SimVascular 2.0: A Sustainable Open Source Software Pipeline for Patient Specific Blood Flow Simulation and Analysis

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Introduction

SimVascular (www.simvascular.org) is an integrated software package that provides a complete pipeline from medical image data to patient specific blood flow simulation that has contributed to numerous advances in personalized medicine, surgical planning, and medical device design.

SimVascular was originally an internal research code developed in the laboratory of Prof. Charles A. Taylor (formerly of Stanford University) and was released as open source code in 2007 but not publicly maintained.

Beginning in September 2013, S2I-SSI funding has been enabling the revitalization of SimVascular with state-of-the-art technology given four specific aims with the goal to expand the user community and enable large-scale simulation-based research studies.

Specific Aims of SimVascular Project

- Launch a new sustainable project with a modular architecture that incorporates benchmarking methods and test suites.
- Provide open source alternatives for all embedded commercial components in SimVascular, providing a free solution for researchers.
- Incorporate new machine learning segmentation algorithms enabling high throughput simulations for research studies with large patient populations for the first time.
- Merge state-of-the-art cardiovascular modeling advancements into a unified platform that includes multi-scale modeling, new optimizations and analysis of unsteady fluid mechanics.

SimVascular 2.0 Open Source Software Pipeline

SimVascular 2.0 now provides a complete open source pipeline for the process of cardiovascular modeling and simulation consisting of five core modules [1-3]. The software architecture and major packages are shown in Fig. 1.

- Updated build process using CMake allowing cross-platform compatibility.
- Integrated test suite with automatic builds, automated testing and Dashboard support.
- Path Planning Module: enables creating vessel paths (centerlines) interactively or using algorithms provided by VMTK.
- Image Segmentation Module: enables the creation of 2-D segmentations of the vessel lumen in a plane perpendicular to the vessel path via a variety of interactive and automatic algorithms. Integrated direct 3-D image segmentation based on algorithms including level set methods is also available.
- Anatomic Modeling Module: enables creation of 3-D solid models of vessels based on 2-D segmentations by custom lofting algorithm. The vessels are then combined (i.e. Boolean union) to create a complete 3-D model of the vasculature of interest. This module can also be used to import 3-D segmentation data from other packages such as ITK-SNAP (www.itksnap.org) to create anatomic models for use in SimVascular.
- Meshing Module: generates a tetrahedral unstructured mesh for the 3-D anatomic model that is suitable for computational hemodynamics. Mesh adaption tools utilizing a-posteriori error estimates are also integrated.
- Blood Flow Simulation Module: enables hemodynamic simulations at realistic flow rates and pressures. Time dependent flow rates or heart models may be defined for the inlet(s), and boundary condition parameters are typically specified at the outlets by fitting available clinical data to a lumped parameter model. If the vessel wall is deformable, its mechanical properties also need to be specified. The 3-D Navier-Stokes equations are solved using a finite element solver with linear elements and the streamline upwind/Petrov-Galerkin (SUPG) method.

Advances in Image Segmentation

- New segmentation methods based on state-of-the-art machine learning algorithms have been developed [4].
- Learning based classifier that leverages the structural context of edges.
- Incorporates multiple features to provide excellent performance under varying conditions.
- Automatic selection of features in context based on which features are most discriminative.
- No parameters to tune providing an adaptive yet reliable framework.
- Increased robustness by voxel patch classification and aggregating overlapping classifiers.

Advances in Anatomic Model Construction

- New code for triangulated surface representations and robust surface intersection algorithms enables combining 2-D and 3-D image segmentation in a single model for analysis as shown in Fig. 3.
- Robust triangulated surface Boolean operations recently implemented correctly join vessels even in complex cases where the popular open source package VTK fails as shown in Fig. 4.
- Custom algorithms to create 3-D surfaces from ordered list of 2-D segmentations have been added as shown in Fig. 5.
- Commercial solid modeling package Parasolid (Siemens PLM Software, Plano, TX, USA) no longer required or supported.

Advances in Meshing Generation

- SimVascular was extended to support meshing where the flow domain of interest is represented by a single region enclosed by a triangulated lumen surface [6]. The lumen surface consists of a set of consistently oriented triangular faces that approximate the lumen boundary.
- The new open source Meshing Module uses VMTK (www.vmtk.org) for boundary layer meshing and TetGen (www.tetgen.org) for volumetric meshing.
- Optional support for the commercial meshing library MeshSim (Simmetrix, Inc., Clifton Park, NY, USA) has been maintained by the implementation of the MeshSim Discrete Model.
- Meshes generated using open source tools and the commercial MeshSim library compared favorably as shown in Fig. 6.

References


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