Design of a Guidewire Simulation to Analyze Damage to Arterial Walls

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Abstract

Strokes are a major factor in the health of many Canadians, with treatment options being inaccessible and possibly dangerous to the patient. The team's client requires a method to quantify the damage caused to arterial walls due to the navigation of a guidewire during endovascular thrombectomy (EVT). The guidewire is oriented using magnetic fields and is mechanically 'fed' forward into the vessel. With this simulation, the client will be able to to objectively compare different navigation methods and guidewire configurations to minimize damage to vessel walls.

The team decided to approach this problem using finite element modeling (FEM), ultimately choosing to prepare their own custom solution using MATLAB, a commercial programming and numeric computing platform. MATLAB was selected over the other options due to the team's familiarity with it and its flexibility to perform the tasks required in one location. The resulting simulation was capable of loading in any arbitrary .STL file representing the volume of the blood vessel (positive geometry) and completing its function with minimal human intervention, other than entering a start and end point within the vessel. It handles the conversion into a 3D voxel representation, performs pathfinding, and then initiates a simulated guidewire trajectory. Due to COVID-19 restrictions, the team was unable to validate and verify the results of the simulator with real-world tests and experiments.

Introduction

In Canada, strokes are the third leading cause of death [1] and the tenth leading contributor to disability adjusted life years [2]. 87% of strokes are ischemic and are caused by the blockage of blood vessels in the brain [3]. Acute ischemic strokes are typically managed through thrombolysis, the use of medication to break down clots. This procedure is being supplanted by endovascular thrombectomy (EVT), a procedure in which a guidewire navigates a catheter to remove a blockage. EVT provides better patient outcomes than thrombolysis, but access to the procedure is limited to major city centres due to the specialized personnel required.

The Advanced Micro and Nanosystems Laboratory is developing a system to navigate surgical guidewires autonomously using modified guidewires and an external magnetic field. As part of this system, the lab requires a simulator to evaluate the forces exerted by a guidewire on vessel walls during the EVT procedure. This simulator will aid in evaluating performance of the novel autonomous guidewires compared to the typical manual approach. It will also help motivate new control strategies not possible with manually-operated guidewires.

Prior to developing designs for this project, the team extensively researched current state of the art methods and techniques related to it. This included existing methods of automated guidewire manipulation and control, which is still only in developmental and testing phases. Although the team researched techniques for blood vessel mapping, they were limited by the equipment made available. For pathfinding, the team looked into different algorithms and their benefits, including the A* algorithm. Most importantly, the team researched finite element methods to determine the best way to model and simulate flexible bodies using rigid body techniques, such as using a mass-spring model.

Design Requirements

The primary function of the design is to simulate the damage to blood vessel walls, resulting from frictional and normal forces, given a path taken by a guidewire. Other aspects of the design include developing a system that can simulate flexible wires interacting with obstacles and finding optimal pathways through a blood vessel that can be utilized by a control system. Beyond the scope of this project, the design could potentially be used to simulate stresses in other medical procedures, such as endoscopy.

The constraints of the design include:

- The results of the system must be within a certain tolerance of similar real-life experiments.
- The system must not exert forces that can perforate vessel walls [4].
- The system must produce constant output if provided repeated input.

The objectives of the design include:

- The system should minimize vessel wall damage below the maximum perforation force [4].
- The system should not deviate more than 0.1 mm and 0.1º from desired position.

The project is a simulation residing on research computers, making use of commercial finite element analysis simulation software. For this reason, the service environment is quite minimal. However, the project requires the simulation of blood vessels within living patients. This means that factors such as heart, viscosity, and vessel rigidity/flexibility should be taken into account when developing the design. Stakeholders for the project include scientists/researchers and medical professionals, who may have interests in how the design can be used for research purposes, especially in applications beyond that of the project.

Methodology

Due to the challenges of physical prototyping with ongoing COVID-19 restrictions, the team decided on a simulation-based approach to aid AMNL in their design of magnetically controlled guidewires. The rescoping of the project midway through its timeline led to a protracted period of research on the current state of the art, followed by rapid convergence to a solid-segment chain guidewire model to be simulated using finite element analysis. The team's knowledge of robot pathfinding, linkage kinematics and dynamics, solid mechanics, and vascular biomechanics was applied during the detailed design process to develop a series of interconnected modules making up the complete simulation. These modules were developed and tested individually before being integrated and tuned. This modular test-and-iterate approach helped the team iron out issues with simulation stability.

A consequence of restrictions and the shortened project timelines was that the team could not perform verification and validation of the model against a physical guidewire. This process is critical for the development of any simulation because it ensures the results of future simulations can be correlated with real-world performance. The inability to complete this validation during the course of the project was a key consideration throughout the design process. This resulted in the team prioritizing solutions that were more modular, easier to interpret, and more tunable.

Design Solution

The solution prepares for the client was a set of finite element analysis (FEA) simulations prepared in MATLAB, given its flexibility as a tool and the team's familiarity with it.

The system is designed to receive the vessel as a solid model of the traversable volume (positive geometry) as shown in Figure 3. This geometry is then converted into a voxel representation, which is better suited for MATLAB computations by filling the model with a grid of nodes regularly spaces (shown in Figure 1). The nodes are then used to determine an optimal path from the start to the end as per the user input. For pathfinding, the team used the A* algorithm, as it allowed the team to introduce and weigh heuristics to adjust the resulting path. An example of this is the team adding a heuristic so that the path finder avoids contact and proximity with the vessel walls.

Once the path is found, the system begins the guidewire physics simulation. The team modelled their approach on examples of prior work done to simulate the physics of a guidewire traversing a vessel [5][6][7]. The guidewire was modelled as a string of rigid cylinders connected end-to-end with joints exhibiting the behaviour of a ball and socket (spheroid joints) with a spring-like restoring force. The blood vessels are modelled as a rigid shell for the guidewire. To replicate the behaviour of a magnetically-guided guidewire in the simulation, the tip was treated as a controlled "fixed" point that was moved along the path.

To approximate a guidewire traversing the vessel in real-time, a quasi-static approach was taken where the guidewire and its forces were simulated at regular intervals along the path. At each step, the tip would be set to a point along the path and the guidewire would be simulated segment by segment from tip to tail (start). The forces exerted on the vessel would be recorded at the end of the step and then compiled at the end of the simulation for analysis.

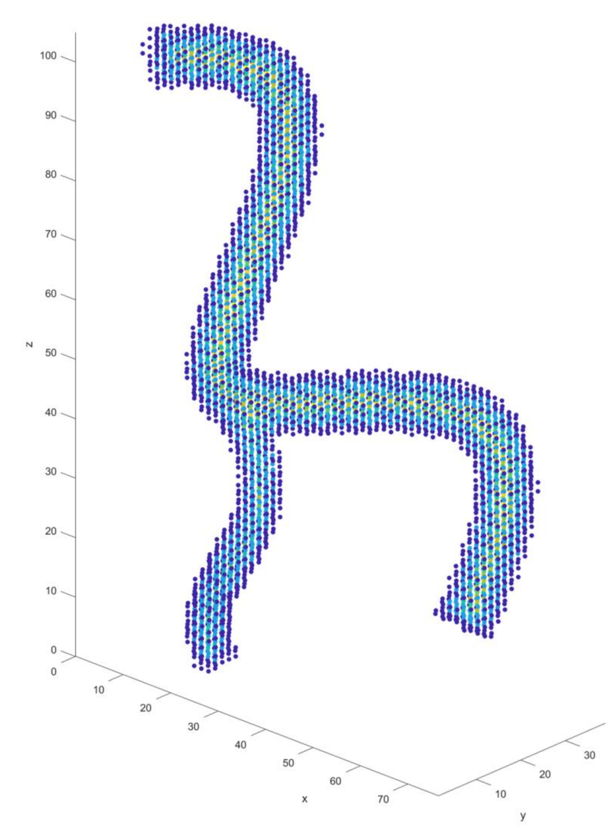

Figure 1: Resulting node grid of an imported vessel. Note: the colour of the nodes indicates the distance to the nearest vessel wall, darker hues correspond to greater proximity.

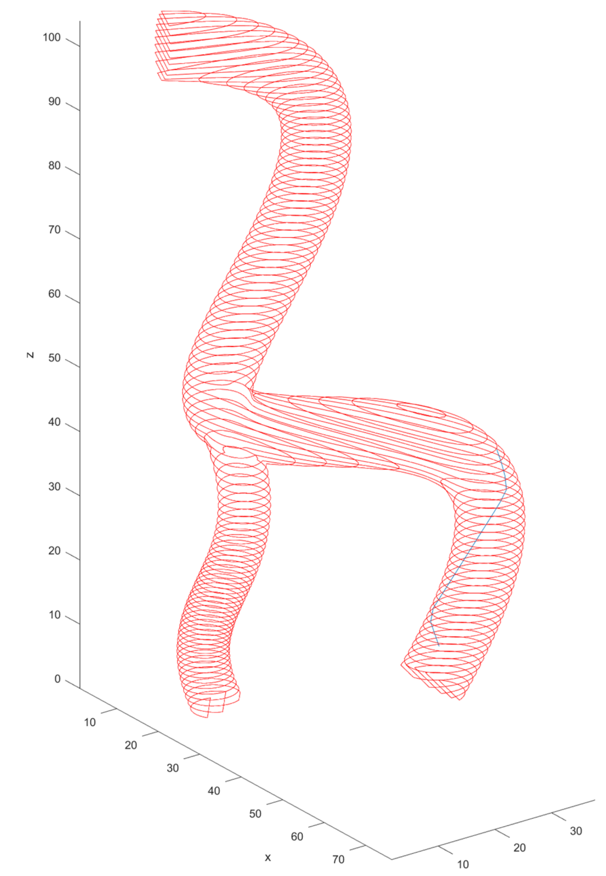

Figure 2: Demonstration of simulated guidewire entering the vessel.

Discussion and Results

The system successfully plots a course to an arbitrarily selected point in a blood vessel, similarly to how one would navigate if aided by magnets. It is then able to determine and record forces applied to the vessel walls as a guidewire is fed through the system to reach this point.

The team tested their system on a variety of test geometries of varying complexity that were generated specifically for this purpose. It is important to note that these vessels are more uniform in their cross sections than what would be present in a patient. Thus, the influence this would have on the system is untested. Regardless, these models were vital in ensuring that the system exhibits behaviours that are qualitatively similar to those observed in reality.

Due to the limitations imposed by COVID-19, the team was unable to use real-world experiments to quantitatively adjust, verify, and validate the system's performance in mimicking reality. Unfortunately, the effect of this missing real-world data is unknown at this time.

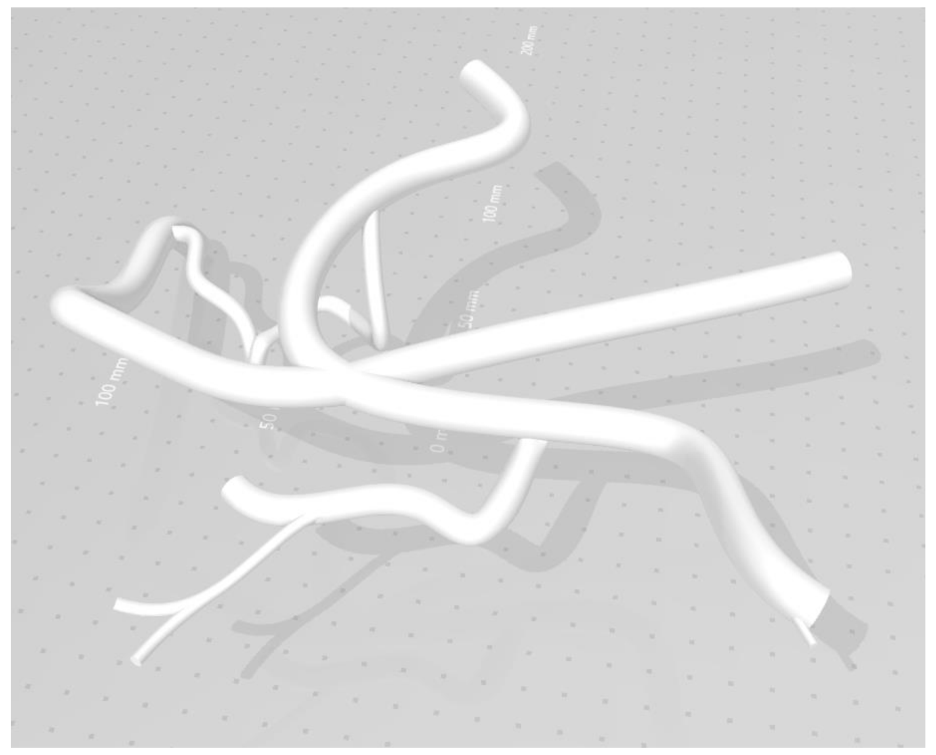

Figure 3: Example of STL representation of a blood vessel used.

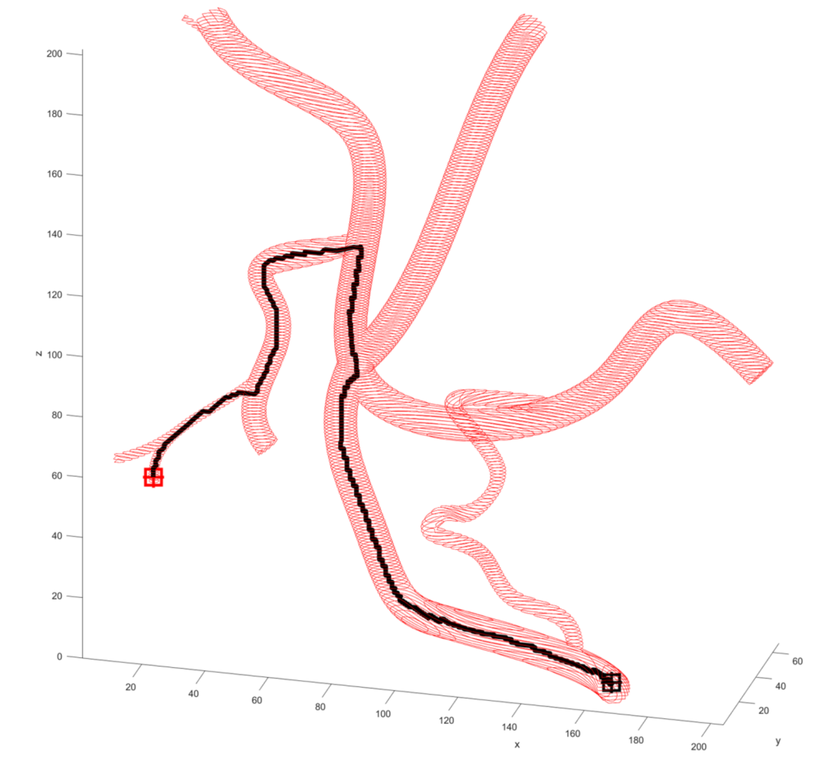

Figure 4: Example of pathfinding result through vessel.

Conclusions and Future Recommendations

In conclusion, a framework for the simulation requested by the client has been successfully prepared and tested by the team. This will allow the client to determine the damage to vessel walls and develop their navigation strategies without requiring laboratory tests. The current results of this simulator should not be treated as truth until verified and validated with experimental data.

Outside of the aforementioned verification of the system's physical performance, there are a few recommendations that team should work on if they wish to continue this project. The recommendations primarily come down to using a more easily optimized and faster framework for calculations by switching to a compiled programming language like C++. Although real-time performance is not critical for this application, speed is helpful to improve the simulation by enabling finer voxel resolutions or faster iteration cycles for optimization. More direct memory management would also enable different and more effective algorithms to be used to improve aspects, such as collision detection, or to enable new features not present in the current solution, such as deformable vessel walls.

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