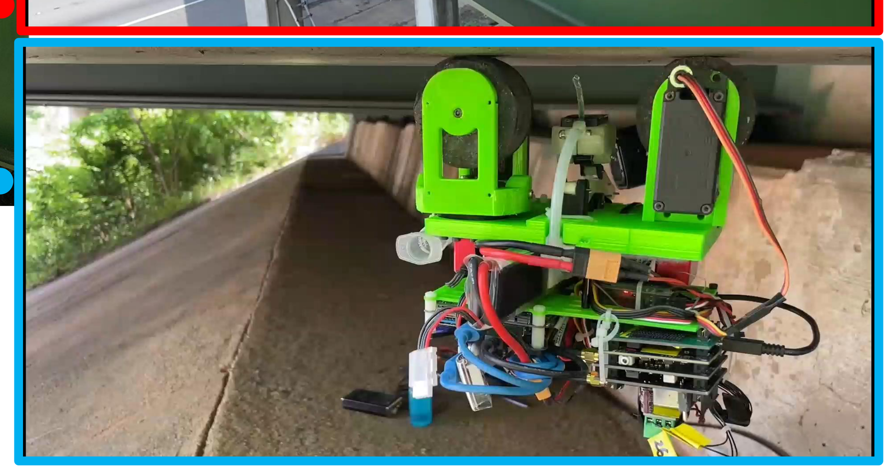
Wireless and Robotic Sensing



- Martlet wireless sensing device specialized for civil structures (Kane, *et al.* 2014)
- Daughter boards to interface with various sensors
- General analog-digital-conversion: on-the-fly programmable gain and cutoff frequency
- Mounted on a magnet-wheeled robot measuring steel thickness (with Prof. H. La's group of UNR)

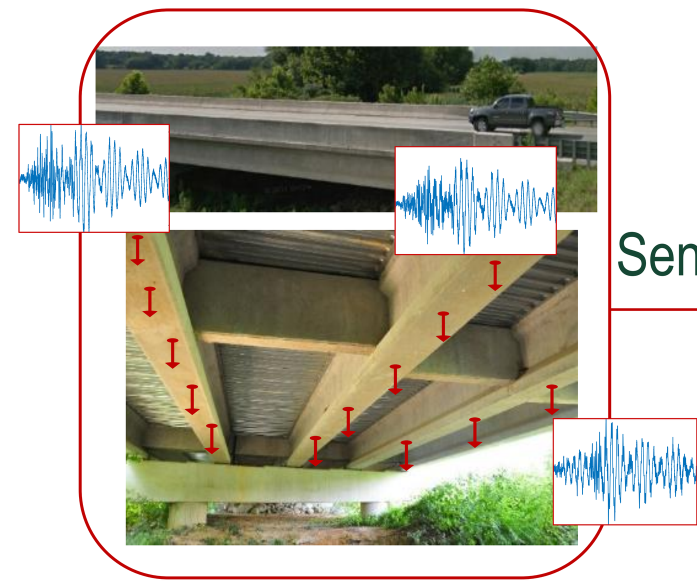




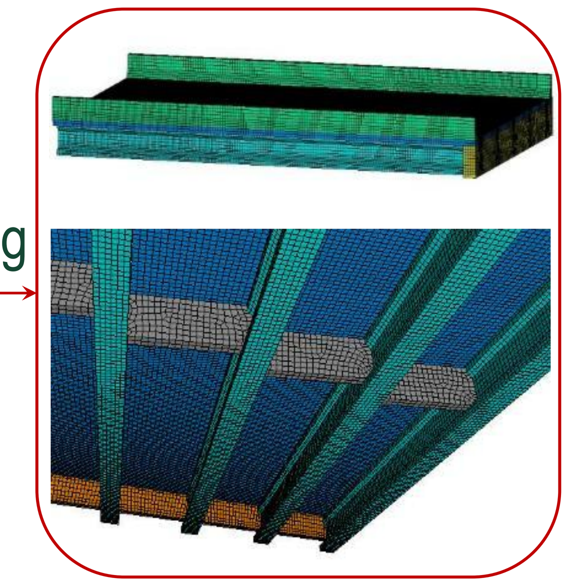


Otuski *et al.* (2023) https://doi.org/10.1061/JENMDT.EMENG-7000

From Data to Digital Twins



Sensing, Computing (Robotics)



Input (by Sensing) → System? (Digital Twin) → Output (by Sensing)

$$\mathbf{M}\ddot{\mathbf{q}}(t)+\mathbf{C}\dot{\mathbf{q}}(t)+\sum_{l=1}^{n_e}\bar{\mathbf{C}}^l\int_{-\infty}^{t}\mu^l e^{-\mu^l(t-\tau)}\,\dot{\mathbf{q}}(\tau)d\tau+\mathbf{K}\mathbf{q}(t)=\mathbf{p}(t)$$

Taking structural dynamics for example, how do we improve the digital twin so that it can accurately characterize as-built behaviors?

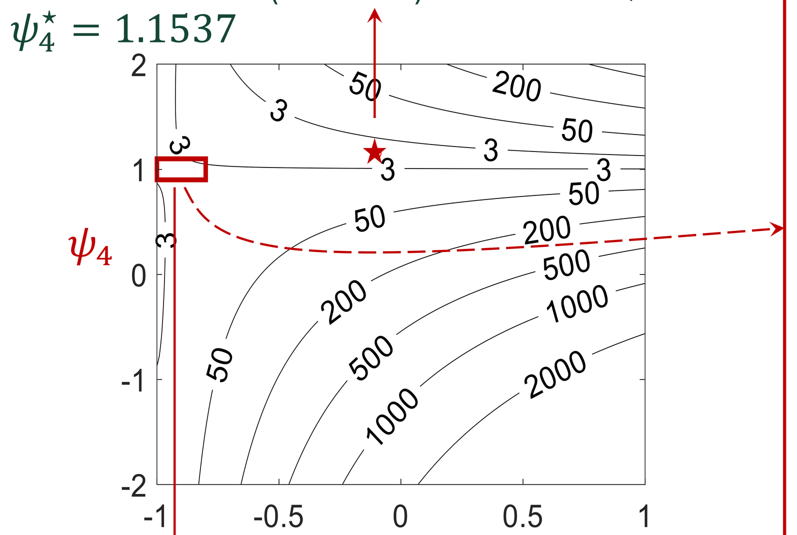
- Inverse problem of finding "optimal" parameter values so that the digital twin behaves more closely to field measurements;
- Formulated as numerical optimization problems – minimize the difference between physical measurements and model prediction;
- Such optimization problems are often nonconvex, making gradient search unable to guarantee global optimality; See Li *et al.* (2018) http://doi.org/10.1002/stc.2263, where the optimization variables are α and (unknown stiffness change) and ψ_4 (unknown mode entry)

$$\underset{\alpha,\psi_4}{\text{minimize}}\quad f(\alpha,\psi_4)=75.60+140.82\alpha+231.65\psi_4+65.86\alpha^2+461.18\theta\psi_4+177.46\psi_4^2+376.02\alpha\psi_4^2+229.53\alpha^2\psi_4+200.00\alpha^2\psi_4^2$$

$$\text{subject to}\quad -1\le\alpha\le 1\quad -2\le\psi_4\le 2$$

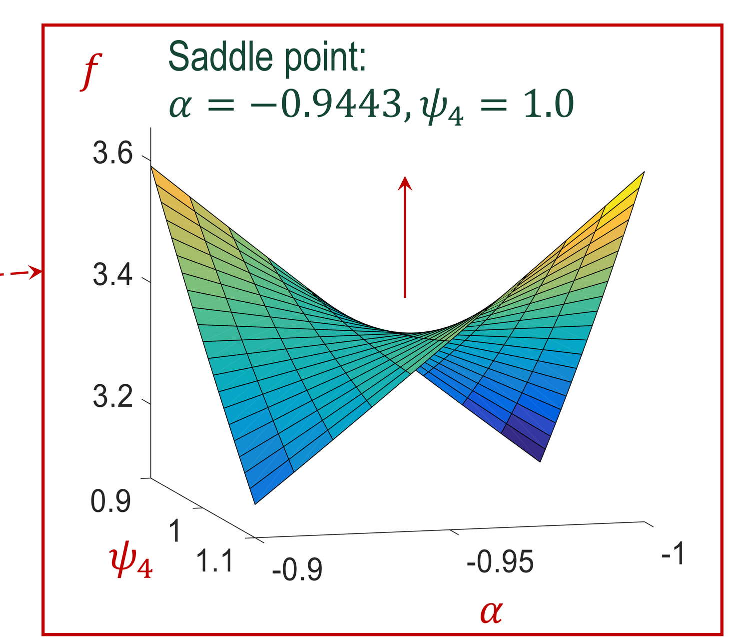
$f(\alpha,\psi_4)$ **Contour Plot**

Global minimum (ideal sol.): $\alpha^\star=-0.1$, $\psi_4^\star=1.1537$



Saddle point: $\alpha=-0.9443, \psi_4=1.0$

$f(\alpha,\psi_4)$ **Around Saddle Point: 3D Plot**



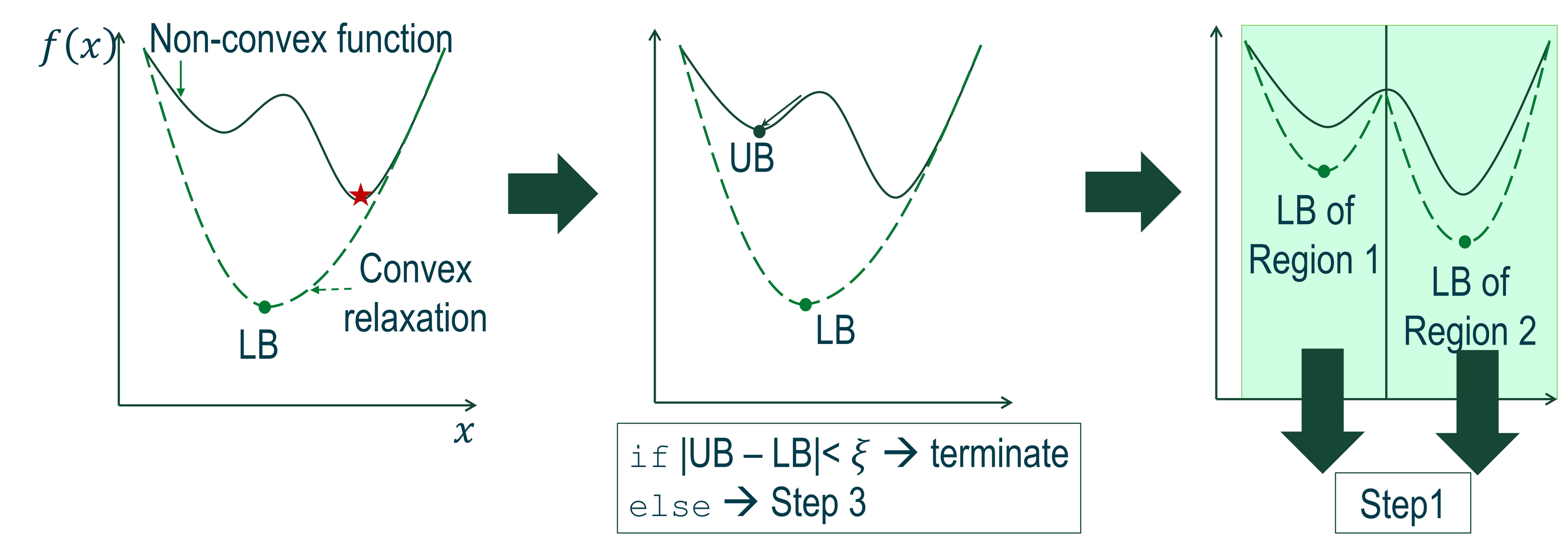
Branch and Bound (B&B)

- Branch-and-bound (B&B) is a specialized algorithm that can guarantee global optimality of non-convex optimization problems;
- The algorithm is validated for a simple 18-story model in Otsuki *et al.* (2021) https://doi.org/10.1007/s13349-020-00468-3.

Step1 (bounding): Solve a relaxed & convex problem
→ LB of the global optimum

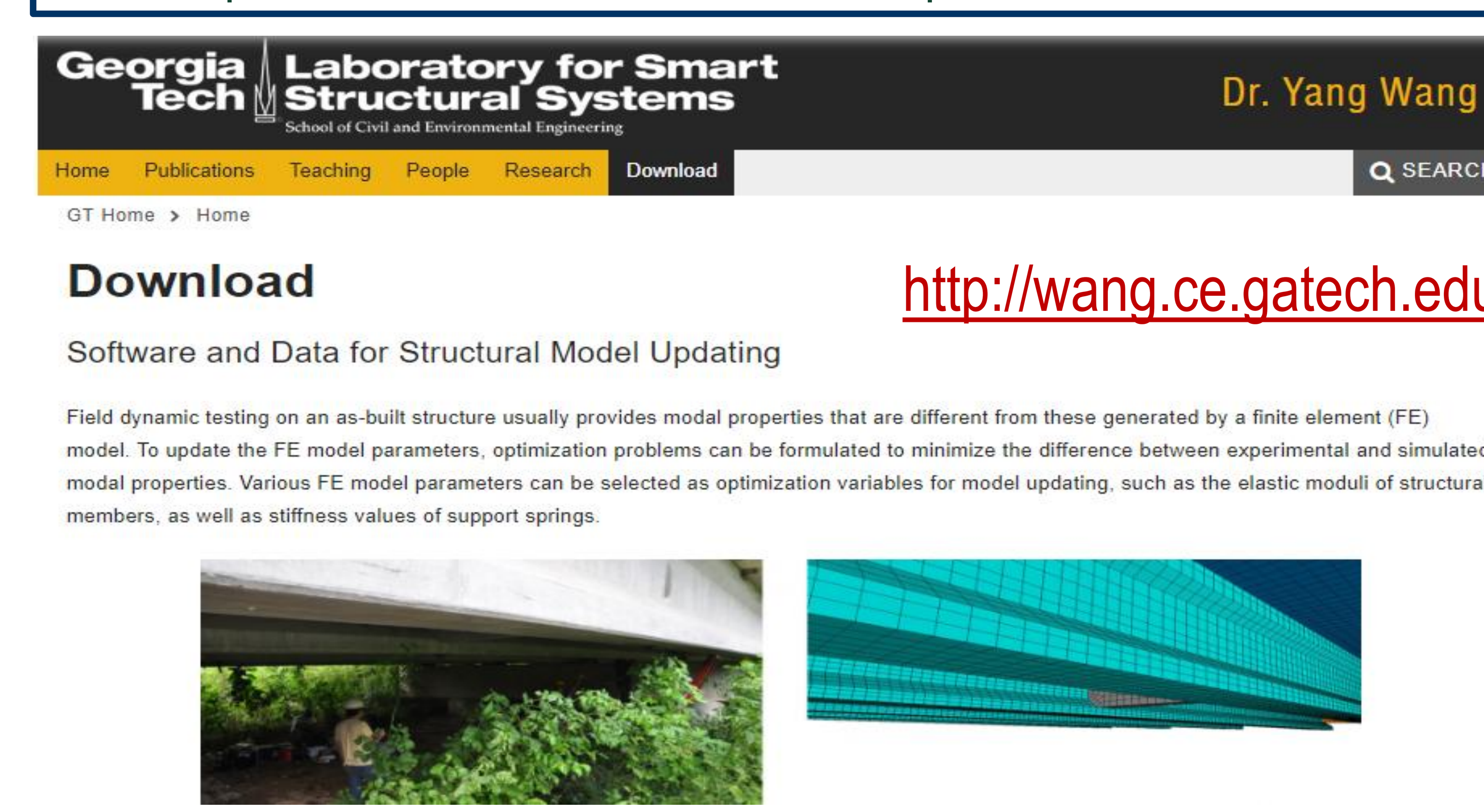
Step 2: Local gradient search obtains a feasible solution of the original problem
→ UB of the global optimum

Step 3 (branching): Subdivide the region



SMU Open-Source Package

- SMU is an Open-Source MATLAB Package on GitHub for Structural Model Updating;
- For better chance of achieving global optimality, SMU supports search from randomized starting points, and allows flexibility using various formulations as well as various optimization toolboxes;
- Efficient gradient search using analytically derived Jacobians; examples with thousands of DOFs are provided.



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Software and Data for Structural Model Updating

Field dynamic testing on an as-built structure usually provides modal properties that are different from these generated by a finite element (FE) model. To update the FE model parameters, optimization problems can be formulated to minimize the difference between experimental and simulated modal properties. Various FE model parameters can be selected as optimization variables for model updating, such as the elastic moduli of structural members, as well as stiffness values of support springs.

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