Simulated vascular reconstruction in a virtual operating theatre

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We present an experimentation environment that combines interactive visualisation of patient specific vascular medical data with a flow simulation environment into an interactive exploration environments that provides a virtual operating theatre in which vascular reconstruction procedures can be simulated.

1. Introduction: the Virtual Laboratory

The research presented here is part of a larger project called the "Virtual Laboratory" (VL, [1]). The VL enables scientists at geographically distributed locations to collaborate and allows seamless use of distributed hard- and software resources. The goal of the VL project is to provide a hard- and software infrastructure for experimentation. To that end, the VL framework offers data storage, data acquisition, simulation and visualisation facilities that can be combined into one interactive experimentation environment (see Figure 1).

In many scientific computing areas, the spatial and temporal complexity of the problem under investigation is too high to analyse analytically or numerically. For these situations, *exploration environments* provide essential methods to explore the problem in a way that allows a researcher to comprehend the information it contains. Exploration environments combine *presentation* and *interaction* functions into one system that together allow exploration of an experiment's behaviour. The data presented to the user as a result of an experiment is either time invariant (the data is loaded and never changes, for example; data that is collected with a data acquisition device) or time variant (the data changes over time, for example; data that is produced by a dynamic process such as a computer simulation).

1.1. Simulated vascular reconstruction: a full-blown case study

The VL architecture is validated by analysis of a prototypical case study of *simulated vascular reconstruction*. This application combines visualisation, simulation, interaction and real-time constraints in an exemplary fashion. By a detailed analysis of the spatial and temporal characteristics of the test case we attempt to recognise generic elements for the design of a computational steering architecture. We begin with a description of the test case.

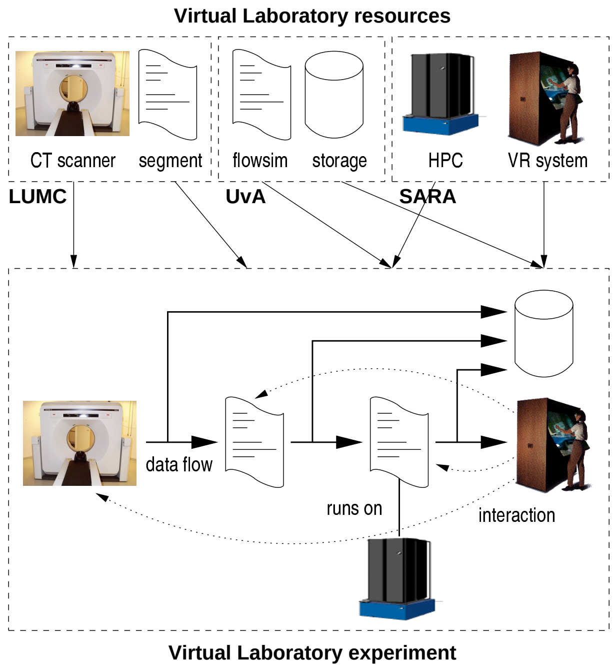

Figure 1. Schematic representation of how Virtual Laboratory (VL) resources distributed over different locations are combined into an experiment.

1.2. Simulated vascular reconstruction

Vascular disorders in general fall into two categories: *stenosis*, a constriction or narrowing of the artery by the buildup over time of fat, cholesterol and other substances in the vascular wall, and *aneurysms*, a ballooning-out of the wall of an artery, vein or the heart due to weakening of the wall. Aneurysms are often caused or aggravated by high blood pressure or wall shear stress. They are not always life-threatening, but serious consequences can result if one bursts.

A vascular disorder can be detected by several imaging techniques such as X-ray angiography, MRI (magnetic resonance imaging) or computed tomography (CT). Magnetic resonance angiography (MRA) has excited the interest of many physicians working in cardiovascular disease because of its ability to non-invasively visualise vascular disease. Its potential to replace conventional X-ray angiography that uses iodinated contrast has been recognised for many years, and this interest has been stimulated by the current emphasis on cost containment, outpatient evaluation, and minimally invasive diagnosis and therapy [2].

A surgeon may decide on different treatments in different circumstances and on different occasions but all these treatments aim to improve the blood flow of the affected area [3]. Common options include thrombolysis, balloon angioplasty, stent placement or vascular surgery. A surgeon resorts to vascular surgery when less invasive treatments are unavailable. In the case of an *endarterectomy* the surgeon opens the artery to remove plaque buildup in the affected areas. In vascular bypass operations, the diseased artery is shunted using a graft or a healthy vein harvested from the arm or leg.

The purpose of vascular reconstruction is to redirect and augment blood flow or perhaps repair a weakened or aneurysmal vessel through a surgical procedure. The optimal procedure is often obvious but this is not always the case, for example, in a patient with complicated or multi-level disease. Pre-operative surgical planning will allow evaluation of different procedures *a priori*, under various physiological states such as rest and exercise, thereby increasing the chances of a positive outcome for the patient [4].

1.2.1. What is needed?

This test case contains all aspects of an interactive dynamic exploration environment that are of consequence in the construction of a generic dynamical computational steering architecture. Our aim is to provide a surgeon with an environment in which he/she can explore the effect of a number of different vascular reconstruction procedures. Such an environment requires the following:

- The environment should be able to present the surgeon with patient specific data at sufficient fidelity so that the patient's infliction can be located. To obtain best understanding on the nature of the problem, the surgeon is presented with a 3D rendering of data obtained from medical scanners (such as CT or MRI) using unambiguous visualisation methods. Note that *visual* realism is not the primary goal here; what is more important here is *physical* realism, and then only of particular issues in fluid flow, as discussed later.
- The environment should allow the surgeon to plan a surgical procedure. As the patient's data is presented in 3D, the environment should also allow the surgeon to interact with this data in 3D, offering methods that allow any surgical procedure to be simulated.
- The environment must be able to show the effect of a planned surgical procedure. As the aim of the procedure is to improve the blood flow to the affected area, the surgeon must have some means to compare the flow of blood before and after the planned procedure. A simulation environment is used to accomplish this that calculates *pressure*, *velocity* and *shear stress* of blood flowing through the artery. The visualisation environment presents the results of the simulations while the exploration environment allows inspection and probing (qualitatively and quantitatively) of the simulation results (i.e. means should be provided to perform measurements, annotate observations, inspect the flow of the blood stream, etc.).

The environment as a whole should be *interactive*, or in other words; it should be fast enough such that a surgeon does not have to wait for the simulation results. The remainder of this paper addresses our approach to achieve this.

2. Implementation of a simulated vascular reconstruction operating theatre

Parts of the components mentioned in the previous section have already been implemented in the course of previous projects. Others require minor adaptations to fit into our dynamic exploration architecture. In the following subsections we will briefly discuss the current status of the visualisation and exploration environment, the interaction environment, the simulation environment and the middleware that combines these together.

2.1. VRE: immersive static exploration

We have previously built a static exploration environment called the *Virtual Radiology Explorer* (VRE [5,6]) which is capable of visualising medical CT and/or MRI data in stereoscopic 3D. Often, data sets acquired with CT or MRI are displayed and evaluated from various perspectives or at different levels, including sets of single slices, stack mode (cine loop) interactive representation of sets of slices, or multi-planar reformation (MPR) represented as single slices or interactive cine loops. Despite the increased possibilities of acquiring data, clinical use of 3D rendering has been hampered by insufficient computing capacity in the clinical environment.

The VRE environment allows medical data from hospitals to be preprocessed on remote high performance computing (HPC) systems for 3D visualisation. High speed networking initiatives such as the *GigaPort* project [7] allow hospitals to make interactive use of HPC visualisation techniques for patient diagnostics. An example of the clinical use of 3D rendering is simulated endoscopy. Simulated endoscopy has several advantages over mechanical endoscopy (shorter acquisition times, increased patient comfort, higher cost-effectiveness, no complications of endoluminal instrumentation, field-of-view extending beyond the surface). In addition, simulated endoscopy can be used in virtual spaces that cannot at all, or only after violation of normal anatomical structures, be reached by mechanical (endo)-scopy.

The VRE environment provides various such methods for the visualisation of medical scans, including volume rendering (using SGI's *Volumizer* [8]), surface rendering (using Vtk [9] and OpenGL [10]), interactive clipping and surface mapping techniques. Mechanisms have been added that allow the VRE environment to be run in a CAVE Virtual Reality theatre [11] or on an ImmersaDesk, allowing the VRE environment to be used in the radiology department.

2.1.1. VRE+: immersive dynamic exploration

VRE+ extends VRE with methods that allow dynamic exploration. Various methods are added to visualise the results of time variant processes (e.g. computer simulations) while they are running. Multi-modal user interaction methods[1] are implemented that allow researchers to interact with these time variant processes to control their behaviour.

2.2. Fluid flow simulation: the lattice-Boltzmann method

The lattice-Boltzmann method (LBM) is a mesoscopic approach for simulating fluid flow based on the kinetic Boltzmann equation [12]. In this method fluid is modelled by particles moving on a regular lattice. At each time step, particles propagate to neighbouring lattice points and re-distribute their velocities in a local collision phase. This inherent spatial and temporal locality of the update rules makes this method ideal for parallel computing [13]. During recent years, LBM has been successfully used for simulating many complex fluid-dynamical problems, such as suspension flows, multi-phase flows, and fluid flow in porous media [14]. All these problems are quite difficult to simulate by conventional methods [15].

The data structures required by LBM (cartesian grids) bare a great resemblance to the

[1] Our system currently supports context sensitive interaction by voice, hand gestures and direct manipulation of virtual 3D objects.

grids that are generated by CT and MRI scanners. As a result, the amount of preprocessing can be kept to a minimum which reduces the risk of introducing errors due to data structure conversions. In addition, LBM has the benefit over other fluid flow simulation methods that flow around (or through) irregular geometries (like a vascular structure) can be simulated relatively easy. Yet another advantage of LBM is the possibility to calculate the shear stress on the arteries directly from the densities of the particle distributions [16]. This may be beneficial in cases where we want to interfere with the simulation while the velocity and the stress field are still developing, thus supporting fast data-updating given a proposed change in simulation parameters.

2.3. Lattice-Boltzmann grid generation and editing

As mentioned earlier, the basic structure of the grids used in LBM bare great resemblance to the medical scans obtained from a patient. To convert the medical scans into LBM grids, the raw data from the medical scanner is first segmented so that only the arterial structures of interest remain in the data set (see also Figure 2). Sufficient contrast must be present in the scans to do this accurately, either using MR *time-of-flight* or through contrast enhancing fluid injections as in CTA. The segmented data set is then converted into a grid that can be used in LBM; boundary nodes, inlet nodes and outlet nodes are added to the grid using a variety of image processing techniques.

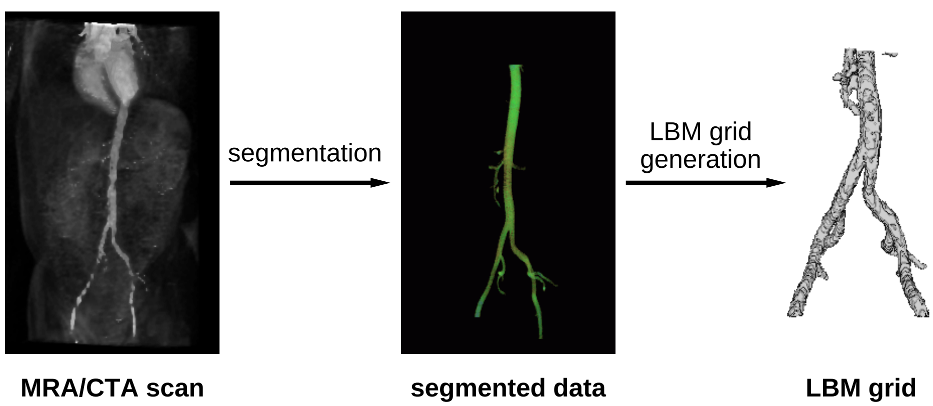

Figure 2. LBM grids are generated from raw medical scans through a combination of segmentation and image processing techniques.

A surgical procedure is simulated through the use of a 3D grid editor. This system allows a user to interactively add and/or remove areas in the LBM grid, according to the procedure that is simulated. Similar grid generation techniques as described above are used to ensure the grids comply to the demands imposed by LBM.

2.4. Middleware

The different components involved in our interactive simulation system are combined in a VL experiment as shown in Figure 1. A middleware layer abstracts the fact that the different components run on heterogeneous computing systems at different geographical locations and handles all communication between them. We are currently experimenting with the High Level Architecture (HLA, [17]) for this middleware layer. By using HLA, the different components can run asynchronously while spatial and temporal effects can be controlled.

3. Discussion and future work

We have presented our views on dynamic exploration environments that support distributed interactive simulation. The simulated vascular reconstruction case study described in this paper is presented as a test case to validate this environment. The prototype of this system (VRE) has been evaluated by radiologists and physicians at the Leiden University Medical Center (LUMC). Based on their feedback, we have extended VRE with multi-modal interaction techniques and distributed simulation support.

The simulated vascular reconstruction operating theatre will be validated through a comparison of fluid flow simulation results and the results of other simulation methods as well as *in vivo* measurements of blood flow through phantom structures and pre- and post-operative MRA scans.

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