Automated mesh processing of aneurysm segmentations for rapid and reproducible hemodynamic CFD simulation

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Abstract

Aneurysms, characterized by weakened vessel walls, pose significant risks to those affected due to the risk of potential rupture and bleeding. Current treatment options aim to modify blood vessel geometry or flow to mitigate these risks, requiring careful planning prior to intervention. Given vascular scans, it is possible to perform patient-specific hemodynamic simulations to aid in this decision, however, the technical manual labor required for setting up such simulations is one of the challenges in preventing widespread adoption of such computational support. This project proposes a toolchain serving as a base for automating the pathway from vascular imaging to simulation by using python and optimized open-source mesh processing libraries. First results showcase the capabilities and shortcomings of the proposed approach and we discuss future work to enhance shortcomings.

1 Introduction

1.1 Problem Statement

The current process of modeling and setting up hemodynamic simulations involves manual steps which are time-consuming and prone to errors. There is a need for an automated, reproducible, and accurate toolchain for mesh processing and CFD simulations to enhance the efficiency and reliability of vascular modeling.

1.2 Dataset

The project was developed with reference to a selection of 8 intracranial aneurysms of canine that were available and considered representative of the general task of setting up hemodynamic simulations from initial segmentation files.

1.3 Objectives

The primary objectives of this research are:

1. To automate the mesh processing pipeline for vascular scans in a scalable and easily extendable way.
2. To ensure compatibility of output meshes with FEBio for CFD simulations.
3. To perform hemodynamic simulations using meshes produced by the toolchain

2 Literature Review

As part of the MATCH challenge, a diverse range of research teams have been tasked with submitting their approaches to vascular modeling and simulating to assess the rupture risk of intracranial aneurysms. [Berg et al., 2018] [Berg et al., 2019] Unfortunately, the outcomes of these studies showcased a fragmented community and lack of common processing platforms. This showcases the complexity of modelling and simulating intracranial aneurysms and a lack of an encompassing software setup which satisfies varied and generally applicable approaches.

Inspiration in this work was also taken from [Rezaeitaleshmahalleh et al., 2024] which proposes a much more complex pipeline, motivated by the similar goal of automating the modeling and simulation process as much as possible and should be considered as a more mature approach compared to this work.

3 Methodology

The development of the proposed pipeline is motivated by a qualitative modelling process. Of particular relevance were the manifold The project contains workflow involves several key steps, including data input, mesh processing, and simulation setup.

3.1 Software tools

The project utilizes a Python environment with specific packages listed in a `requirements.txt` file to allow for a simple recreation of the environment via ‘python pip‘ or various ‘conda‘ distributions. Key tools include:

- `pyvista` for general mesh visualization and processing.
- `vmtk` (Vascular Modeling Toolkit) for vascular-specific modeling and mesh processing.
- `pymeshfix` for repairing common defects and increasing chance of manifold mesh
- `tetgen` for tetrahedralization of the surface mesh into a volumetric mesh.

3.2 The pipeline

For the step-by-step documentation of processing steps in the developed modelling pipeline, we refer to the README in the code repository since its documentation is focused on more technical aspects of the software toolkit itself.

4 Results

4.1 Output mesh analysis

The results of this project demonstrate the partially successful automation of the mesh processing pipeline with a number of caveats. The toolchain is capable of processing volumetric meshes suitable for CFD simulation in only one input case, depending on the ordering of processing steps or precise positioning of in and outlets, up to 3 of the 6 input files may be successful converted into volumetric meshes. There are common themes that dictate the success of the modelling procedure. One is the challenge of boundary artifacts interfering with creating a smooth manifold surface for tetrahedralization. In figure 1 we observe a case where such non-manifold boundary behavior interferes with the processing steps. Here, the inlet tubular extension was not performed. This is frequently the case for challenging boundary cases where malformed edges bend inwards and prevent the capping of the boundaries during for the calculation of centerlines, thus failing. In several other meshes, this is a unrecoverable scenario.

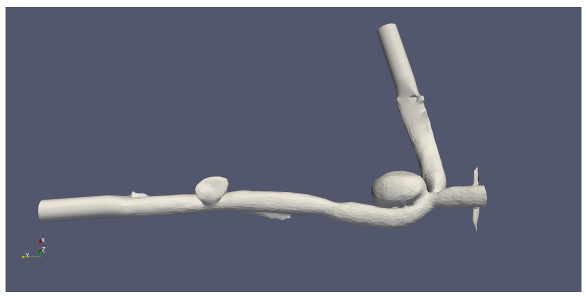

Figure 1: Volumetric mesh with missing inlet flow extension

The most successful volumetric mesh can be observed in figure 2 where minor imperfections but otherwise smooth surfaces and well-formed tubular extensions can be seen.

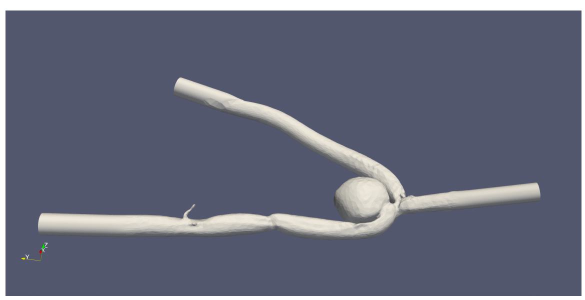

Figure 2: Generally well-formed volumetric mesh

Lastly, in figure 3 we notice a large number of connected but for simulation irrelevant vascular structures. The current modelling approach is not capable of removing such structures reliably and undesirable tubular extensions of unrelated vascular structures may be performed.

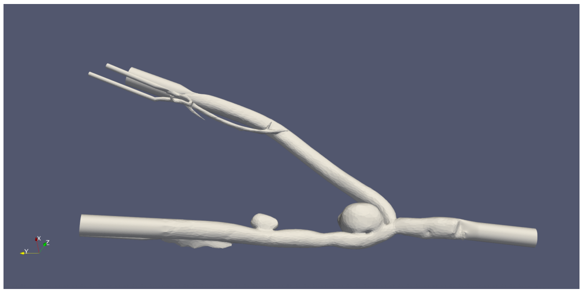

Figure 3: Mesh with numerous irrelevant vascular structures

4.2 Visual inspection as guiding principle in the qualitative modelling process

One useful feature emerging from the development of the toolchain for inspecting effects of different steps is a plotting functionality. There are two modes, in the first, all meshes of interest are compared to a baseline mesh (usually the initial mesh). This can be seen in figure 4.

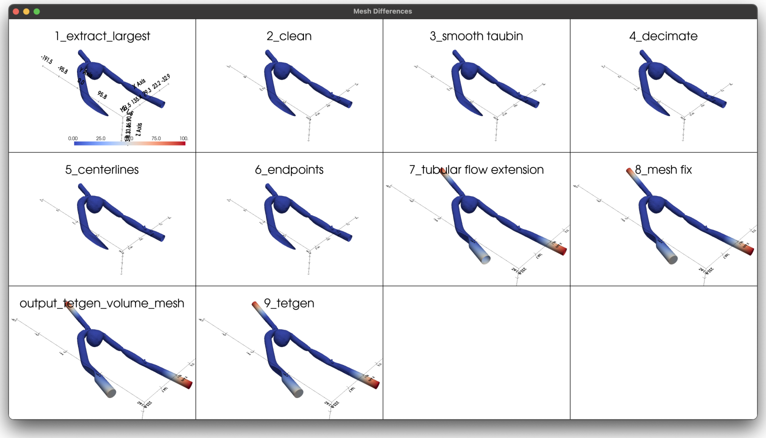

Figure 4: Plotting the point-wise distance of all intermediary meshes with reference to the initial mesh

Alternatively, one can visualize changes relative to each mesh's predecessor in the processing chain (chain reference) as exemplarily shown in figure 5. In both cases, the interactive visualization allows direct inspection of areas of interest and the effects the toolchain processing steps have there.

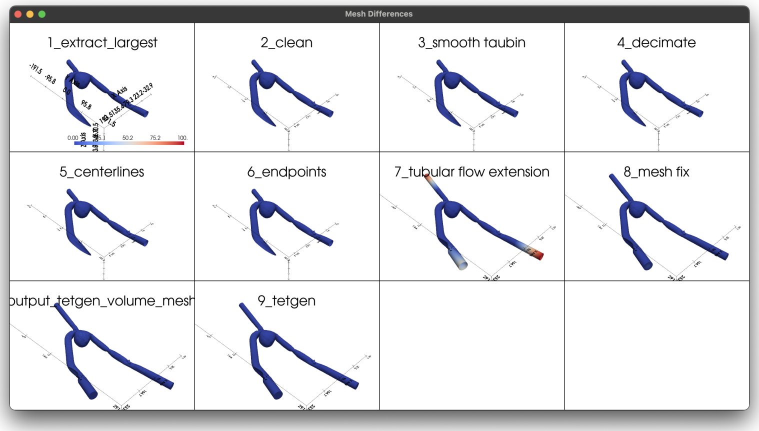

Figure 5: Plotting the point-wise distance of all intermediary meshes with reference to their relative predecessor

4.3 CFD

Computational Fluid Dynamic simulation using Newtonian fluids were performed by defining normal velocity surface loads at the boundaries and zero flow boundaries at the vascular wall surface. However, as the setup has not been completed, the interpretation of the output quality of meshes and their simulations is not possible.

5 Discussion

Overall, the modelling procedure developed fails to encompass the diverse set of challenges that input meshes showcased. A number of improvements would be required to achieve satisfactory quality and reliability which will be discussed in following.

5.1 Manifold handling

Much time was spent on ensuring the manifold behavior of meshes, frequently challenged by complex boundary scenarios. The use of dedicated mesh-fixing functionality was only introduced later and whilst not always reliable, proved very helpful in handling certain non-manifold edge cases. Remeshing has occasionally been effective at improving mesh-fixing algorithms, but the proper placement within the toolchain is still unclear and thus this compute-intensive feature has been omitted.

5.2 Quantitative approach

If one is able to define a quantitative metric or collection thereof that encompasses the desirable qualities of output meshes and satisfy a valid volumetric mesh, an interesting approach may be the use of evolutionary algorithms to perform optimization of both parameterization of processing steps as well as their placement within the processing chain. If such an optimization is performed on a larger dataset, it may be possible to reverse-engineer the correct order, processing steps and their parameterization.

5.3 Aneurysm modelling

Smoothing and various decimation and remeshing functionality will inevitably affect key geometric properties of aneurysms such as their opening area and shape which is critical to preserve for reliable measuring of stress on vascular walls during hemodynamic simulation. As such, it may be of particular interest to segment the aneurysm and isolate processing to all but the boundary of aneurysm and the rest of the vasculature. Such a step can be performed using growth algorithms starting from a seed placement or manual annotation, amongst others.

6 Conclusion

Whilst a number of open problems persist in the proposed toolchain, the underlying software project and experiences documented could help in future work of the modelling and simulation of vascular segmentations. More numerical and quantitative approaches could make use of valueable lessons learned in this project to develop a more robust modelling suite.

References

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