Whole Heart Modeling – Spatiotemporal Dynamics of Electrical Wave Conduction and Propagation

Hui Yang

杨 徽

Associate Professor
Complex Systems Monitoring, Modeling and Control Lab
The Pennsylvania State University
University Park, PA 16802

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   - Fractal surface simulation
   - Isometric graphing for surface characterization
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Introduction

- **Computer Simulation**
  - Describe complex phenomena
  - Predict system behaviors
  - Optimize control action
  - Improve system performance

- **Whole-heart Modeling and Simulation**
  - Overcome many practical and ethical limitations in real-world biomedical experiments
  - Offer greater flexibility to test their hypothesis and develop new hypotheses

- **Circulation Research** - “Biophysics-based cardiac modeling has the potential to dramatically change the 21st century cardiovascular research and the field of cardiology.”
Challenges

- Spatiotemporal dynamics
  - **Reaction process**: dynamic variables are interacting with each other
  - **Diffusion process**: dynamic variables spread out in space

- High dimensionality
  - Approximately 2 billion heart muscle cells

- Complex geometry
  - Euclidean vs. Fractal
Fractal

- Man made structures
  - **Euclidean geometry** ( > 2000 yrs ) : Triangles, circles, squares, rectangles, trapezoids, pentagons, hexagons, octagons, cylinders

- Natural objects
  - **Fractal geometry** (100 yrs)
  - Rough edges, non-uniform shapes
  - Self-similarity: human heart, flowers, trees, mountains, ...
Literature - Fractal characterization and modeling

- **Mandelbrot** - "A rough or fragmented geometric shape that can be subdivided in parts, each of which is (at least approximately) a reduced/size copy of the whole"

- **Characterization of fractal dimension**
  - Monofractal - homogeneous self-similarity across scales, characterized by a single fractal dimension.
  - Multifractal - non-homogeneous self-similarity across scales, singularity spectrum to characterize scaling properties

- **Modeling the fractal object or process**
  - Iterative or recursive function systems
  - Rough surfaces - shear displacement algorithm, diamond-square algorithm
  - Heart rate time series - random cascade model

- **Gaps**
  - Little has been done to develop simulation model of spatiotemporal dynamics on fractal geometry
  - Modeling differences between fractal and Euclidean geometry have not been fully investigated before

- **Need to fill the gaps**
Literature - Dimensionality reduction

- High-dimensional data are difficult to visualize and interpret
- Dimensionality reduction approaches
  - Principal component analysis (PCA)
  - Multidimensional scaling (MDS)
  - Self-organizing map (SOM)
  - Isometric feature mapping (ISOMAP)
- Most of previous studies focused on the reduction of high-dimensional data and then the extraction of useful information from the low-dimensional data.
- **Gaps** - Few previous approaches considered the construction of simulation models in the low-dimensional space.
- **Need to fill the gaps**
Fractal surface simulation

Random midpoint displacement algorithm

Initialization:
// Start with an square with pixel values at four corners drawn from a Gaussian distribution \( N(\mu, \sigma^2) \), where \( \mu = 0 \) and \( \sigma = 1 \).

While \( i \leq \text{desired iterations} \)

Center point:
// The center is the average of its four neighbors plus a random value \( \delta_i \) generated from a Gaussian distribution \( N(\mu, \sigma_i^2) \), where \( \sigma_i^2 = \frac{1}{2^{2H(i+1)}} \sigma^2 \).

Edge point:
// The edge point is the average of its neighbors plus a random value \( \delta_i \) generated from a Gaussian distribution \( N(\mu, \sigma_i^2) \), where \( \sigma_i^2 = \frac{1}{2^{2H(i+1)}} \sigma^2 \).

\( i = i + 1 \)

End

Calculate the fractal dimension:
// The simulated fractal surface is monofractal and the fractal dimension \( D_F \) is determined as \( D_F = 3 - H \).
Isometric graphing for surface characterization

- Isometric graphing algorithm*
  - Construct neighborhood graph
  - Compute shortest paths – geodesic distances: e.g., Dijkstra’s algorithm
  - Construct low dimensional embedding: classical MDS
  - Euclidean distance $\rightarrow$ Geodesic distance

Reaction-Diffusion Modeling

- **FitzHugh-Nagumo (FHN) model**

\[
\frac{\partial u}{\partial t} = c_1 u (1 - u)(u - a) - c_2 u v + \nabla^2 u \\
\frac{\partial v}{\partial t} = b(u - dv)
\]

where \( a = 0.13; b = 0.013; c_1 = 0.26; c_2 = 0.1; d = 1.0; u: \) membrane voltage; \( v: \) recovery variable.
R-D Model on the Heart

- **Healthy heart**
  - Near-periodic electrical impulse

- **Arrhythmia heart**
  - Atrial fibrillation
  - Rapid, disorganized and irregular electrical impulse
Spatiotemporal pattern recognition

- Spatiotemporal data
  - \( Y(s_i, t), t = 1, \ldots, T \)
  - \( s_i \) - spatial location, \( i = 1, \ldots, N \)

- Hyper-distance matrix: spatiotemporal dissimilarity

\[
D_T(l,m) = \left[ \sum_{i=1}^{N} (Y(s_i, t_l) - Y(s_i, t_m))^2 \right]^{1/2}
\]
Self-Organizing Network Embedding

- **Spring-Electrical Model**
  - Nodes — electrically charged particles
  - Edges — springs between nodes
  - The **repulsive force** exists between any pair of nodes

  \[
  f_R(l, m) = -\frac{1}{\|x_l - x_m\|^2} \times e^{D_T(l,m)}
  \]

  The **attractive force** exists only between two connected nodes

  \[
  f_A(l, m) = \|x_l - x_m\|^2 \times e^{-D_T(l,m)}, l \leftrightarrow m
  \]

  The combined force at a node \(l\): \(f(l, x)\)

  \[
  \sum_{l \neq m} -\frac{(x_l - x_m)}{\|x_l - x_m\|^3} \times e^{D_T(l,m)} + \sum_{l \leftrightarrow m} \|x_l - x_m\| \times (x_l - x_m) \times e^{-D_T(l,m)}
  \]

- **Minimal energy network**: \(x^* = \arg\min_x \sum_{l=1,...,T} f(l, x)^2\)
Low-dimensional Pattern

Regular Surface

Fractal Landscape

Healthy

Arrhythmia
GPGPU Acceleration

- Computer Setting
  - Intel dual core i3-2100 CPU @ 3.10GHz with 16G DDR3 memory, Nvidia Telsa C2075 graphic card with 6GB global memory, Window 7 (64 bit) operating system
  - GPU - NVidia CUDA platform and OpenGL - rendering loop iteration and GUI mechanism

- CPU-based simulation
  - The algorithm traverses through all cells in the 3D heart model to finish one iteration, and determine the status (timer value) of each cell. Then, OpenGL is called to render the whole heart according to the status of cells.

- GPU-based simulation
  - Instead of iterating through the heart, we issue every cell a thread, which will increase the timer of the thread, look up the neighbors, and calculate and store the states for the cell if applicable. We, then, launch 148516 threads to the GPU multicore processors and run these threads in parallel.
GPU vs. CPU

- GPU Case 1 - OpenGL/CUDA coop
- GPU Case 2 - fast data transferring within shared memory
- 728,321 cells in the whole-heart model,
- Improve the speed of computing by approximately 30-fold
GPU Simulation Demo
Summary

- **Challenges**
  - Complex geometry: Fractal nature of high-dimensional systems
  - Geometric preservation: Geodesic distances vs. Euclidean distances
  - Large-scale simulation of complex biological systems
  - Spatiotemporal dynamics of electrical conduction and propagation

- **Methodology** - spatiotemporal dynamics on fractal surfaces
  - Characterization and modeling of fractal geometry
  - Fractal-based simulation and modeling of spatiotemporal dynamics
  - Recognizing and quantifying spatiotemporal patterns.

- **Parallel computing - GPGPU**
  - GPU yields 30 times faster than CPU-based simulation models
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Hui Yang
Associate Professor
Complex Systems Monitoring Modeling and Control Laboratory
Harold and Inge Marcus Department of Industrial and Manufacturing Engineering
The Pennsylvania State University
Tel: (814) 865-7397
Fax: (814) 863-4745
Email: huy25@psu.edu
Web: http://www.personal.psu.edu/huy25/
Questions?