Particle-Based Simulation and Visualization of Tubular Flows

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Abstract. *In this paper a method to efficiently simulate fluid flows through tubular structures, such as pipes and blood vessels, is introduced. The structure's centerline acts as a guide in pushing the fluid, which is simulated through the Smoothed Particle Hydrodynamics method. We employed a color coded classification on the particles to show variations of physical quantities along the tubular length.*

1. Introduction

Liquid flow (hereafter referred to simply as "flow") can be applied in applications like CAD systems, video games and virtual surgery simulators. The method in this paper is concerned with interactivity and flexibility allowing its use in real time environments, depending on the model complexity and level of detail. The method aims to perform a simplified guided flow simulation through arbitrary tubular structures, employing a Lagrangian (particle-based [Müller et al. 2003]) method to simulate the fluid, the Smoothed Particle Hydrodynamics (SPH) method [Monaghan 2005].

This paper's contributions are two-fold: First, a new method to efficiently obtain the approximate centerline of tubular structures is briefly discussed, and then the same centerline is used to simulate guided flows inside arbitrary tubular triangle meshes with no connectivity information.

2. Method

Approximate Centerline

According to Jiang, a centerline is "a curve that traverses the center of a hollow organ" [Jiang and Gu 2005]. In this work, we use an updated version of [Carvalho et al. 2006] to obtain cross-sections of tubular objects. Given two user-positioned planes, the algorithm works by firing lines between the planes and checking the lines' intersection with the object. If an intersection is found, a new plane is placed at the line segment's midpoint, and the algorithm proceeds recursively (Figure 1). The centerline is built by linking the centroids of neighboring cross-sections with line segments.

Simplified Guided Flow Simulation

The SPH method's appeal relies on the possibility to work with discrete values of physical quantities that control the fluid's state for each particle and are interpolated with the aid of *Smoothing Kernels*, which are radial symmetric weighing functions. Müller [Müller et al. 2003] discussed a simplified version of the Navier-Stokes equation for the

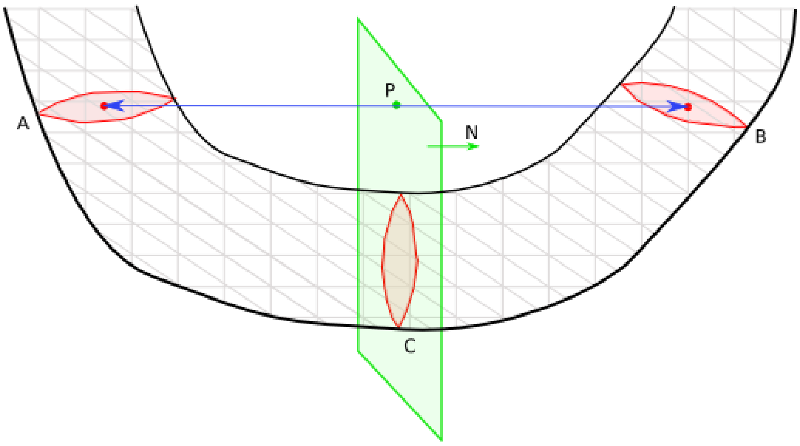


Figure 1. A line (in blue) is traced between the centroids of the two cross-sections *A* and *B*, resulting in a new plane with normal *N* which generates the new cross-section *C*.

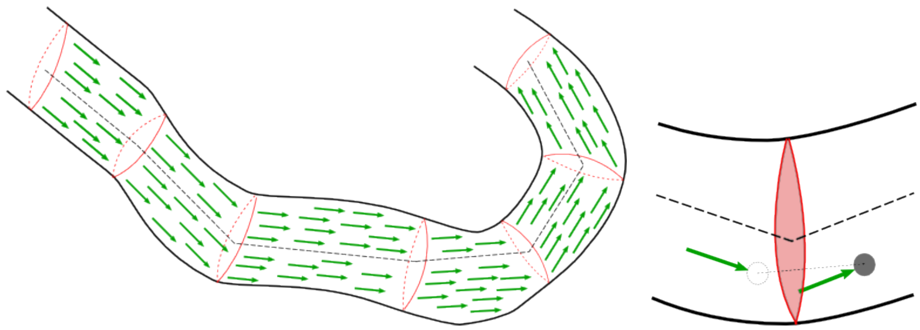
conservation of momentum for incompressible fluids involving physical quantities such as density, pressure and viscosity which are represented by continuous fields with difficult analytical solutions. Müller applied the SPH method to solve the equation's right hand side to calculate the force acting on each particle. The simplified equation supports the application of an external force, in our case the centerline guided force.

External Centerline Force

The idea is to use the approximate centerline as a simplification of the tubular structure's shape to guide the fluid particles. The centerline line segments' direction vector is used to apply an external force that pushes the particle forward on its field of influence (Figure 2) — the particle is under the influence on the closest centerline segment. At the simulation's initial step each particle's "region" is identified and stored. At every simulation step, each particle trajectory is checked to confirm it has crossed any of the cross-sections. If a particle's trajectory crossed the cross-section S_i and if the centerline sets (the line segments L and the polygonal cross-section S) are ordered such that the first vertex of line L_i corresponds to the centroid of polygon S_i, then the new direction of the centerline force acting on this particle is the direction of line L_i.

Since the sets containing the cross-sections and the line segments are ordered, it is expected that a particle that crossed the cross-section S_i last will cross the polygon S_{i+1} next. In practice, due to the dynamics of the fluid it is possible that the particle be pushed back momentarily against the flow. Still, only the trajectory's intersections with S_{i+1} and S_i need to be checked, making the process very efficient. The result is a spatial subdivision in which a particle is always at a known region delimited by two cross-sections.

The last cross-section in the set S is a special case; as Figure 2 shows, if there are n line segments, there are $n + 1$ cross-sections. If a particle crosses the last cross-section it is not associated with any force vector, because there is no line segment to provide the direction. We decided to move the particle back to the beginning of the centerline in this case. The positive points about that are that the fluid is constrained to the region of interest on which the centerline was built and that the particles are reused avoiding the need to track, destroy and create new ones.



(a) (b)

Figure 2. Particles suffer the influence of the line segment in the centerline region they're in. The force changes direction once the particles passes through a cross-section.

Although the set of line segments and cross-sections are only an approximation of the tubular structure's shape, the actual resolution of the mesh is irrelevant to the force computation once the centerline has been generated, as only the cross-sections and the line segments are used.

3. Visualization Experiments

In this section we present the results of visualization and simulation experiments performed on common desktop-grade hardware. The centerline algorithm was applied in a polygonal mesh representing an artery reconstructed by the marching cubes algorithm. This segment is interesting from a simulation point of view because it presents a few anomalies, such as a stenosis-like narrowing and an aneurysm-like bulge.

Figure 3(a) shows three different representations of the same frame of the simulation near the bulge area, with the fluid flowing from the structure's right to its left. The left-most figure displays all particles rendered with a solid blue color. On the middle image, the particles are color-coded according to their *pressure* value. Particles that fell in the bulge get "squeezed" together and are red-colored, representing an area of high fluid pressure. The traffic of particles near that region has a direct impact on their *velocities*, as shown in the final image. Particles in the bulge are almost stationary and blue-colored, as they cannot get out. The flow of the rightmost particles is red and fast because of the lack of collision obstacles and the higher degree of freedom to move, but as the particles near the trouble bulge-area their speed slows down considerably.

Figure 3(b) is a different case. Each image shows the state of the simulation of a small amount of fluid in different points in time. The centerline force is being exerted from the right to the left of the structure. On the first image, the particles have just arrived at the beginning of the uphill inclination — the particles that hit the artery's wall directly are under heavier pressure. The middle image shows the centerline force acting on pushing the particles upwards, towards the stenosis-like narrowing. This narrowing limits the intensity of the flow so that the particles begin to accumulate at the narrow opening's location. Thus, the pressure on the region increases.

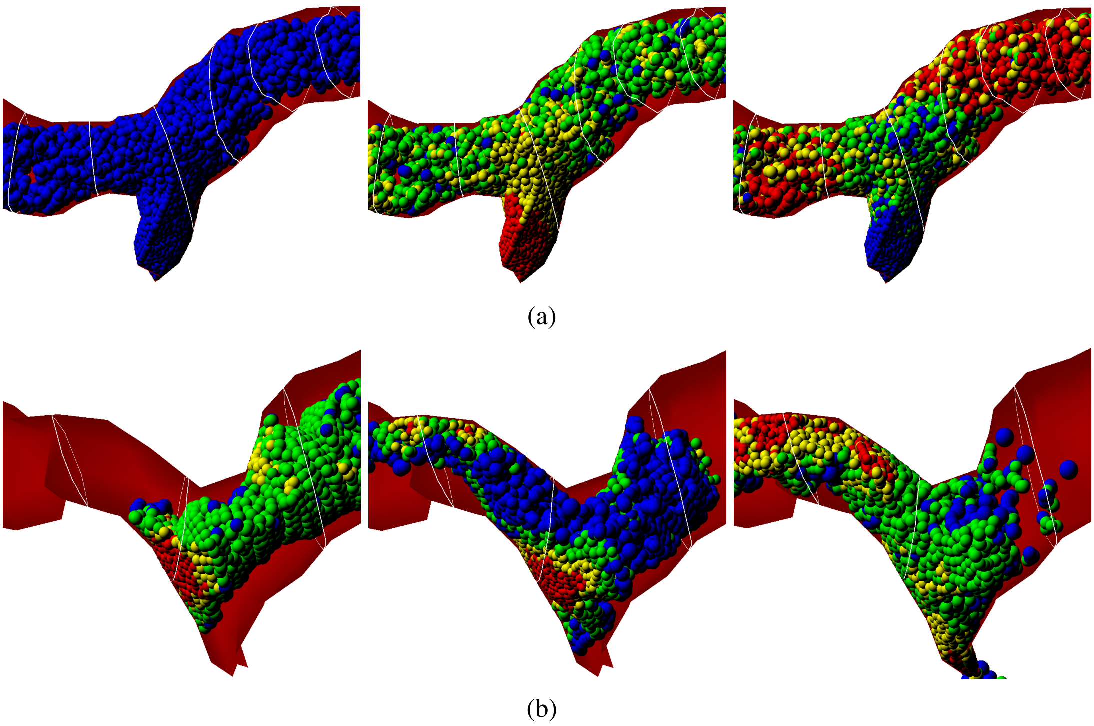


Figure 3. Example simulations with color-coded particles to visualize physical quantities.

4. Discussions and Conclusions

In our opinion the centerline approach worked as an efficient and realistic manner to simulate an external force acting on the fluid. The approximate centerline algorithm takes an average of 60 milliseconds to process a polygonal mesh with about 2000 triangles. Once the centerline has been generated, the actual computation of the centerline force acting on the particles takes an average of 2 percent of the time of each simulation step. For a scene like the one on Figure 3(a), the centerline force computation takes an average of 2 milliseconds per frame for 4000 particles, and 4 milliseconds for 8000 particles for a centerline composed of regular line segments. This value is linearly dependent on the number of particles, but independent of the number of triangles in the mesh, since the method deals only with the cross-sections and the line segments.

The inner characteristics of the SPH algorithm allowed to obtain updated values of the physical quantities of fluid's particles and to apply them on our color coded classification. In the experiments on Section 3 we could observe the variations of the pressure and velocity among the particles, in a simple and intuitive way.

Although the experiments data were taken from medical images, the fluid's parameters used were artificial. We aimed at evaluating the flow behavior regarding the reaction to an external force and on the collision with polygons of an arbitrary mesh. A future step is the acquisition of patient-custom anatomical information and the adaptation of the method to support such data, both in the fluid simulation and the external force computation. This implies the use of deformable structures to model the vessels.

Because of the lack of proper anatomical parameters and the absence of deformable structures to model the structure, it is hard to compare the method with previous, existing techniques. For example, the coupling of a 3D model of the cardiovascular system in a specific region of interest with a 1D representation for the rest of the system has been employed to perform a more accurate simulation with physically feasible parameters. This approach is taken by Blanco et al. [Blanco et al. 2007] using tetrahedral meshes built from real medical image data to represent the artery in 3D to evaluate variations in the inflow boundary between the 1D and the 3D models. Other methods include the adoption of pseudo-particles to implement a repulsion-attraction force [Müeller et al. 2004], and impulse-based techniques to add "stickiness" to simulate cohesion and perform the interaction with rigid bodies [Clavet et al. 2005].

The Asclepios research team at INRIA [Ayache et al. 2008] has extended experience in the field of analysis and simulation of medical images, and such expertise can be invaluable to obtain better anatomical data and in the realistic simulation of cardiovascular phenomena.

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