Deliverable D10.4.2

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euHeart

Personalised & Integrated Cardiac Care: Patient-specific Cardiovascular Modelling and Simulation for *in silico* Disease Understanding & Management and for Medical Device Evaluation & Optimization

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Deliverable D10.4.2
Final report on the simulator for radiofrequency ablation

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Abstract:

This deliverable describes the final status of Task 10.4 of Workpackage 10 of the euHeart project. The aim of this task is to develop a prototype of an endovascular simulator of cardiac radiofrequency ablation. More precisely, its purpose is to simulate the patient-specific catheter navigation and radiofrequency ablation of ventricular tachycardia.

Since deliverable 10.4.1, work on the simulator prototype has focused on the development of a user interface and the integration of two software components : endovascular simulation and electrophysiology simulation.

The first component aims at modeling the deformation of catheters and guidewires inside vessels and to generate a realistic visualization of the visible X-ray images. The second component is focused on the simulation of electrophysiology. We have chosen the Mitchell-Schaeffer phenomenological model to represent the evolution of action potential on the myocardium.

The integration of those 2 software components is difficult because they should both run simultaneously in real-time. To this end, we have developed a multi-thread framework allowing to parallelize the computation of the catheter deformation and the cardiac electrophysiology while sharing a minimum number of information. We have also developed a user interface that can display X-ray images, 3D view of the heart and simulated electro-physiology signals measured at the tip of the catheter.

An example of simulation is provided starting from the endovascular navigation from the veina cava and finishing with the radiofrequency ablation of endocardial tissue inside the right ventricle.

Contents

1   Introduction

This deliverable (D10.4.2) is part of euHeart Workpackage 10 (WP 10) and describes the final status of the development of a prototype of an endovascular simulator of cardiac radiofrequency ablation. The objective is to simulate the patient-specific catheter navigation and radiofrequency ablation of ventricular tachycardia. The software must allow the real-time navigation of catheters inside the myocardium and the pacing, electrophysiology measurement and tissue ablation at the location of the catheters. It should also be interfaced with a specific hardware device (haptic device) that enables the user to feel the interactions of a catheter with the patient-specific virtual anatomy in real-time.

The task 10.4 was first handled by the company PolyDimensions. Following the bankruptcy of the company, INRIA took the lead on this task from Month 33 with the remaining resources.

This deliverable summarizes the novel development of the simulator since month 48 when deliverable (D10.4.1) was produced. To make it self-contained, we have written again the description of the simulator objectives and its main software structure, as formulated in D10.4.1. We have also provided a summary of the development for the endovascular navigation and electrophysiology navigation.

This deliverable is structured into 4 main parts:

- **Introduction**. The section provides the objectives of the simulator, and describes the main software and hardware components.

- **Endovascular Simulation**. It summarizes the advances in terms of simulating catheter navigation and X-ray rendering.

- **Electrophysiology Simulation**. It summarizes the electrophysiological model development and the simulation of extra-cellular potential.

- **Integration and User Interface**. It describes how catheter navigation and electrophysiology are integrated together and presents the user interface.

- **Results**. It describes one simulation scenario including navigation and radiofrequency ablation.

- **Conclusion and Perspectives**.

2   Simulator Objective and Setup

2.1   Objectives of Endovascular Simulation of Radiofrequency Ablation

The objective of task 10.4 is to create a prototype to simulate the ablation of cardiac tissue through catherization. The practical interest of such simulator are :

- to train cardiologists / electrophysiologists to perform cardiac radiofrequency ablation and more precisely ablation on VT cases.

- to rehearse a complex procedure based on patient specific datasets.

- to help the development and design of new catherization cardiac proce-
  dures that can be tested *in silico* on personalized cases.

We have chosen to develop this prototype in close link with the Workpack-
age 6 which is dedicated to the planning of cardiac radiofrequency ablation.
More specifically, the targeted procedure of this prototype is the simulation of
the radiofrequency ablation of tissue of patients suffering from ischemic Ventric-
ular Tachycardia (VT). This electrophysiological pathology is characterized by the
presence of scars (necrotic tissue caused by an infarct) in the myocardium sur-
rounded by a peri-infarct zone where necrotic, fibrosed and healthy tissue can
be found. The heterogeneity of tissue modifies the conduction velocity property
of the depolarization and repolarization waves as well as their distance (action
potential duration) as a function of the wave speed (restitution properties). Those
changes are such are under certain circumstances, spiraling waves may be cre-
ated around the scar regions thus leading to tachycardia and even in some cases
fibrillation.

The objective of the simulator prototype is to simulate the ablation of my-
ocardial tissues in the left ventricle in order to suppress the possibility to obtain
re-entry patterns.

A typical scenario of simulation would be the following :

1. Navigation of a guidewire from the femoral vein / artery into the right / left
   atrium. The guidewire is handled by a user through a hardware tracking
   device (see section2.2). The navigation is controlled by a simulated X-ray
   view of the thorax where the catheter and the heart are visible.

2. Insertion of a guidewire in the apex of right ventricle going through the
   tricuspid valve. The catheter inserted in this guidewire would be used for
   pacing the heart with various stimuli.

3. Insertion of a guidewire in the left ventricle next to the scar region. The
   catheter inserted in this guidewire would be used for performing radiofre-
   quency ablation and measuring extra-cellular potential in the endocardial
   surface of the left ventricle.

4. Simulation of pacing (overdrive, S1-S2) from the catheter in the right ven-
   tricle. The extra-cellular potential measurements in the left ventricle is sim-
   ulated and displayed on the screen.

5. Simulation of radiofrequency ablation from a catheter located in the left
   ventricle. The extent of ablated tissue depends on some power setting and
   the duration of ablation (which cab be controlled by a foot-pedal).

6. The simulation of pacing and ablation are iterated until the re-entry patterns
   can no longer be observed.

2.2 The Hardware Setup

The simulation hardware is mainly composed of :

- a screen where X-ray images and biosignals are displayed.

- a computer with mouse and keyboard. It consists of PC computer with 8 cores running Microsoft Windows and with a latest graphics card (with Graphical Processing Unit).

- a catheter tracking device inside which real catheters are inserted and manipulated by a user.

The hardware used to track guidewires and catheters has been acquired from the Mentice corporation as the VIST-C system. This system can be connected to a computer (see Fig 1). A C++ driver library allows to read the position of guidewires and catheters and to set the position of a brake in order simulate some force feedback.
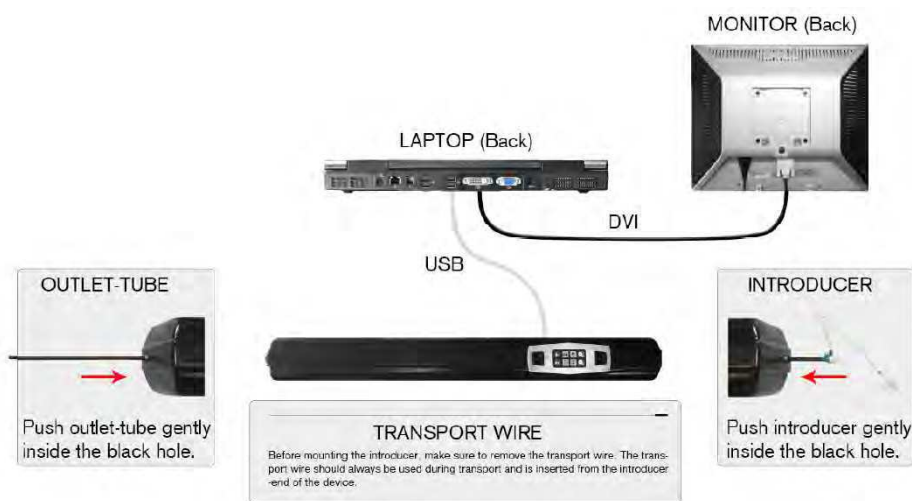

Figure 1: (Left) Hardware used to track up to three catheters and guidewire; (Right) Example of a user using the simulation setup.

This hardware setup is therefore quite sophisticated in order to simulate realistically the navigation of catheters inside the heart. Example of a user manipulating the simulator is shown in Fig. 2.

2.3 The Software Components

The software components that are needed to develop the simulator include :

- **Hardware driver**. This component allows to read the positions of catheters and guidewires from the Vist-C system and to set the brake status.

- **Catheter Navigation**. It takes as input the motion of real catheters and guidewires in the tracking device and simulate the motion of virtual catheters inside the vessels and the heart. In particular, it computes the contact between catheters and vessels walls and models the mechanical behavior of catheters.

Figure 2: (Left) Hardware used to track up to three catheters and guidewires; (Right) Simulation hardware setup.

- **X-ray Visualization**. It simulates the visualization of the thorax and catheters on a X-ray imaging system.

- **Cardiac Motion Simulator**. It simulates the cardiac motion of both ventricles and atria.

- **Cardiac Electrophysiology Simulator**. It simulates the propagation of transmembrane and extracellular potential inside the myocardium.

- **Pacing and Radiofrequency Ablation Simulation**. It models the injection of currents from pacing leads located inside the right ventricle and the action of ablation catheters.

- **BioSignals Visualization**. it visualizes the simulated electrophysiology signals on the screen.

The simulator prototype is being developed on the SOFA (Simulation Open Framework Architecture) platform[1]. SOFA is an open source framework mainly developed at INRIA which is dedicated to interactive medical simulation. The main features of SOFA is to be cross-platform, extremely modular and open to general purpose GPU (Graphics Processing Unit) computation. A document describing the features of SOFA can be found in this paper[ACF+07].

2.4 Main Challenges

We are planning to develop a new generation of cardiac endovascular simulator based on physics-based modeling of the cardiac electrophysiology. However, the following challenges needs to be met :

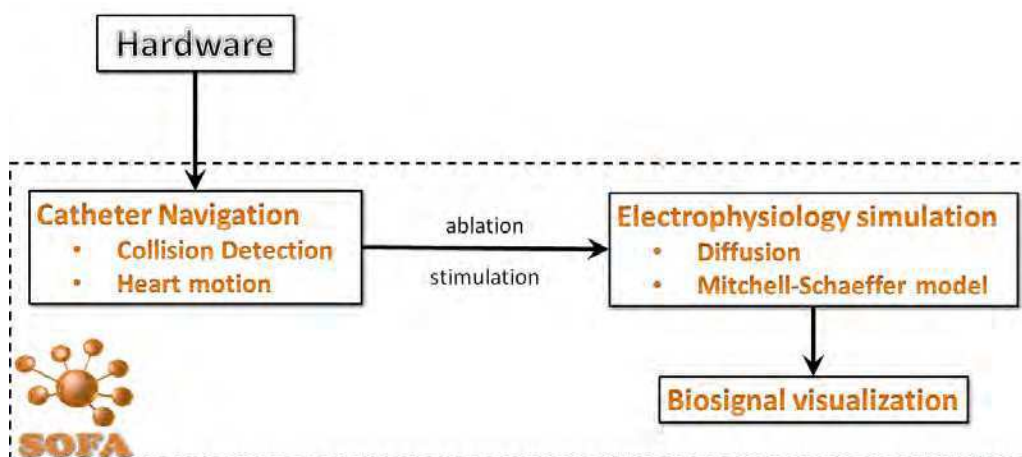[1]SOFA is available at this site: `www.sofa-framework.org/`

Figure 3: Structure of the simulator.

- **Real-time simulation of electrophysiology**. Simulation of cardiac electrophysiology usually requires very fine mesh of heart easily reaching almost a million (tetrahedral) elements. Thus simulation of electrophysiology propagation requires several hours or even days on large computers. A important challenge is to make this computation in real-time.

- **Simulation of Catheter Navigation inside moving structures**. Most simulation of catheter navigation has been done on static vascular structures. It is required to perform this navigation on a beating heart. Difficulty especially arises to properly compute the contact between catheters and vessel walls.

- **Software Integration**. This prototype requires to integrate two physical simulations (mechanical model of the catheters and electrophysiological model of the heart) together with a user interface.

3   EndoVascular Simulation

Taking advantage of the multi-modal representation of the objects in SOFA to describe the physics, graphics and collision model, we optimized and sped up all these steps of the simulation individually. Only improvement from the previous work described in Deliverable 10.4.1 are reported below.

3.1   Physics simulation of catheter

To model the wire-like structure of the catheter and guidewire, we use the beam element model described in [DCLN06] and [DMD$^+$08].

To improve the accuracy of the beam model while preserving the computational speed an algorithm that dynamically changes the density of the beam distribution along the structure has been implemented. The density of the beams

is decreased along the straight shape and increased along the curved shape. The density distribution of the beams is recomputed at every simulation step according to the shape of the structure.
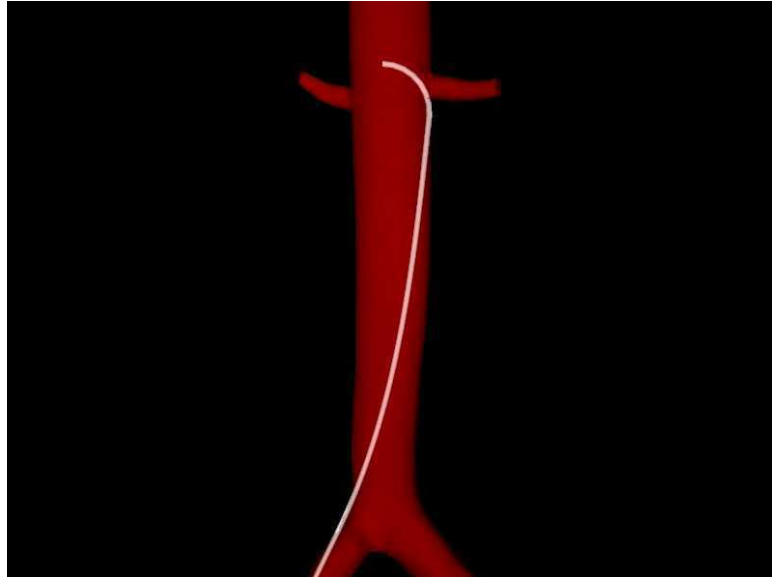
(a) visual model
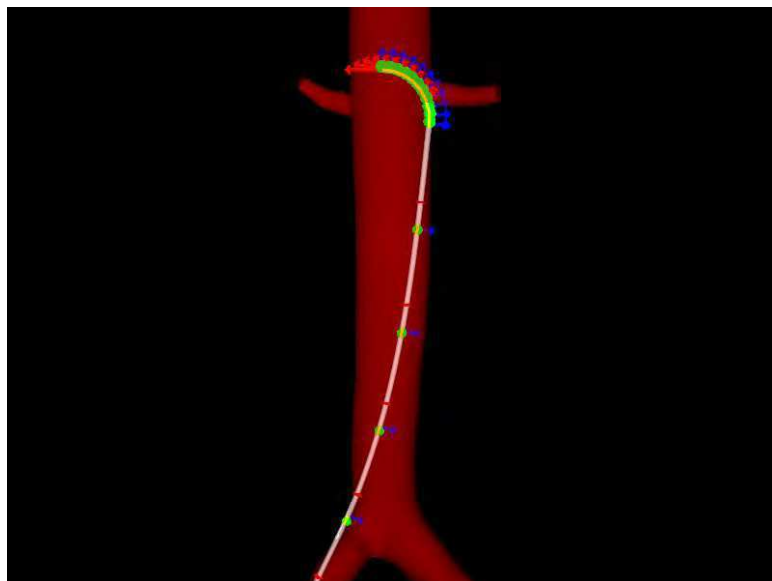
(b) beam model

Figure 4: beam distribution along the catheter structure.

The contacts between the catheter and the heart and the vessel walls are solved implicitly using the Lagrange multiplier techniques.

3.2 Collision Detection

We represent all the collision objects in the simulation as a bounding volume hierarchy of geometric primitives. These bounding volume hierarchy must be computed at every simulation step for all the deformable objects.

The catheter and guidewire collision structure are represented as a set of points and segments and all the other objects in the scene as a set of points segments and triangles.

To speed up the collision detection between the catheter structure and the animated surface mesh of the heart, we created a new coarse and smooth triangular mesh and recomputed all animation frames based on this new mesh. Decreasing the number of triangles accelerates the bounding volume hierarchy tree computation for the heart mesh. By smoothing the surface, the sliding of the tip of the catheter has been eased along the heart inner surface (endocardium). The drawback is of course that there is no longer a perfect match between the mesh used for graphics rendering and the one for collision detection.

3.3 Simulation of X-ray

The X-ray simulation is a two pass rendering algorithm that computes the path length traveled by each ray of the beam through every object and computes the intensity applying the radiation absorption law the intensity for each ray of the beam.

The X-ray algorithm has been improved with a silhouette shader effect that adds a thicker contour to the objects. This shader is applied only to some bones like vertebra and ribs to simulate how their inner structure appears in a X-ray image. To find the vertices on the silhouette, the shader tests if the angle between the point of view vector and the vertex normal is within a threshold close to 90 degrees. The opacity alpha value is increased for all the vertices on the silhouette. The silhouette is alpha blended with the X-ray rendering in one additional rendering pass.

| (a) | (b) |

Figure 5: Vertebra X-ray rendering with (a) and without (b) the silhouette shader.

Figure 6: Catheter endovascular navigation in the simulator.

4 ElectroPhysiology Simulation

The electrical activity of the heart is due to ion exchanges between cells in the myocardium. These cells can be polarized, i.e. there is a potential difference between the inside and the outside of the cell membrane.

As presented in Deliverable 10.4.1, different classes of models aim at modeling the electrophysiology at different scales. Biophysical models are complex models focusing on the cellular scale ([TNNP04]). Phenomenological models ([RF61], [AP96], [FK98], [MS03]), derived from biophysical models, capture the action potential dynamics at the organ scale. Finally, Eikonal models ([Kee91], [Jac10]) correspond to a static non-linear PDE for the depolarisation time derived from the previous models. A phenomenological model, called the Mitchell Schaeffer model [MS03] is used in this work.

4.1 Phenomenological Model: Mitchell Schaeffer model [MS03]

As all phenomenological models, it has few parameters, and each of these parameters has a physiological meaning. The model equations are reminded below:

$$
\begin{cases}
\partial_t V_m = div(D\nabla V_m) + \dfrac{zV_m^2(1-V_m)}{\tau_{in}} - \dfrac{V_m}{\tau_{out}} + J_{stim}(t) \\[4mm]
\partial_t z = \begin{cases}
\dfrac{(1-z)}{\tau_{open}} & \text{if} \quad V_m < v_{gate} \\[3mm]
\dfrac{-z}{\tau_{close}} & \text{if} \quad V_m > v_{gate}
\end{cases}
\end{cases}
\tag{1}
$$

where V_m is a normalized transmembrane potential and z is the gating variable associated to the sodium ion influx, thus depicting the repolarization phase.

The diffusion term is defined by an 3x3 anisotropic diffusion tensor $D = d \cdot diag(1, r, r)$ so that the conductivity in the fiber direction is 2.5 times greater than in the transverse plane ($r = \frac{1}{(2.5)^2}$). d is the diffusion coefficient.

4.2 GPU Implementation

All electrophysiology equations and the associated solvers have been implemented on GPU. A simulation on GPU uses the graphic card (GPU) of the computer to perform computations instead of using the Central Processing Unit (CPU). However, an efficient implementation on GPU is very complex since every step of the computation has to be cleverly shared out among each processing unit. In our approach, we decided to rely on CUDA toolkit (dedicated for NVIDIA's GPU).

Using a lumped integration method, the ionic term of Mitchell Schaeffer is a nodal value, i.e. computed at each vertex separately. Therefore this part of the computation is a highly parallel task.

Due to strong neighboring dependencies, the memory access during the computation of the diffusion term is more sensitive. An innovative and very efficient algorithm has been developed in [ACF11] to tackle the writing conflict issue.

4.3 Extra-cellular Potential from Mono-Domain Models

In the context of cardiac arrhythmia, catheters are inserted inside the heart cavities during the intervention. Some of these catheters can explore electrical signals on the surface of the heart wall (endocardium). These electrical signals corresponds to the extra-cellular potential, noted U_e.

Since it captures the action potential V_m (also called transmembrane potential), the Mitchell Schaeffer model is a "mono-domain" model. Only "bi-domain" models can simulated both intra-cellular U_i and extra-cellular U_e potentials (where $V_m = U_i + U_e$). Using the Mitchell Schaeffer model, we should therefore not be able to simulate the extra-cellular potential measured with a catheter.

However, Coudière et al. propose in [CCT12] a method to compute the extracellular potential from an extended mono-domain model. In this work, the homogenized bi-domain equation is written as a function of V_m, U_i and U_e:

$$A(C\partial_t V_m + I_{ion}(V_m, w)) = \text{div}(G_i \nabla U_i) \qquad (2)$$
$$A(C\partial_t V_m + I_{ion}(V_m, w)) = \text{div}(G_e \nabla U_e) \qquad (3)$$

where A, C, G_i, G_e, I_{ion}, w are, respectively, the ratio of surface of membrane per unit volume, the membrane capacitance per unit area, the intra- and extracellular electrical conductivity tensors of the tissue, the total ionic current and the state variable of the cell membrane.

Based on the assumption of equal anisotropy ratio, i.e. $G_i(x) = \lambda G_e(x)$, on the normalization condition:

$$\forall t > 0, \quad \int_\Omega U_e(x, t) \, dx = 0 \qquad (4)$$

it can be shown that, the extra-cellular potential U_e can be expressed as follows:

$$U_e(x,t) = \frac{\lambda}{1+\lambda}\frac{1}{|\Omega|}\int_\Omega (V_m(y,t) - V_m(x,t))\,dy \tag{5}$$

Mono-domain models are only expressed according to the transmembrane potential. This method allows to recover an estimation of the extra-cellular potential from the transmembrane potential and can therefore be named "extended mono-domain."

Considering a bipolar catheter, a first approximation of the Equation 5 is:

$$U_e(x,t) \approx U_e(x_1,t) - U_e(x_2,t) \tag{6}$$
$$U_e(x,t) \approx -\frac{\lambda}{(1+\lambda)}(V(x_1,t) - V(x_2,t)) \tag{7}$$

where $U_e(x_1,t)$ is the transmembrane potential measured at the tip of the catheter and $U_e(x_2,t)$ is the transmembrane potential measured at the closest neighboring point representing the second electrode of the catheter. This assumes that the orientation of the catheter is taken into account which is work in progress.

5 Integration of ElectroPhysiology & Navigation Simulation

5.1 Multithreading Approach

To integrate the electrophysiology and the navigation simulation we exploited the CPU parrallelism and we decided to use a tasks scheduling architecture (Fig. 7). That's an efficient way to scale the computation to all the CPU cores available on a machine.

The work load is broken down into tasks and a scheduler is used to map the tasks on each single CPU.

A task must be consider as a block of code that executes a fraction of the work independently of other tasks and can run concurrently. On a multi-core processor it's possible to execute as many tasks simultaneously as the number of CPUs.

The scheduler creates a thread for each CPU, takes care of the threads synchronization and maps the tasks execution into threads, finding a new task to start when one finishes. This becomes very powerful considering that a task can itself create and spawn new tasks.

5.1.1 Main Simulation Tasks Design

We splitted the simulation in three main tasks: endovascular navigation, electrophysiology and graphics rendering. To reserve the GPU for the electrophysiology compuatation and considering the graphics task is only a small fraction of the computation time required for the electrophysiology we decided to execute this two main tasks serially. The endovascular navigation is executed in parallel with the electrophysiology.
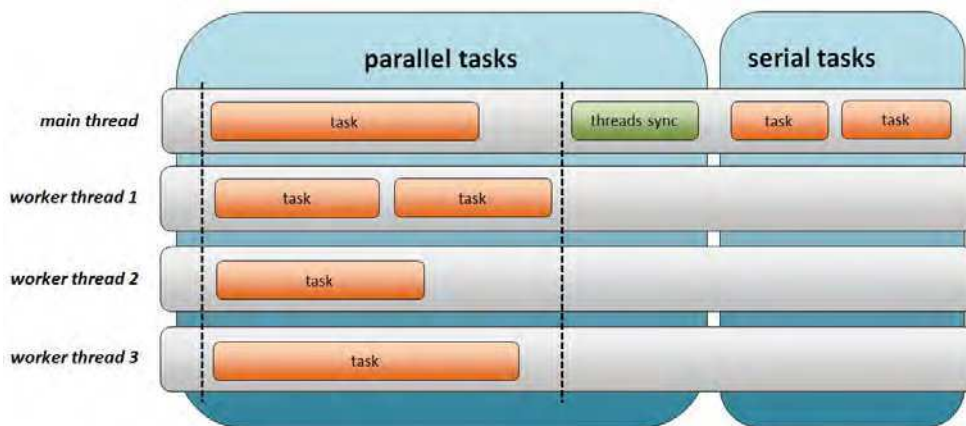
Figure 7: Tasks and scheduler architecture.

The main loop of our multithreading architecture is splitted in a a parallel part executing concurrently the endovascular navigation and electrophysiology simulations and a serial part executing the graphics rendering (Fig. 8).

5.1.2   Communication between Tasks

An important aspect to take in account in a multi-thread design is the data synchronization between concurrently tasks and to find the best tradeoff between keeping the serial execution time at a minimum and avoid using the synchronization locks.

We manage the sharing of data between the tasks without being bound by synchronization locks. To avoid the use of synchronization locks each main task has its own copy of the data to share and the data synchronizatin is executed in serial just before the graphics task is executed (Fig. 8). The choice of running the graphics task serially prevent us the need of synchronizing the data between graphics and the other main tasks and reduce the amount of data to exchange after each simulation loop.

5.1.3   Example: Interaction with a Catheter

We will now illustrate this communication between the two threads with an example. One feature of our simulator is to be able to interact with the electrophysiology using the catheter. This is a crucial feature since it allows the user not only to measure the computed extra-cellular potential (see Section 4), but to stimulate or carry the ablation in the target area as well. However, this requires many exchanges of data between both electrophysiology and navigation threads.

For more flexibility, different meshes can be used for electrophysiology and for navigation (collision detection). First, the collision detection is done in the navigation thread. Since the user has be able to interact with the electrophysiology using the catheter, we need to send the collision information to the electrophysiology thread.
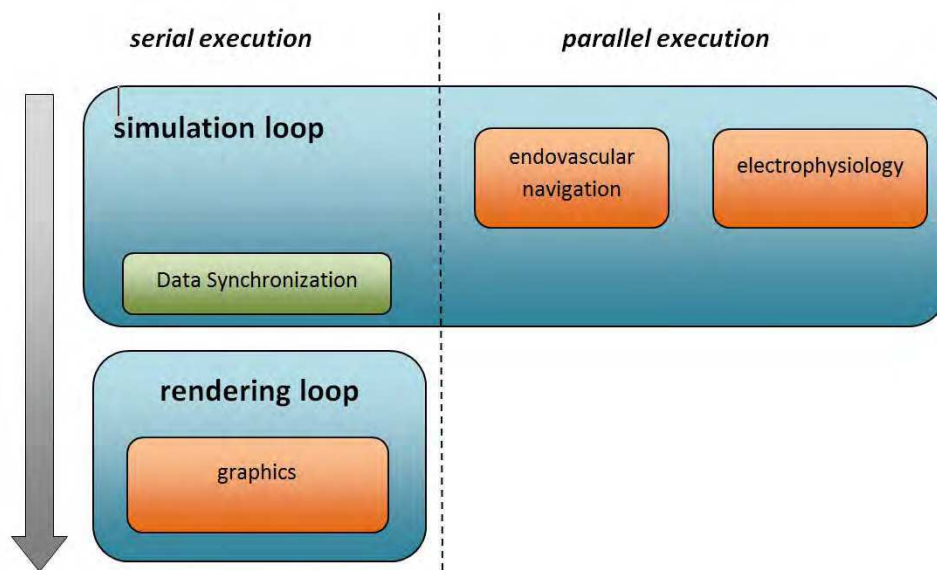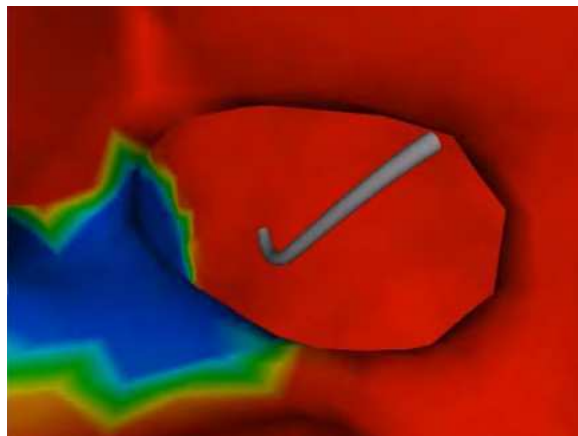
Figure 8: multi-thread architecture.

Figure 9: Catheter in contact with the heart wall.

If different meshes are use for electrophysiology and navigation, the location of collision on the electrophysiology mesh can be far from the location of collision on the navigation mesh. Based on this information from the navigation thread, the colliding triangle on the electrophysiology mesh is searched. To do so, the projection of the catheter tip is searched on the surface.

Once the colliding triangle is found, the extra-cellular potential can be computed using the method of Coudière et al. [CCT12]. The user can also decide to inject a stimulation current or to carry out an ablation.

5.1.4 Synchronization of Cardiac Motion

As explained in the previous report, we recorded the motion field of the myocardium for one heart beat. The positions of the mesh are updated to simulate the muscle contraction based on this record. The mechanical contraction is now synchronized with the electrophysiology computation.

5.2 User Interface

The graphical user interface has been developed using the Qt framework library. In its current version, it is a basic interface that has been designed to display the most relevant information to the user either expert or not. Three views in different windows are provided to display the X-ray rendering of the scene the electrophysiology signals and a 3D view of the heart. All views are updated in real-time during the graphics task execution. Note that the 3D view is mostly for not expert user and for debug purposes and should not be displayed for simulation under real condition.

The main window displays the X-ray rendering view and some command buttons that allows the control of the simulation. It's possible to load scenes representing different cases or different positions of the catheters. It is possible to start stop and reset the simulation, and capture screenshots. The user can use the mouse to rotate around the 3d scene but to better control the X-ray tube motion of the fluoroscopy we planned to use the joysticks and the pedals provided by the hardware device.

The electrophysiology window is a 2D view where the simulated extracellular potential signals measured on the endocardium of the ventricles by electrode catheters are plotted.

The third window displays a 3D map of the heart. It's used to show and map the electrical activity on the two ventricles and display with red dots the points on the heart surface already ablated by the catheter. In the future, we plan to simulate the reconstruction of endocardial surfaces based on contact mapping systems such as NavX and Carto systems.

Main window displaying the X-ray view

3D map heart view
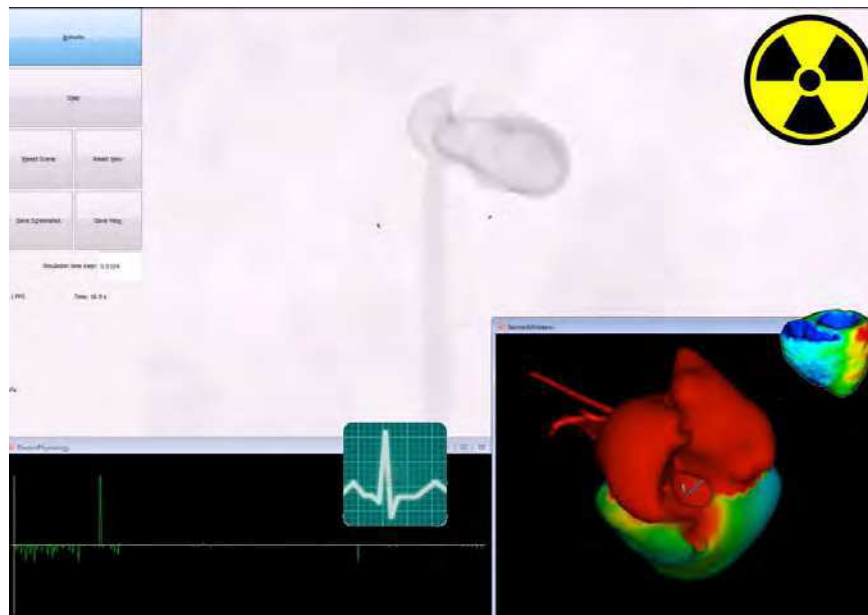

Electrophysiology signals view

Figure 10: View of the simulator GUI.

6   Results of Simulation

In this section, a generic scenario will be detailed. This scenario aims at showing the features of our training simulator.

First of all, the user has to insert a catheter inside the device (see adjacent figure). In the simulation, the catheter is inserted in the inferior veina cava.


Once the catheter is inserted, the user can navigate through the vascular system. At this point of the simulation, the user can obviously not measure any electrical signal. The navigation in the inferior veina cava leads to the heart: in the right atrium (see adjacent figure).
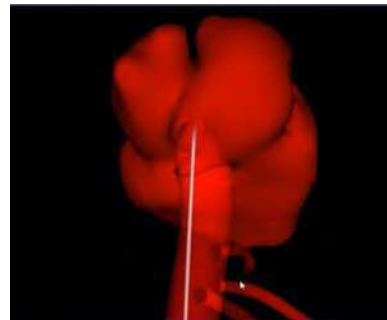

Inside the heart cavities, the user can finally interact with the electrophysiological model. As soon as the catheter collides with a wall, the catheter measures the local electrical activity (see electra-cellular potential signals in the adjacent figure).
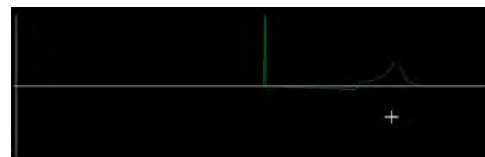
Secondly, the user can interactively perform an ablation of tissue next to the catheter if that catheter is in contact with the myocardium. The figure shows an area that has been ablated in red. This area does not conduct the electrical wave any longer.
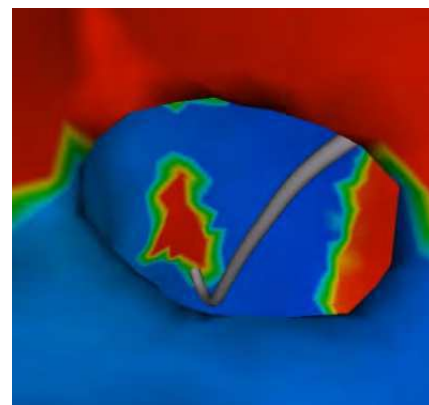
In radio-frequency ablation proce-
dures, pacing is also an important step
that allows cardiologists to evaluate
the outcome of the ablation. This fea-
ture is also available in our training
simulator. The adjacent figure shows
a stimulation initiated by the catheter
(depolarization wave starting in blue).
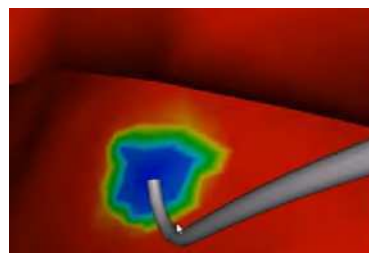
7 Discussion and Conclusion

7.1 Conclusion

The final status of Task 10.4 has been presented with the description of the 2
main components (endovascular simulation and electrophysiology simulation)
and their integration.

From the work described in Deliverable 10.4.1, the main development has
been related to the improvement of each component, their integration and the
development of a basic user interface. For the simulation of endovascular nav-
igation, the focus has mainly been on the optimization of the number of beams
representing each catheter, the use of different meshes for the collision detec-
tion and graphics rendering and the improvement of X-ray visualization with a
silhouette shader.

For the electrophysiology simulation, real-time computation has been achieved
thanks to a GPU implementation of a phenomenological model on a coarse
mesh. Additional developments include the simulation of extracellular potential
by using an extended monodomain approach.

Finally, the integration of the two real-time physical components (catheter
navigation and electrophysiology) has been achieved by running both tasks in
separate threads and by exchanging a minimum amount of data. A basic user
interface has been created allowing to switch between a X-ray navigation system
and a 3D view of heart with ablated regions. Also the user interface allows to
display extra-cellular potentials measured at the tip of the catheters.

To conclude, the current status of the simulator prototype integrates all main
software components required for endovascular simulation of radiofrequency ab-
lation. Using a regular PC with a high end graphics card, we have shown that it is
possible to manage both physical simulation in real-time. There are still several
aspects of the simulator that need to be improved and that are the topic of the
next section.

7.2 Limitations and Perspectives

The current prototype has undergone a limit number of tests. It is important that
a simulation scenario be clearly defined with a clinical interest. A first possible
target of simulation would be to ablate tissue in the right ventricle in order to
eliminate an ectopic focus creating extra systolic beats. Another possible target
is the ablation in the ventricle in case of a Wolff-Parkinson-White syndrome. One

difficulty to achieve this type of simulation is to simulate the insertion of catheters through the mitral or tricuspid valves.

Regarding more technical aspects, there are a number of developments that are needed to improve the simulation:

- **Endovascular Navigation**

    - Optimization of the collision model to improve the computation performance.

    - A simplified flow model inside the veins and arteries should be introduced to simulate the injection of an X-ray dye.

    - The mechanical effects of the mitral and tricuspid valves could be added.

- **Electrophysiology Simulation**

    - Better simulation of extra-cellular potential taking into account the various types of electrode catheters.

    - Simulation of radiofrequency ablation. The extent of the ablated tissue around the RF probe must be better modeled by taking into account the applied power and the duration of application as well as the applied force.

- **Graphics User Interface**

    - Improve general appearance and provide multiple screens interface.
    - Improve display of electrophysiology signals
    - Ability to display medical images with 3D mesh
    - Ability to control the C-arm bearing the X-ray tube with a joystick located on the hardware device.
    - Simulate endocardial surface reconstruction as done for Carto or NavX systems.

After the completion of the euHeart project, we plan to further develop the simulator. Possible exploitation of the simulator is planned in one additional FP7 project proposal (related to atrial fibrillation). Possible technology transfer towards a commercial company such as Mentice will be discussed in the coming months.

8 Acknowledgements

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