CAREER: Embracing Complexity: A Fractal Calculus Approach to the Modeling and Optimization of Medical Cyber-Physical Systems

Quantifying Fractal Behavior in Biological Systems: Novel Mathematics and Algorithms for Understanding the Brain

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- 1453860
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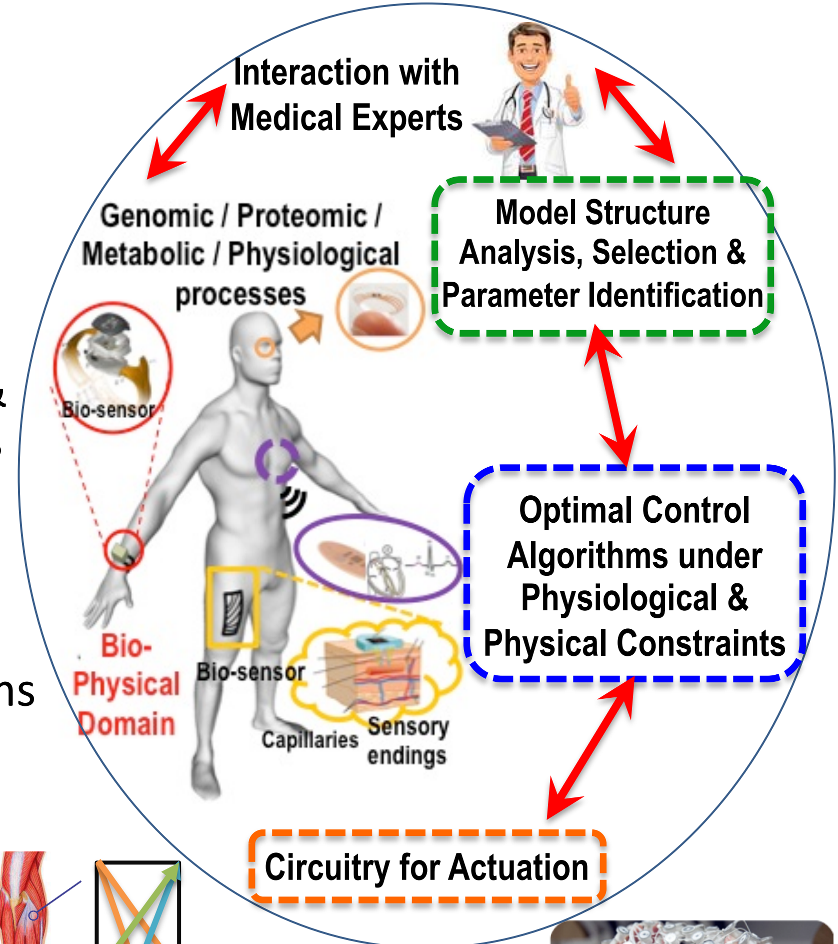
Description

Challenges:

- Physiology exhibits ***non-Gaussian***, ***multi-fractal*** and ***non-stationary*** characteristics
- Modeling ***inter-patient asymmetric variability*** & ***interdependence*** among physiological processes
- Accurate ***yet compact*** models of physiology

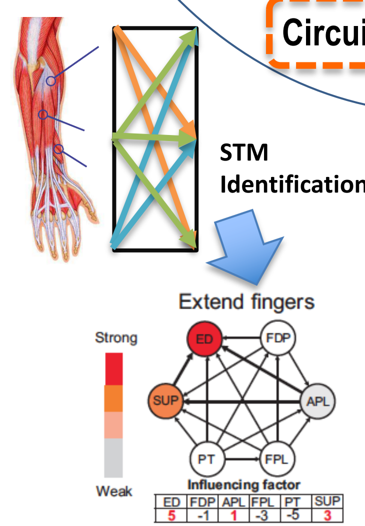
Approach and Scientific Impact:

- **Compact *accurate*** mathematical models
- Fast and accurate **model identification** algorithms
- **Fractal control** algorithms

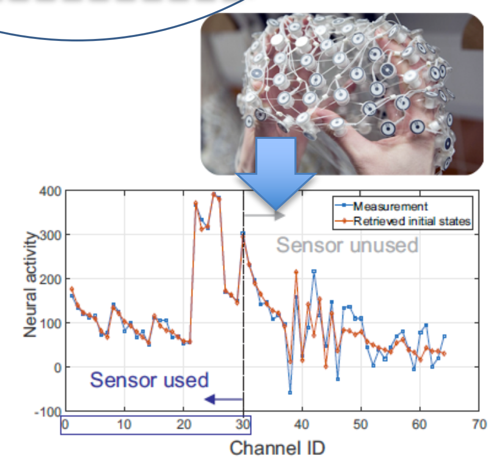


Spatio-Temporal Fractal (STM) modeling of physiological processes:

- Proposed a ***maximum causal non-extensive entropy principle*** by exploiting micro-dynamics (increments) of the processes to construct STF
- Robust data-driven algorithm to infer *fractal directed interdependence* of physiological processes described by STF
- *Guaranteed optimality* to achieve *full observability* of the physiological system described by STF with *minimal sensing efforts*

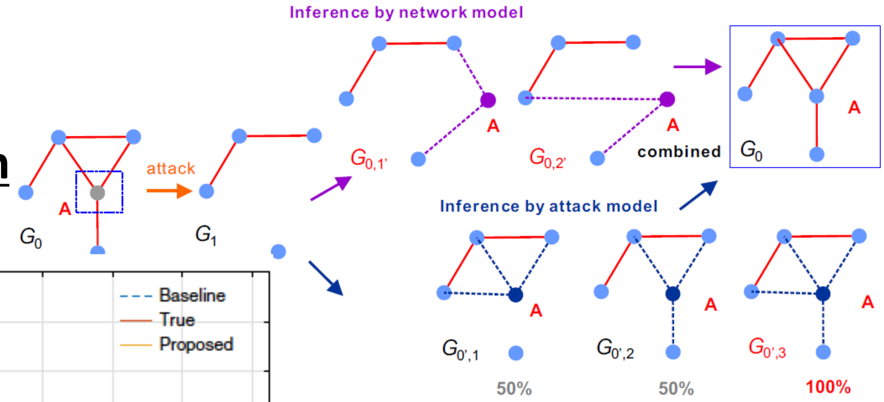


Fractal directed interdependence

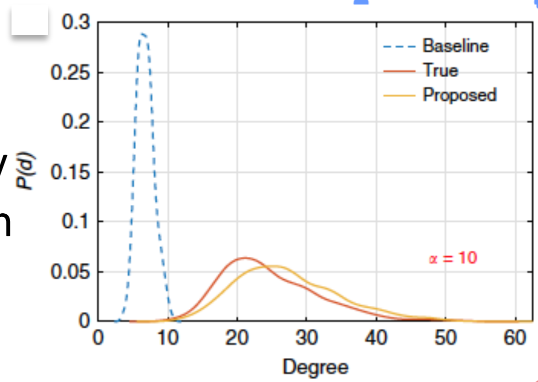


Minimal sensor placement by STF Identification

Findings

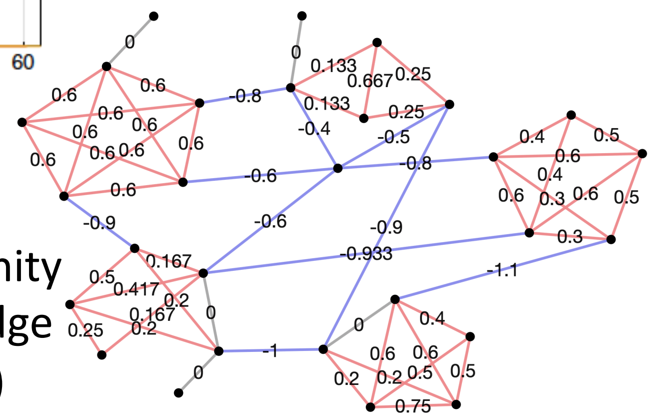


Finding 1: Mathematical & Algorithmic Approach for Reconstructing Complex Interdependency in CPS under Malicious Interventions



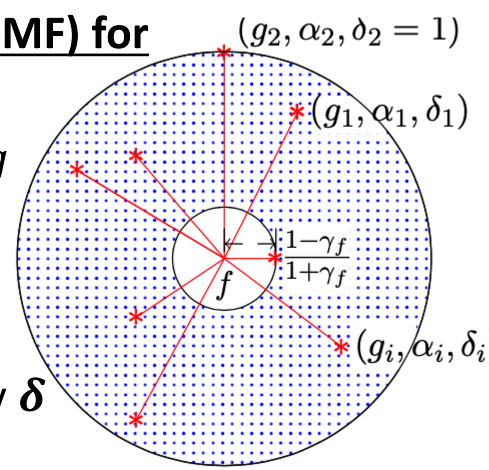
- Causal inference tool capable to decipher complex interdependency of a composable CPS with unknown component dynamics and unknown attacks

Finding 2: Curvature-based Approach to Decomposing and Mining Cyber-Physical Systems Interdependency



- Ollivier-Ricci curvature can reveal the hierarchical & community structure of a CPS interdependency without a priori knowledge on the number and size of communities (in polynomial time)

Finding 3: The Mathematics of Approximate Submodular Functions (ASMF) for Nonsubmodular Optimization in CPS



- Nonsubmodular function f is $\boldsymbol{\delta}$ away from a submodular surrogate g
- Lemma: $\boldsymbol{\delta}$ cannot be arbitrarily low for any function f being limited by $\delta \geq \frac{1-\gamma_f}{1+\gamma_f}$, where γ_f is submodularity ratio
- *Theorem*: $\boldsymbol{\delta}$-ASMF has constant performance guarantee penalized by $\boldsymbol{\delta}$
  - Applications: Bayesian D-optimality, minimum eigenvalue, Bayesian E-optimality