8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineeering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

VIRTUAL STENT DEPLOYMENT WITH SIMPLEX MESHES

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Key Words: *Biomedical engineering, stent deployment, intracranial aneurism, deformable simplex meshes.*

ABSTRACT

Intracranial stenting is nowadays an important resource for overcoming different technical limitations in endovascular therapy. A clear example is when intra cranial stens are used for improving the occlusion of wide-necked aneurisms in coil embolization therapy thus protecting the parent vessel. In intravascular therapy, the geometry of the stent is closely related to the outcome of the therapy, so the proper representation of the stent geometry is an important factor. In this work, deformable simplex meshes (Delingette [1]) are used for finding the deployed state of a stent inside an artery. A first work for stent deployment based on simplex deformable meshes was proposed by Flórez-Valencia et al. [2], where the authors suggest to initialize the simplex mesh using a cylinder that is deformed under the effect of internal and external forces. In the mentioned work a second order evolutionary framework is used, which in its discretized version can be rewritten as:

$$\mathbf{p}_i^{\tau+\triangle\tau} = \mathbf{p}_i^\tau + (\mathbf{p}_i^\tau - \mathbf{p}_i^{\tau-\triangle\tau})(1-\widetilde{\gamma}) + \widetilde{\alpha}\mathbf{f}_{int}(\mathbf{p}_i^\tau) + \widetilde{\beta}\mathbf{f}_{ext}(\mathbf{p}_i^\tau) + \widetilde{\lambda}(\mathbf{f}_{axial}(\mathbf{p}_i) + \mathbf{f}_{radial}(\mathbf{p}_i)) \quad (1)$$

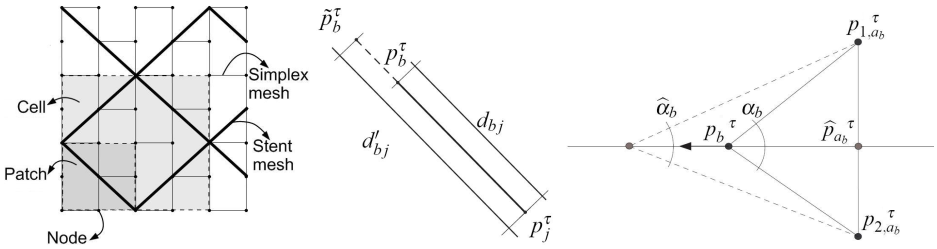
where $\widetilde{\alpha}$, $\widetilde{\beta}$ and $\widetilde{\lambda}$ are weighting parameters and $\widetilde{\gamma}$ depends on the time step size, and $\mathbf{p}_i \in \mathcal{P}$ is the set of points in the simplex mesh. When the iterative process ends, the stent mesh is adjusted to fit the vessel wall. With this approach the stent geometry inside the artery is obtained, maintaining a regular mesh and preserving the good properties of the mesh. One of the main limitations of this method is that no stent geometric characteristics are considered (e.g., stent struts length, angle between them, stent mesh pattern, etc.).

Proposed methodology In the proposed method, a *stent shape constraining* force is considered. This stent force will guide the movement of stent mesh points such that the stent equilibrium shape (i.e., deployed geometry) is approximated when the deformation ends. With this in mind, we propose to consider a *stent internal force* term that accounts for the above mentioned constraints. Introducing this new term and considering $\widetilde{\lambda} = 0$, Eq. 1 can be written as

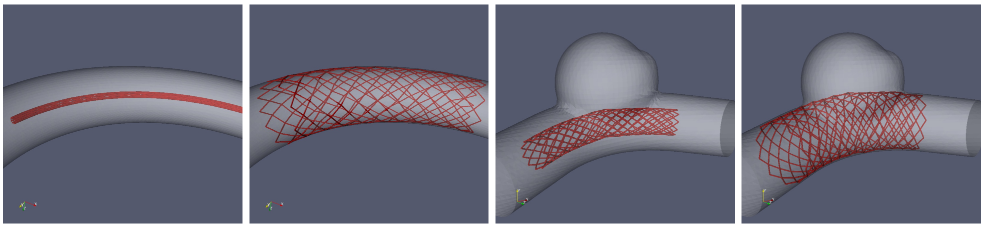
$$\mathbf{p}_i^{\tau+\triangle\tau} = \mathbf{p}_i^\tau + (\mathbf{p}_i^\tau - \mathbf{p}_i^{\tau-\triangle\tau})(1-\widetilde{\gamma}) + \widetilde{\mu}\big(\mathbf{f}_{int}(\mathbf{p}_i^\tau) + \widetilde{\beta}\mathbf{f}_{ext}(\mathbf{p}_i^\tau)\big) + (1-\widetilde{\mu})\mathbf{f}_{stent}(\mathbf{p}_i^\tau), \quad (2)$$

where $\widetilde{\mu}$ is a parameter between 0 and 1, and is used to balance the contribution of simplex mesh forces and the stent constraining forces. In order to maintain the stent shape characteristics, we add an internal stent force, that is, $\mathbf{f}_{stent}(\mathbf{p}_b^\tau) = \mathbf{f}_{length}(\mathbf{p}_b^\tau) + \mathbf{f}_{angle}(\mathbf{p}_b^\tau)$ being $\mathbf{p}_b^\tau \in \mathcal{P}_{stent} \subset \mathcal{P}$ the subset of points of the simplex mesh that form stent mesh. Next the two terms are studied in more detail (Figure 1 (a) and (b)).

Strut length constraint: The strut length force acts on the current point attracting it to a position where the length of the corresponding strut more closely meets its length restriction (i.e., the length of strut in the stent deployed position, usually obtained from stent manufacturers). We define $\mathbf{f}_{length}(\mathbf{p}_b^\tau) = \chi(\tilde{\mathbf{p}}_b^\tau - \mathbf{p}_b^\tau)$ with, $\tilde{\mathbf{p}}_b^\tau = \mathbf{p}_b^\tau + \sum_{j\in\mathcal{N}(b)} \zeta_{bj}(\mathbf{p}_b^\tau - \mathbf{p}_j^\tau)$, being $\mathcal{N}(b) \subset \mathcal{P}_{stent}$ the set of neighbors of point $\mathbf{p}_b^\tau$, and where ζ_{bj} is negative if $d'_{bj} > d_{bj}$ and positive otherwise. In the former, d'_{bj} is the reference length of the strut between points $\mathbf{p}_b^\tau$ and $\mathbf{p}_j^\tau$ at the deployed state and d'_{bj} the length at time τ.



(a) Stent and simplex mesh. (b) Strut and angle constraints graphical interpretation.



(c) Stent in the initial and deployed state for a curved vessel. (d) Stent in the initial and deployed state for a vessel with an aneurism.

Figure 1: Deployment example for two different vessel geometries.

Strut angle constraint: An angle constraining force term is used to guide the points movement, namely $\mathbf{f}_{angle}(\mathbf{p}_b^\tau) = \varepsilon(\widehat{\mathbf{p}}_b^\tau - \mathbf{p}_b^\tau)$ with $\widehat{\mathbf{p}}_b^\tau = \mathbf{p}_b^\tau + \sum_{a_b \in \Lambda(b)} \phi_{a_b}(\mathbf{p}_b^\tau - \widehat{\mathbf{p}}_{a_b}^\tau)$, being $\Lambda(b)$ the set of angles formed between $\mathbf{p}_b^\tau$ and the elements in $\mathcal{N}(b)$, with $\widehat{\mathbf{p}}_{a_b}^\tau = \frac{\mathbf{p}_{1,a_b}^\tau + \mathbf{p}_{2,a_b}^\tau}{2}$, and $\phi_{a_b} = sign(\cos(\alpha_b) - \cos(\widehat{\alpha}_b))$, where α_b is the value in radians of angle a_b and $\widehat{\alpha}_b$ is its reference value at deployed state.

The initial condition of the simplex mesh is obtained from the centerline of the vessel under consideration. In order to represent the stent geometrical characteristics, a background stent mesh is constructed using some of the points of the simplex mesh. In this background mesh, the stent mesh connectivity and geometrical properties are stored. The deployment algorithm can be stated as following (δ is arbitrary in $(0, 1]$):

Algorithm 1 Virtual stent deployment with constrained simplex deformable meshes

Require: Vessel geometry, vessel centerline, stent geometry description.
Ensure: Deployed stent geometry.

```
Create an initial stent and simplex mesh around the vessel centerline and set END = false.
while not END do
    Compute the simplex mesh forces (internal and external forces over all the points).
    Compute the stent shape constraints for all the stent points.
    Compute the displacement at each point according to the force acting on the point.
    Move mesh geometry using the displacements at each point p_i according to Eq. 2.
    if dst(p_i, vessel wall) < ϵ holds for δ% points in P then
        END = true
    end if
end while
```

Results In Figure 1 (c) and (d) are presented some preliminary qualitative results for this method. Work in progress in this line is the use of more complex arterial geometries obtained from real patients. Is also work in progress, the development of more appropriate stopping criteria as well as quantitative evaluation and validation of the results with clinical data obtained from medical images.

Acknowledgements This work was partially generated within the framework of the Integrated Project @neurIST (IST-2005-027703), which is co-financed by the European Commission, and also partially supported by MEC TEC2006-03617, ISCIII FIS2004/40676, and CDTI CENIT-CDTEAM grants.

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