Toward an Intelligent Data and Visualization Desk for Endovascular Surgery

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Abstract

The Intelligent Data and Visualization (IDV) Desk is a system which combines numerical simulation with high-definition visualization and large data storage into a single desk. These three sub-systems are interdependent. They are connected to the network to get external information from various imaging systems and to provide data mining and data processing. The IDV desk is used in endovascular applications. The challenge is to provide to surgeon an interface to access all the data of interest at once on multiple displays. The interface must be friendly and very intuitive to the surgeon.

1 Motivations

In industry, computational applications are traditionally used in the design process: for example, aeronautic, energy and transport industries, are among the most demanding for such scientific tools. The design cycle can last from one year to more than twenty years and it relies on proven engineering principles. Also, computational tools are becoming part of the decision process in many new important areas such as medical surgery. In this context, there are two dramatic differences from standard engineering processes: every situation is different and the computational solution should be patient specific. While there are known families of artery diseases, many factors such as age, weight, general physical condition, or genetic background of the individual create large variability in artery conditions affecting the flow, the elasticity of the wall, or the geometry of the lumen. Simulations should be completed rapidly in order to offer the possibility to investigate different scenarios in the surgery and to integrate multidimensional data interactively. Simulations in medical surgery are often image based and should provide essential information graphically. The end user might not be an engineer. Therefore, the application interface should be designed to integrate seemingly into a surgeon's working environment. When considering endovascular surgery one should perform an image based simulation extracting first information from an angiogram and then incorporate some phases contrast MRI data or ultrasound data. This simulation may, for example, create a segmented image that is associated to shear stress or pressure measurements at the artery wall, or indicate zone of recirculation that are potentially dangerous to the patient. Finally, in these types of applications, the uncertainties on data as well as on image based simulation are fairly high. It is important that a simulation comes with safeguards in the format of error estimator, statistical measurement, or graphic indicators.

In such application areas, simulation will be considered as a mature tool if and only if its outcome can be processed by an end user who is neither a computer scientist nor a mathematician. It demands that the simulation is robust enough to run with a broad variety of input data, can detect errors, and provide indicators on uncertainties [16]. But too much information kills information: the problem is to deal with the abundance of data and possible simulation scenario. Ideally, the end user should have all the information needed at his fingers tips and should not waste time with technicalities. While our approach is general and may apply to other medical and non medical areas, we will concentrate in this paper on the endovascular surgery application.

According to the American Heart Association, cardiovascular disease is an underlying cause of death accounted for 37.3 percent of all deaths, or one of every 2.7 death in the United States in 2003. Statistics from 2006 show that heart disease is still the number one killer in the US. Many of these deaths are due to the rupture of an aneurism or the narrowing of blood vessels, also called stenosis, that lead to insufficient blood supply to vital organs [1, 2].

Endovascular surgery is a relatively new procedure to treat such problems that may develop in blood vessels. In recent years, we have seen the development of intravascular balloons, stents, and coils that can

be put in place through arteries with minimum invasive procedures. Endovascular surgery is performed by radiologists, neurosurgeons, cardiologists and vascular surgeons. This surgery is essentially guided by imaging such as X-ray techniques.

The challenge is to provide to surgeons an interface to access all the data of interest at once on multiple displays. The quantity of data to be accessed is huge. We are dealing with a large spectrum of image modalities and numerical formats. The system should provide fast access to the data because surgeons have limited time to decide on the procedure. The interface must be friendly and very intuitive to the surgeon. Finally there are additional requirements such as ensuring that the patient data are kept private (HIPAA - Health Insurance Portability and Accountability Act) and the system is reliable.

The individual subsystems that are shown in this paper, namely the visualization, the simulation, and the database are all freely available to some extent. The novelty of the system presented in this paper is to combine all this elements into a single integrated solution. To our knowledge, there is no related work to refer to.

We are presenting in this paper our Intelligent Data and Visualization (IDV) desk concept that is a system which combines numerical simulation with high-definition visualization and large data storage into a single desk. The system has been conceived starting with the endovascular application in mind. In this paper we will describe successively our hardware and software solution in section 2, the simulation engine and database/web interface aspect in section 3. Section 4 will illustrate our application scenario. In section 5 we will summarize our finding and comment on our current ongoing work.

2   Hardware/Software solution

Our basic idea was to design a standalone solution that can be connected to the network to get external information from various imaging systems, and provide most of the services in terms of data mining and data processing. Next, we will describe the hardware configuration of the IDV desk.

2.1   Hardware implementation

The IDV desk is designed to be cost effective and rely on the integration of off-the-shelf components.

We have started from a standard computer desk and used four workstation tower water cool computers. These components are mounted on supports hanging below and on each side of the desk. An array of two

rows by three columns of 22 " wide screen monitors are placed on the table, in such a way that their orientation can be adjusted by the user.

This setup allows at the same time customization of the desk and a large flexibility on the usage of the system. Figure 1 shows the IDVdesk.
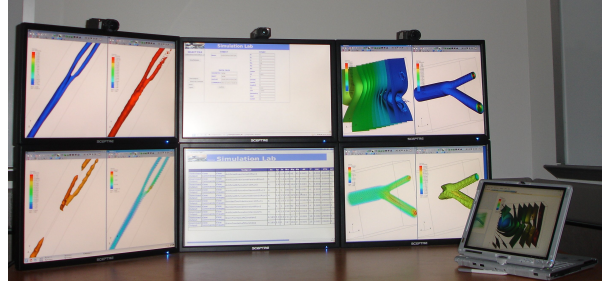

Figure 1: IDV desk in action.

Each workstation is based on multi-core processors on each workstation with 2 to 8 gigabytes of RAM.

With the idea of performance computing and parallel processing in mind, we interconnected the workstations by a Gigabyte Ethernet switch. Three of the PCs are used for parallel simulation as well as parallel visualization. Each of these has a high-end graphic card with two DVI outputs and controls a column of two displays. One of the drawbacks of this assembly is the heat generated by the graphic cards and the multi-core processors. In order to limit the noise that would be generated by a conventional fan, we use water cooling to remove the heat from the workstations. Overall the IDV desk hardware is fairly silent to the user and can be installed in a standard office.

The fourth workstation is a data server with two sets of disks. It has two slow 7200 rpm disks with large capacities for storage (1 TB) and one fast 10000 rpm disk with less storage (150GB). The goal of the fast disk is to pre-fetch the data to speed up data mining. This amount of storage is adequate for 1500 patient studies.

The overall cost of the IDV desk is less than $12 K for 16 cores and 16 GB of main memory. From the hardware point of view, it is a flexible system where each component can be customized to some degree. To make this system effective, we had to combine several interesting open source software. We will describe in the next section the various software components of the system.

2.2   System Software Solution

The idea behind the IDV desk is to allow the simulation and the visualization of multidimensional

data. The system should be flexible on the software side as much as it is on the hardware side. The goals are to compute, store, visualize, and retrieve data in a secure way.

As for the hardware, each component is chosen to perform a specific task. The underlying OS running on the three workstations in charge of the visualization and the computation is Linux. It allows to have a system that is customizable, secure and it is one of the most used operating systems for running parallel computations. It is also more stable for 64 bits architecture than some other OS. The database is built on top of Windows Server 2003. For the ease of development of the database architecture, and the tight integration with its environment, the choice was made to develop the database with SQL Server 2005.

The other components that we integrate in the IDV desk are off-the-shelf softwares distributed with open source licenses. For instance, to avoid to be encumbered by several mouse and keyboards for each workstation, we can control the IDV desk with a single keyboard and a single mouse thanks to the software Synergy http://synergy2.sourceforge.net/. Synergy allows sharing a single mouse and keyboard between multiple computers with different operating systems, each with its own display, without special hardware. It is intended for users with multiple computers on their desk since each system uses its own monitor(s). Redirecting the mouse and keyboard is as simple as moving the mouse off the edge of the screen. Synergy also merges the clipboards of all the workstations into one, allowing cut-and-paste between them.

An other way of controlling the information that is displayed on the IDV desk is to use a laptop or a tablet PC. This allows the control of the important data remotely. In order to perform this task, we need to achieve remote desktop control. Using the software such as rdesktop/Krdc, Krfb and Kompose, we can easily manage the information graphically from any remote device. Kompose offers a great new way to manage a big number of windows on different virtual desktops. It creates a full screen view where every window is represented by a scaled screenshot of its self.

Thanks to the KDE environment it is possible to create those screenshots "on the fly" while you are working without much overhead. We are now going to describe the application software that run on the IDVdesk with this system.

2.3 Application software solution

The visualization is done using Visit (http://www.llnl.gov/visit/) which is developed by Lawrence Livermore National Laboratory. This software allows to display multidimensional data and to navigate synchronously in space and time between different modalities. Visit also offers the possibility to have predefined behavior through its scripted engine. This, for example, allows a surgeon to run a simulation and automatically have access to the resulting set of data. On the performance side, Visit has native parallelism in its core engine and therefore, can make use of multicore/multiprocessors systems.

The numerical simulation is based on the Incompressible Navier-Stokes equations to model the flow, a phase contrast MRI image processing to get the correct inlet and outlet blood flow characteristic, and a level set method to derive the image segmentation of the artery in the Region Of Interest (ROI) [5, 6, 7, 10].

The overall simulation is based on the artery image in the ROI. Level set image and Navier-Stokes flow are coupled thanks to an immersed boundary method that is first order accurate but a very robust numerical method. This technique avoids the need for meshing of three dimensional complex objects that is often the bottleneck in finite element simulation. Our method is fairly simple since we can work with Cartesian grid and is very efficient on parallel architectures with standard scalars processor thanks to a domain decomposition technique. The interested reader can find more details on our flow solver and domain decomposition technique in [3, 4, 8, 9, 10, 11].

Rigorous error estimate with unsteady Navier-Stokes flow in the context of finite volume approximation are not covered by the current applied math literature. This is still an open problem. We have however used the classical concept of manufactured solution [14] and our optimized extrapolation method to build error indicators in the simulation environment [15]. This solution is far from perfect but may still be useful to the end user.

The next challenge is to provide a database organization and web interface that can be flexible enough to integrate all modalities involved in image analysis and image based simulation in order to evolve with the constant progress made in this application domain. Further the interface should be intuitive enough to be used by non computer specialists. We are presenting our data storage solution in the next section.

3 Database and Web Interface

In Figure 2, a high level representation of the system architecture is given. WIMI (Web Interface to Medical Information)[12] uses a traditional three tier architecture consisting of a database, web server, and client. This model was chosen because it offers the most flexibility to the end user. The web application

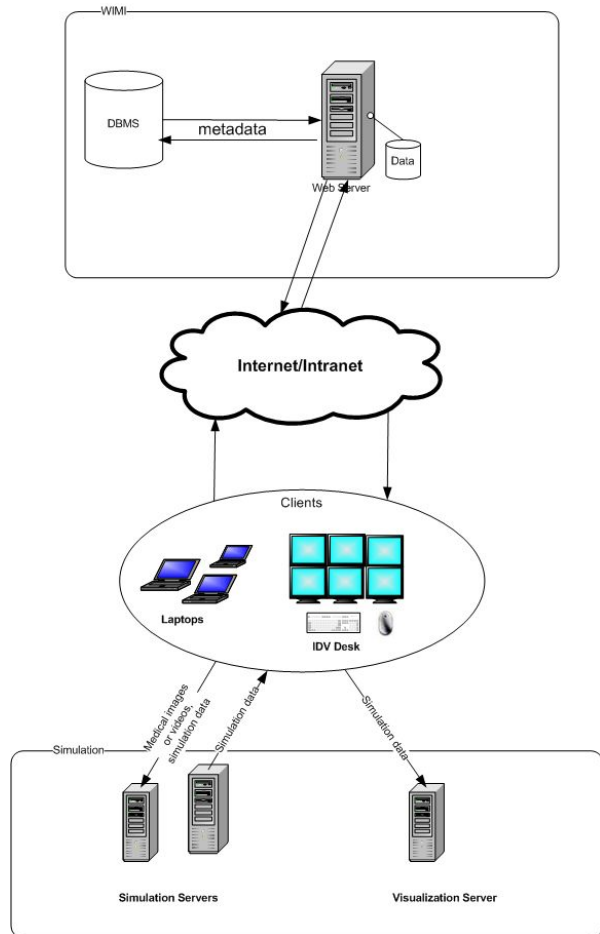was implemented using ASP.NET 2.0 and javascript.

Figure 2: WIMI Architecture.

The user connects to the web application over a secured network via the use of Secure Socket Layer (SSL) protocol with 128-bit encryption. Medical data and simulation data are transferred over this secured connection ensuring that patient information is protected as required by regulations such as HIPAA. Access to WIMI is limited to those that are registered users with valid passwords. The passwords are encrypted and stored in the database itself.

WIMI is designed with a novel idea of integrating the simulation datasets with medical images which needs further flexibility. We originally planned to use the popular DICOM schema as it is [13], but storing the simulations and images together needed some modifications of the DICOM schema.

The DICOM database schema contains tables for patient, study, series, and images. Using this schema, all the images created for many series of studies conducted on a patient can be stored. WIMI also does the same, and in addition stores simulations created using the medical images. In order to store this, we added two more tables: Parameters and ParamsInStudy.

3.1 Search Options in WIMI

WIMI offers three different searching techniques: Search by Comments, Search by Parameter, and Search by Patient through which the users can retrieve the required information. The nature of the data stored in the database creates the need for search based on different factors. The database schema used in WIMI makes these searches efficient.

Search by Comments Each simulation dataset in WIMI is associated with a technical note (also called comments) written by the doctor while creating the simulation. These notes help the doctor in providing the details of the simulation for a future reference. This makes the need for a search based on comments vital.

As WIMI allows many studies for a patient and each study is associated with different simulation dataset, a search based on only one keyword would result in many datasets with lot of similarities. Search by comments allows the doctor to search with multiple keywords. This helps the doctor in significantly reducing the size of the result set.

Search by Parameter It allows the doctor to select a parameter among all the parameters present in the database and search for specific range of values. The system then displays all the matching studies.

Search by Patient It allows the doctor to view all the patient names present in the database, sorted alphabetically. Then the doctor can view all the studies conducted on that patient which constitutes the patients stored history.

All the three different search techniques return the best matched results in the form of thumbnails each representing a study performed on that patient. On selecting the desired thumbnail, the doctor can choose to view additional information like all stored images, all stored videos, parameters and technical notes. Further, the doctor is also provided the option to download the dataset for changing parameter values to create a new simulation.

3.2 Parser

The different parameters and values used in creating the simulation datasets are stored in a metadata file. WIMI parses this file to extract all the parameters and their corresponding values to store it in the
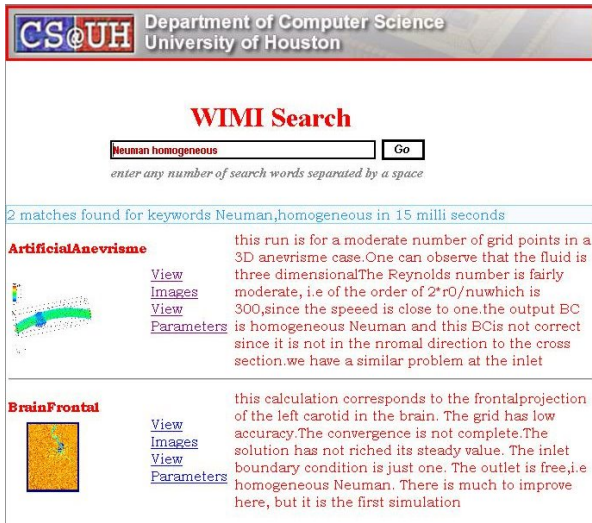
Figure 3: WIMI database search.

Figure 4: WIMI database schema showing all the tables with primary and foreign keys.

database. The parser is flexible enough to extract any new parameter used while creating a new simulation.

3.3 WIMI Database Schema

Simulations performed on blood vessels that supply blood to vital organs can be different dimensions (2D & 3D). Each simulation may require completely new parameters. The WIMI database schema (shown in Figure 4) is flexible to allow this. The total list of the parameters that are currently present in the system are stored in the Parameters table. Each parameter and its value is stored as a record in the ParamsInStudy table with a pointer to the studyid in the Study table. This schema has many advantages like:

- new parameters used in creating simulations can be dynamically added into the database.

- all the parameters of a study can be retrieved by knowing just the patientid and the studyid

- Parameters table which holds all the parameters makes important features like search by parameter implemented efficiently.

3.4 Image Viewer

Each simulation dataset in WIMI has images of the study on a patient. The number of images varies depending on the modality (X-Ray, MRI, etc.). If the doctor needs to look at the previous images of the patient, he can do so using the Image Viewer in WIMI. It allows to view the images quickly and zoom-in and zoom-out on a selected image.
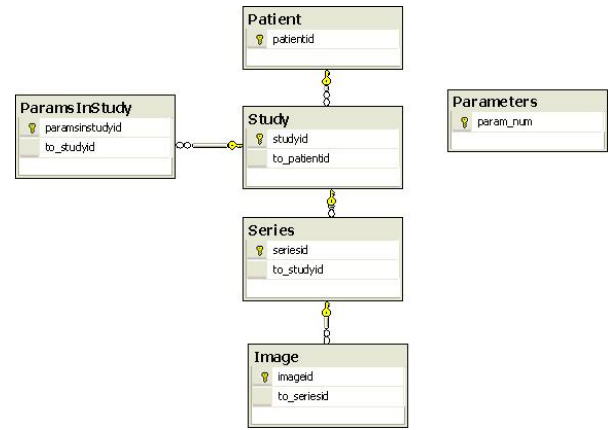
WIMI has three different image viewers:

- IDVImageViewer exploits the presence of multi screens on the IDV desk and shows each image on one screen;

- MRIImageViewer displays all the slices in a grid with scrolling ability. This is appropriate for MRI modality because the number of slices each MRI has vary between 50-200 and displaying them as thumbnails would make the webpage very complex for the doctor to use;

- WIMIImageViewer displays the images stored in the database on the page directly as thumbnails since the number of images is small.

Depending on the need of the doctor one among the three image viewers can be used.

4 Application Scenario

The mission of the IDV desk is to facilitate the visualization of multidimensional data and to integrate in the surgeon's working environment without disrupting it. Therefore, the workflow of the IDV desk that combines the different sub-systems (described in sections 2 and 3) need to be simple for an inexperienced user. Most of the technical aspect should be hidden behind simple GUI elements. Figure 5 shows the workflow that we are currently using.

It shows that most of the tasks interact with the database. It is a convenient, fast and, reliable method for the user.

From a performance perspective, each step is designed to be optimized to some level. For instance, the time to retrieve the data and to view it is done in the order of minutes. Only significant elements appear to
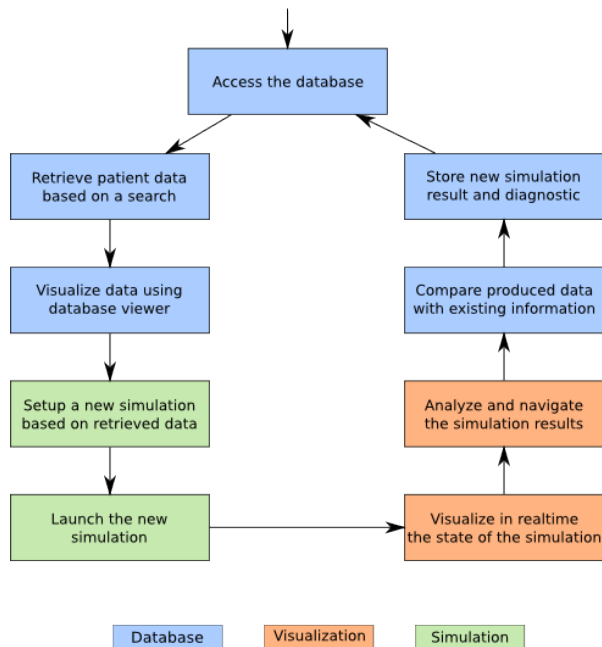
Figure 5: Workflow off the IDV desk centered on the three main sub-systems

5 Conclusion and Perspective

We have presented in this paper a cost effective solution that integrates simulation, visualization, and data management into a stand alone digital processing desk. Our prototype system has been designed to process efficiently the work flow in planning and/or studying endovascular surgery. Many of the concepts and solutions presented in this paper can be used in other applications, where the decision process relies on the efficient and interactive (parallel) processing and data management of simulations. We feel however that it is critical to close the interaction loop between the user and the system and add ears and eyes to our IDV desk system. In other words, the IDV desk needs additional sensors to gain the intelligence to help the user. We are currently working on improving the human computer interaction aspect of this project by adding voice and movement recognition interfaces.

the user, and graphical hints such as thumbmails of images stored in the database make the identification of the relevant data fast.

The simulation setup is also a fast step that can be done in seconds since it is only requiring that the user selects the input images that are to be used in the simulation.

The next step, that is the simulation, is the bottleneck of the workflow. Depending on the system that it is used to run the simulation. It can take from few minutes on a 64 node cluster to possibly one hour if it runs on the local machine. The IDV desk was designed to accommodate more cores. Thus, it will improve the local computation time.

In order to verify that the simulation gives results that are coherent with the expectation of the user, it is possible to visualize in real time the data produced by the application.

Once the simulation is completed, the analysis step that consists of comparing the simulation results with information stored in the database is where the real work for the user starts. His diagnostic is then stored in the database along with the produced data.

In the final step, the user has the choice of accessing the database again to restart a simulation. This is necessary in case the results obtained previously are not conclusive.

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