Inverse Design Process: New Methodology to Design Medical Devices with BIG DATA

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Purpose:
Reverse the traditional forward design process, to create a more efficient and effective pipeline for medical device design.

Background:
Millions of dollars are spent on medical devices each year to improve patient health. These devices came to fruition through a linear design process. To reach a final design many ideas are eliminated without complete consideration of the potential impact. The parameterized designs are structurally analyzed and stress/strain data are generated. This process is time consuming and significantly bounds the design space by not considering all possibilities.

Inverse Design Process:
Capitalize on computational speeds, simulation models and visualization environments to prepare specific output parameters for each design. These designs are visually displayed and presented to the user for inspection and refinement until an optimal design is selected.

Proof-of-Concept Device:
Cardiac leads experience many environmental factors that cause failure, including: anatomical geometric constraints, device shape, deformation, blood flow and tissue fibrosis. Tissue fibrosis is the encapsulation of the device by scar tissue and alters the environmental factors experienced by the cardiac lead over the lifespan of the device. The severity of tissue fibrosis is patient specific and increases the complexity of an extraction procedure. The most common complication is rupturing the wall of the heart and requires immediate open-heart surgery to repair the tear. Understanding and modeling the complex environment of the heart would improve the design of the cardiac leads and inform surgeons of patient specific complexities that impact selection of cardiac lead devices.

Computer Science:
This research asks the question of how to effectively build a system that utilizes high performance computing architecture to efficiently prepare and query simulation data for remote visualization and interaction. Using GPU compute nodes and rendering nodes, we plan to build a visualization engine that iteratively sifts through a dynamically indexed set of simulations. Based on user input, we can hope to quickly find which simulations most closely resemble the desired parameters without moving the data.

Future Work:
Develop the processes that automatically generate the FEA, CFD and Fibrosis models for new design instances with varying parameters. Currently, all design instances are generated manually. The NICE GPU nodes will be used to build a real-time remote visualization system which has an interactive connection to the Missabi GPU enabled compute nodes. These GPU nodes, coupled with the remote visualization, can allow real-time processing of the simulation data at scale from any machine. As users interactively explore the available datasets, analytics are gathered which queue more simulations to be run for further analysis.

References:


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Medical devices came to fruition through a linear design process. Each device is parameterized into basic geometric and material variables and the acceptable ranges for each value. These parameterized values are used to organize the design instances. The parameterized devices are structurally analyzed by finite element analysis (FEA), blood flow is modeled through computational fluid dynamics (CFD) using human specific anatomical models, and tissue fibrosis is simulated to understand the environment surrounding the each model. Each design space will include hundreds of design instances.

Parameterized Cardiac Lead in Right Atrium

Visuizations of Fluid Flow Simulations: A) Fluid visualization B) Interactive fluid flow in CAVE C) Particle visualization D) Anatomical Heart Model

Fluid Flow Simulations from Abaqus: A) Pressure B) Velocity, Resultant: t=0 seconds C) Velocity, Magnitude D) Velocity, Resultant: t=0.3 seconds

 MSI Contribution:
The Minnesota Supercomputing Institute (MSI) provides unique and vital resources necessary to store, process, and visualize the results of this research. In an ongoing project, data sets are generated through the use of the specialized software provided by MSI, specifically Mimics for anatomy segmentation and Abaqus for FEA / CFD simulation. MSI storage capabilities create a shared repository that is synchronized with collaborators at the University of Chicago. Models and simulations continue to be added to the repository. Running real-time particle advection using CUDA and high-end graphics cards for rendering, the GPU computer nodes and NICE GPU nodes are ideal for this application. In addition, the LCE-MSI Visualization Laboratory (LMV) will be used to interactively design medical devices in virtual reality.

Discussion:
This is an ongoing collaborative interdisciplinary work, which hopes to answer both medical engineering questions related to device design and large data visualization questions in computer science. For engineering science, the focus is largely on segmenting of heart anatomy, defining parameter sets and simulations of leads within the heart, and developing fluid flow and fibrosis models. This allows for the systematic generation of large amounts of data useful for design. For computer science, the focus is primarily on development of interactive visualization tools for both fluid flow and solid deformation simulation.

Conclusion:
A process and set of tools have been developed to interactively generate and explore coupled CFD and FEA simulations. This information helps understand how to parameterize the engineering problems of medical devices, for example cardiac pacemaker lead design. However, in order to enable the inverse design process described above, much work on how to index the simulations, and appropriate visualization techniques need to be developed. In addition, continuous data generation needs to be aggregated to refine the engineering problem and the design space.

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**MSI Software Resources**
- Anatomy Processing (Mimics, Sag3D, etc.)
- FEA Simulations (Abaqus, FEBio, etc.)

**MSI Based Shared Filesystem**
- Device Database
- Device Design ONE
- Device Design TWO
- Device Design THREE

**Collaborators Contributions**
- CFD Simulations (Abaqus)
- FEA Simulation Database
- Virtual Heart

**Inverse Design Process**
- Simulation (Automated Data Generation)
- Design Space (Results)
- Design Instance ONE
- Design Instance TWO
- Design Instance THREE
- Design Instance FOUR
- Design Instance FIVE

**Utilized MSI Resources**
- GPU
- GPU
- GPU
- GPU

**External Resources**
- VR Cave
- VR Power Wall
- NICE Nodes
- GPU
- GPU
- GPU

**Computational Science and Engineering**
The inverse design process starts with a computer-aided design (CAD) model of a device. Each device is parameterized into basic geometric and material variables and the acceptable ranges for each value. These parameterized values are used to organize the design instances. These parameterized devices are structurally analyzed through finite element analysis (FEA), blood flow is modeled through computational fluid dynamics (CFD) using human specific anatomical models, and tissue fibrosis is simulated to understand the environment surrounding the each model. Each design space will include hundreds of design instances.

**Computer Science**
The focus is primarily on development of interactive visualization tools for both fluid flow and solid deformation simulation.