Robust and High-Fidelity Guidewire Simulation with Applications in Percutaneous Coronary Intervention System

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Abstract

Real-time and realistic physics-based simulation of deformable objects is of great value to medical intervention, training, and planning in virtual environments. This paper advocates a virtual-reality (VR) approach to minimally-invasive surgery/therapy (e.g., percutaneous coronary intervention) in medical procedures. In particular, we devise a robust and accurate physics-based modeling and simulation algorithm for the guidewire interaction with blood vessels. We also showcase a VR-based prototype system for simulating percutaneous coronary intervention and mimicing the intervention therapy, which affords the utility of flexible, slender guidewires to advance diagnostic or therapeutic catheters into a patient's vascular anatomy, supporting various real-world interaction tasks. The slender body of guidewires are modeled using the famous Cosserat theory of elastic rods. We derive the equations of motion for guidewires with continuous energies and integrate them with the implicit Euler solver, that guarantees robustness and stability. Our approach's originality is primarily founded upon its power, flexibility, and versatility when interacting with the surrounding environment, including novel strategies in the hybrid of geometry and physics, material variability, dynamic sampling, constraint handling and energy-driven physical responses. Our experimental results have shown that this prototype system is both stable and efficient with real-time performance. In the long run, our algorithm and system are expected to contribute to interactive VR-based procedure training and treatment planning.

CR Categories: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—[Physically based modeling] D.2.2 [Software Engineering]: Design Tools and Techniques—[Computer-aided software engineering (CASE), performance measures] J.3 [Life and Medical Science]: Medical information systems— [I.6.3]: Simulation and Modeling—Applications;

Keywords: Guidwire Simulation, Vessel Interaction, Percutaneous Coronary Intervention System

1 Introduction

Virtual surgery simulation aided by interactive techniques and graphics environments is of great significance for medical training and simulation. Nowadays, because of rapid advancement in medical imaging and specialized medical devices, minimally-invasive surgery is becoming one of the most popular interventional methods for various illnesses, such as heart stent operation. This paper focuses on simulating the percutaneous coronary intervention — guidewire interaction with blood vessels in a virtual-reality environment. During the surgical operation, the guidewire is inserted into heart through blood vessels. To aid surgical planning and treatment, we develop a VR-based prototype system that affords the utility of flexible, slender guidewires to advance diagnostic or therapeutic catheters into a patient's vascular anatomy, supporting various real-world interaction tasks.

In this paper we develop a physics-based real-time system to simulate the guidewire and vessel behaviors and interactions with high fidelity during interventional therapy to facilitate various diagnosis tasks and enhance medical practitioners' skills for invasive treatment. Compared with other existing systems, our system can achieve full automation, high accuracy, real-time response, and faithful interaction with participating media, with a goal to help doctors improve their operative skills in minimally-invasive therapy procedures. The main contributions of our paper are summarized as: (1) The guidwire length is adaptive to the surrounding media and is represented by a hybrid model of geometry and physics. The guidewire's control points are sampled adaptively based on local curvature and physical properties. (2) The interaction between the vessel and guidewire are integrated with a two-way coupling in real-time. (3) The guidewire's motion equation is solved by implicit Euler solver to guarantee stability and robustness. (4) Our applications in the percutaneous coronary intervention system are further augmented by the force sensing device as input.

2 Related Work

Modeling and simulation of elastic rods is an active field in medicine, biology, computer graphics, etc. Guidwires that we are trying to model can be regarded as an elastic rod.

Mass-spring Models. A popular method to simulate curve-shaped deformable models is the mass-spring model. The model discretizes an elastic rod into a set of mass-points that are linked by springs. A typical application is that Andrew et al. [Selle et al. 2008] simulated hair. A biggest limitation of this model might be that it can not handle material torsion easily.

Non-physical Models. There are some non-physical methods being used to simulate curve-shaped deformable models. Such as Brown et al. [Brown et al. 2004] simulated knotted ropes, and Rungjiratananon et al. [Rungjiratananon et al. 2010] simulated complex hairstyle. Non-physically-based methods are oftentimes highly related to geometry processing and lack of physical realism, which are not proper to use in any virtual-reality based medical system.

Models based on Cosserat Theory. The Cosserat-theory-based approaches consider the material frames when formulating the strain-stress relations. Duratti [Duratti et al. 2008] presented an interventional radiology system by Cosserat rod model similar to ours. But they just implement the basis functionalities. Tang et al. [Tang et al. 2010] proposed a realistic elastic rod model to simu-

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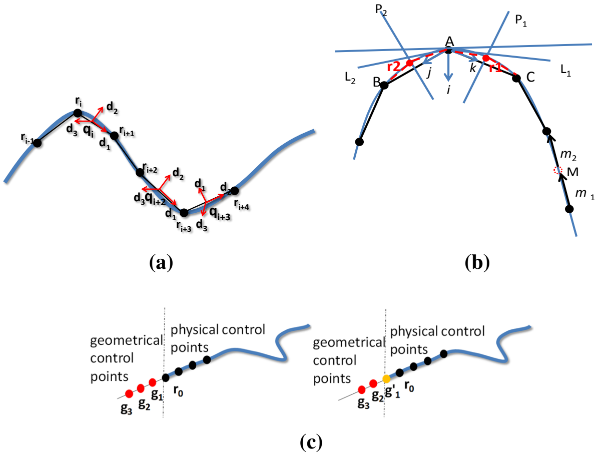


Figure 1: *(a) illustrates the centerline of the guidewire is discretized into N spatial control points r_i. The orientation of each element is represented by a quaternion q_j. (b) illustrates the adaptive sampling. $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the two additional points and M is the deleted point. (c) illustrates two different stages of the hybrid model. The yellow point is a point just being transformed from a ghost point to a physical control point. The dotted line is the threshold for popping up the ghost points and transforming.*

late minimally invasive vascular interventions. Even though their approach is real-time, the motion of the guidewire is only constrained to follow the centerline of the vessel. Sueda et al. [Sueda et al. 2011] simulate highly constrained strands but without torsion.

3 Guidewire Modeling

We now describe the model of guidewire we have designed in our system. It may be noted that for a function $y(x,t)$, $y'(x,t)$ denotes the spatial derivative, while $\dot{y}(x,t)$ denotes the temporal derivative.

3.1 Discrete Representation of Guidewire

Our guidewire model is based on the continuous Cosserat theory [Antman 1991] of the elastic rod. In order to facilitate the simulation of the guidewire in the system, we further discretize the guidewire into N spatial control points $\boldsymbol{r}_i = \boldsymbol{r}(\sigma_i, t), i \in [1, N]$ as shown in Fig. 1a. For each element, a local frame $\boldsymbol{d}_k(\sigma, t), k = 1, 2, 3$ is defined to control its orientation.

The spatial derivative $\boldsymbol{r}_i'$ of the centerline is obtained by

$$\boldsymbol{r}_i' \approx \frac{1}{l_i}(\boldsymbol{r}_{i+1} - \boldsymbol{r}_i), \tag{1}$$

where l_i is the rest length of each segment. The local frame $\boldsymbol{d}_k(\sigma,t)(k = 1, 2, 3)$ can be compactly represented by quaternions $\boldsymbol{q}_j = (q_1, q_2, q_3, q_4)^T_j, j \in [1, N-1]$, since the $\boldsymbol{d}_k(\sigma,t)(k = 1, 2, 3)$ comprise a rotation matrix. It may be noted that, the quaternion $\boldsymbol{q}$ here is constrained by $\|\boldsymbol{q}\| = 1$ in order to represent a rotation. What's more, we use $\frac{\boldsymbol{r}_i'}{\|\boldsymbol{r}_i'\|} - \boldsymbol{d}_0(\boldsymbol{q}_j) = 0$ as a constraint that links the control points and the local frames.

3.2 Energy Formulation

Based on the model of the guidewire, we now deduce the potential energy, kinetic energy, and dissipation energy of the guidewire. The potential energy V is the sum of stretch and bending energy. The kinetic energy of the guidewire T is the sum of the translational and rotational energy. The dissipation energy D is the sum of translational dissipation and angular dissipation energy.

$$V = \frac{1}{2}\int_0^1 K_s(\|\boldsymbol{r}'\| - 1)^2 d\sigma + \frac{1}{2}\int_0^1 \sum_{k=1}^{3} K_{kk}(u_k - \hat{u}_k)^2 d\sigma, \tag{2}$$

$$T = \frac{1}{2}\int_0^1 \rho\pi r^2 \dot{\boldsymbol{r}} \cdot \dot{\boldsymbol{r}} d\sigma + \frac{1}{2}\int_0^1 \sum_{k=1}^{3} I_{kk}(u_k)^2 d\sigma, \tag{3}$$

$$D = \frac{1}{2}\int_0^1 \gamma_t \boldsymbol{v}'^r \cdot \boldsymbol{v}'^r d\sigma + \frac{1}{2}\int_0^1 \gamma_r \boldsymbol{\omega}'^r \cdot \boldsymbol{\omega}'^r d\sigma, \tag{4}$$

where K_s is the stretching stiffness constant, $u_k = \boldsymbol{d}_k \cdot \boldsymbol{\omega}$ represents the orientational rate of change, ρ is the density of the guidewire, r is the radius of the guidewire, I is the inertia tensor. γ_t is the translational friction coefficient, $\boldsymbol{v}'^r$ is derivative of the velocity, γ_r is the rotational friction coefficient, $\boldsymbol{\omega}'^r$ is the spatial derivative of the angular velocity in the reference frame. All the equations in Sec. 3.2 are given in continuous form. To obtain the discretized form, we could simply replace the continuous variable with Eq.1.

3.3 Guidewire Dynamics

The movement of each control point is governed by its energy discussed in Sec. 3.2. The variational formulation results in the Lagrangian equation of motion $\frac{d}{dt}\frac{\partial T}{\partial \dot{\boldsymbol{g}}} - \frac{\partial T}{\partial \boldsymbol{g}} + \frac{\partial V}{\partial \boldsymbol{g}} + \frac{\partial D}{\partial \dot{\boldsymbol{g}}} = \boldsymbol{f}$, where $\boldsymbol{g}$ refers to its global coordinates, and the vector $\boldsymbol{f}$ collects the external forces that act on the guidewire.

We integrate the system with the implicit Euler solver to guarantee robustness and stability of the system. In practice, we interate Equ.5 to arrive at numerical solutions.

$$\begin{cases} \boldsymbol{r}_i^{t+h} = \boldsymbol{r}_i^t + h\boldsymbol{v}_i^{t+h} \\ \boldsymbol{v}_i^{t+h} = \boldsymbol{v}_i^t + \frac{h}{m_i}F^{t+h} \\ \boldsymbol{q}_j^{t+h} = \frac{1}{2}\boldsymbol{Q}_j^{t+h}\begin{pmatrix} 0 \\ \boldsymbol{\omega}_j^{t+h} \end{pmatrix} h + \boldsymbol{q}_j^t \end{cases}, \tag{5}$$

where $\boldsymbol{\omega}_j$ is the angular velocity and $\boldsymbol{Q}_j$ is the quaternion matrix that allows to conduct the quaternion multiplication consistently as a matrix-vector multiplication.

4 Interactions with the Surrounding Environment

In our system, we focus on developing a robust physically-based model to simulate the guidewire during the insertion. In order to handle different types of situation during the insertion, we design a hybrid model of geometry and physics allowing the model to be of arbitrary length. We also dynamically sample the control points adaptively during insertion. Meanwhile we employ a two-way coupling of the guidewire and vessel.

4.1 Hybrid Model of Geometry and Physics

The guidewire inserting into the vessel in the virtual-reality based training system could be very long. However, considering real-time performance requirement, it is not necessary to simulate the long guidewire with a large number of control points at the very beginning. Instead, we present a hybrid model of geometry and physics to simulate guidewire of arbitrary length in real-time.

We introduce ghost points to the hybrid model. The ghost points are invisible and only exhibit geometry properties. During insertion, as soon as the end of the guidewire is beyond a certain threshold, some necessary ghost points shall pop up to expand the end of the guidewire. The new ghost points only last a short period of time before being converted into physical points, during which the ghost points only do simple geometric transformation. After exceeding the threshold, the ghost points are switched to physical control points. The physical characters of the newly transformed points are obtained by linear interpolation with the help of the last two control points. Fig. 1c illustrates the hybrid model of geometry and physics.

4.2 Adaptive Sampling

The blood vessel could be extremely complex. A constant interval between the control points may lead to less accurate simulation or computational time unreasonable due to the different curvature.

In order to solve the above problem, we further optimize our system by adopting the adaptive sampling strategy. During the insertion, we take the shape of the guidewire into account. If the curvature of the guidewire is large but the interval between the control points is not small enough to characterize the guidewire behavior accurately, the control point splits at this location. Two control points are added. On the other hand, if the curvature of the guidewire is small and the interval between the control points is too small, delete the control point at this location to reduce computation, meanwhile re-distribute its mass to the adjacent points. More detailed principle of adaptive sampling is shown in Fig. 1b.

4.3 Two-way Coupling with Blood Vessel

When being inserted into the vessel, the guidewire makes contact with the vessel so that the guidewire will bend as the result of the force generated by the collision. At the meantime, the vessel also subjects to the contact force resulting from elastic deformation. The force between guidewire and vessel is decomposed into two orthogonal directions, which are orthogonal and tangent to the vessel surface respectively. The orthogonal force leads to elasticity and the tangent force leads to friction.

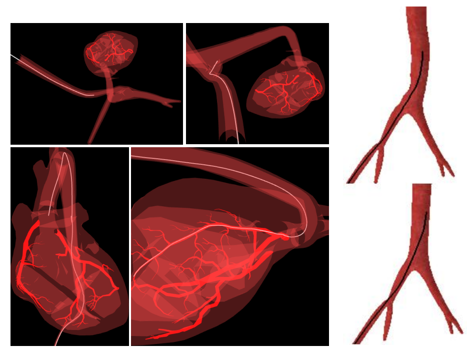
Under the influence of the orthogonal force, we adopt the TLED model [Joldes et al. 2010] to simulate the vessel deformation, and the guidewire will respond accordingly. Meanwhile, the guidewire interacts with the vessel via a friction tangent to the vessel. We treat this external friction here as multiple external impulse effects on the control points. According to the impulse theorem, the external friction force of the control point $\boldsymbol{r}_i$ can thus be formulated as $F_i = \gamma \frac{dm_i \boldsymbol{v}_i}{dt}$, where γ is the friction coefficient between the guidewire and its surrounding vessel, m_i is the mass of the point $\boldsymbol{r}_i$, and $\boldsymbol{v}_i$ is the velocity of the i-th point.

5 System Components and Functionalities

5.1 Percutaneous Coronary Intervention Simulation System

Our goal is to apply our method to virtual-reality based medical training and treatment. To achieve such an ambitious goal, our techniques must be physically accurate, efficient, and flexible. To satisfy these requirements, we integrate the hybrid model of physics and geometry, adaptive sampling, constraint handling mechanism and two-way coupling with blood vessel in our system. Our system considers the cardiac minimally invasive surgery as a typical example. We insert the guidewire from the aortic arch and push it to travel along the vessel. We use a force sensing equipment to control the guidewire's inserting action. Sliding and turning the sensing equipment are equivalent to push and rotate the end of the guidewire. Fig. 2a illustrates some different stages of the guidewire being inserted into the blood vessel. Fig. 3 shows our prototype system (intended to be used for VR-based medical training and treatment).

Our prototype system has demonstrated to be physically accurate, efficient, and flexible. More importantly, it is also efficient enough to run in real-time. According to Table 1, it can be concluded that our system's time complexity is linear with respect to the number of control points.



(a) **(b)**

Figure 2: *(a) illustrates some different stages of the guidewire being inserted into the blood vessel. (b) illustrates the difference between the deformation that couples with blood vessel and no deformation.*

System Architecture. Based on the aforementioned algorithms, we have designed a percutaneous coronary intervention simulator. During such surgery, doctors send the guidewire into heart through vessels to treat the stenotic coronary arteries of the heart. As illustrated in Fig. 3, the simulator consists of 3 modules, guidewire and vessel physical simulation, collision detection and response, X-ray and photorealistic rendering modules. In order to guarantee the efficiency of the system, we use different levels of detail for the model in different modules. The physical module employs the simplest model to increase the efficiency and the render module uses the most accurate model to enhance the rendering effects.

Graphical User Interface. As shown in Fig. 4, our system connects to a force sensing equipment as input. A real guidewire is equipped on a track and can move back, forth and twist. While the user manipulates the real guidewire being inserted into the vessel, the sensors prob the input force and moment driving the virtual guidewire moving forward.

The software GUI of our simulator is also shown in Fig. 4, in which the left part is the control panel and some plotted graphs to show heartbeat, blood pressure, and the right part is the rendering window with X-ray view and photorealistic view of the guidewire intervention operation. While the doctor inserts the guidewire into the vessel, the guidewire movement, the plumped vessel and pumped heart are all shown immediately in the X-ray and 3D realistic rendering windows simultaneously. Compared with the real operation, in our system, the doctor can better understand how the guidewire is moving in the vessel, how it is interacting with the vessel and how the pumping heart is affecting the guidewire motion.

Number of Initial Control Points	Force Calculation	Collision Handling	Adaptive Sampling	Status Update
167	0.43	1.52∼2.21	0.03∼ 0.08	0.10
250	0.61	1.60∼2.32	0.03∼ 0.09	0.14
317	0.76	1.78∼2.53	0.05∼ 0.11	0.19
480	1.18	1.95∼2.60	0.07∼ 0.18	0.27

Table 1: *Timing statistics in different stages of the simulation. All the timings are measured in millisecond.*

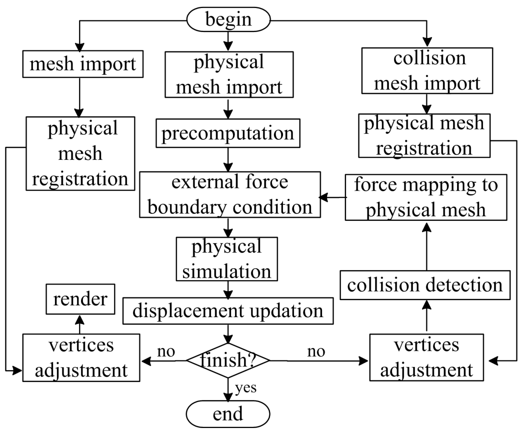


Figure 3: *The flowchart of the percutaneous coronary intervention simulation system.*

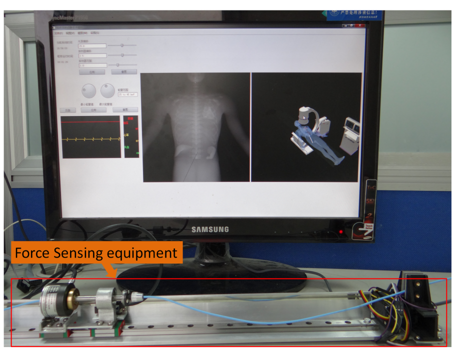


Figure 4: *An overview of our prototype medical training system.*

5.2 Interacting with Blood Vessel

In previous years, several work has been done to simulate guidewire inserting into the blood vessel. However, they all focus only on the deformation of the guidewrie but not the deformation of the vessel. To ameliorate, we further take the vessel's deformation into account. Fig .2b illustrates the difference between two-way coupling with blood vessel and no coupling with blood vessel. It is evident that our two-way coupling with blood vessel makes the deformation of the blood vessel possible.

Limitation. There still remain some limitations of our model and algorithm that call for immediate improvement. Our method neglects the moment of inertia of the guidewire's cross-section where we can not handle the rotation of the cross-section. Also, as we only focus on the guidewire being inserted in the blood vessel, we have not yet considered its possible self-collision.

6 Conclusion

We have developed a prototype physically-based medical training system to simulate the guidewire insertion into the blood vessel and its physically realistic interaction with surrounding materials. We design a robust physically-based model of the guidewire which affords the guidwire to free move (forward or backward), bend, or twist subject to all the surrounding constraints and collision contact. Meanwhile, the surrounding vessel gives rise to synchronized deformation tightly coupled with the blood vessel. Moreover, we optimize our system by employing the hybrid handling of geometry and physics and adaptive sampling control points, all of which aim to make our system flexible, efficient, and accurate with more functionalities towards real-time performance. The powerful applications being applied in the coronary intervention simulator can be a great help to improve doctors' operational skills.

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