Augmented Reality for Scientific Visualization: Bringing DataSets inside the Real World

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Abstract. Scientific Visualization is a fundamental tool for data analysis. On the other hand, Augmented Reality (**AR**) is a new technology that involves the overlay of computer graphics on the real world. Scientific visualization methods and AR have been combined for medical imaging applications. In this paper we combine both these technologies for scientific data analysis. As a result we can augment the reality through graphical representations created from the numerical datasets. Besides, a simulated system can be superimposed on a real scene to get more insights about a phenomenon. In this text this paradigm is demonstrated and its consequences for scientific data analysis discussed.

1 Introduction

Scientific Visualization is a computer-based field concerned with techniques that allow scientists to create graphical representations from the results of their computations, as well as to visualize features of interest in a dataset obtained through imaging instruments [11].

Moreover, it is desired that experts can share a graphical representation of a dataset, see it from their respective points of view, communicate with each other, and interact with the *virtual* data representation [3].

Besides, and more important for this paper, scientific datasets are generated from numerical simulations that try to get the behaviour of real *objects* in face of some conditions. The combination of the physical surrounding with the visualization of the synthetic data may bring valuable insights about the phenomenon as well as the validation of the numerical simulation. This is the point that we are going to highlight in this paper.

The scenario is very suitable for Augmented Reality (AR) methods [1]. This technology involves the overlay of computer graphics on the real world (Figure 1) and is not totally explored yet. AR is within a more general context termed Mixed Reality (MR) [9], which refers to a multi-axis spectrum of technology that covers Virtual Reality (VR), AR, telepresence, and other related technologies.

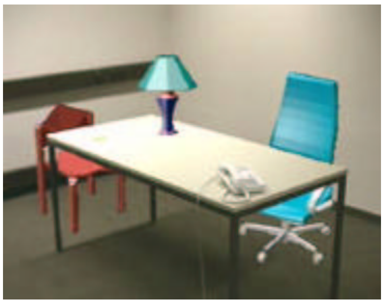


Figure 1: AR example with virtual chairs and a virtual lamp.

Virtual Reality is a term used for computer-generated 3D environments that allow the user to enter and interact with synthetic environments [3][14][16]. The users are able to "immerse" themselves to varying degrees in the computer's artificial world which may either be a simulation of some form of reality [4] or the simulation of complex data [18][3].

In telepresence, the fundamental purpose is to extend an operator's sensory-motor facilities and problem solving abilities to a remote environment. In this sense, telepresence can be defined as a human/machine system in which the human operator receives sufficient information about the teleoperator and the task environment, displayed in a sufficiently natural way, that the operator feels physically present at the remote site [13]. Very similar to virtual reality, in which we aim to achieve the illusion of presence within a computer simulation, telepresence aims to achieve the illusion of presence at a remote location.

AR can be considered a technology between VR and telepresence. While in VR the environment is completely synthetic and in telepresence it is completely real, in AR the user sees the real world *augmented* with virtual objects, in our case, graphical representation of a dataset. AR systems can take advantage of Head-Mounted-Displays [16], $3D$ pointers, cameras and traditional bi-dimensional displays to show the mixed image (see section 3).

The idea of superimposing computer-generated images over the users' view of the reality for scientific visualization purposes was already explored in [6]. However, in that case, the physical surrounding is just the place in which users see and interact with the virtual object (see section 2). In our case, we still keep the data visualization and users collaborations/interactions taking place in the physical environment; but, unlike in [6], the data being visualized describes the physical behaviour of the environment (or some part of it). Up to the best of our knowledge it is the first time that such idea is explored for scientific data analysis.

This paper is organized as follows. Next section describes related works. Section 3 discusses AR and scientific visualization to highlight the main points of this paper. Experimental demonstrations and discussions are offered in section 4. Final comments are given on section 5.

2 Related Works

When dealing with scientific visualization applications there are two valuable aspects that must be preserved: interaction with virtual objects and collaboration between users.

These requirements encompasses aspects from user interfaces paradigms, display technology and input devices [11]. Scientific visualization experts very quickly realized that these requirements can not be properly addressed by usual desktop architectures. Henceforth, new paradigms and technologies had to be incorporated in the scientific visualization background.

Virtual reality (**VR**) techniques is a known example [14]. Adopters of VR devices realized the benefits from stereoscopy, tracking, $3D$ navigators and interactive exploration by $3D$ pointers, for scientific data exploration (see [16] and references therein). Among the wide variety of VR system available, the CAVE (Computer Automatic Virtual Environment) technology is the most complete one for data visualization [16, 14].

The CAVE technology was first developed at the University of Illinois at Chicago. It built a multi-person 10x10x9 foot theater, with images rear-projected on the walls (screens), and projected down onto the floor (Figure 2.a). Four projectors, one for each screen, are connected to graphics pipes of one or more high-end workstations.

In the CAVE at Illinois, 1024x768 resolution stereoscopic images are displayed on each screen at 96 Hz. Viewers wear Stereographic liquid crystal shutter glasses (CristalEyes) to view the stereoscopic images. One user's head is tracked with a 6 degree-of-freedom tracking system, and images are generated from that user's viewpoint. A wand (3D equivalent of a mouse) is also tracked. The wand has three buttons and a small, pressure-sensitive joystick. It is used by viewers to interact with and control CAVE applications.

CAVE systems suffer from the drawback that true stereoscopic images can be rendered only for one leading user wearing the head tracker - the users have to remain close to the leading user, because distortions increase proportionally to their distance to the tracked point of view.

The same problem occurs in the Virtual Workbench [10]. In this case, stereoscopic images are projected onto a large, frosted glass surface which is mounted in a wooden frame. The display system also accounts for the current position of the user's head when creating the stereoscopic images. ImmersaDesk, pictured in Figure 2.b, follows a similar technology [15].

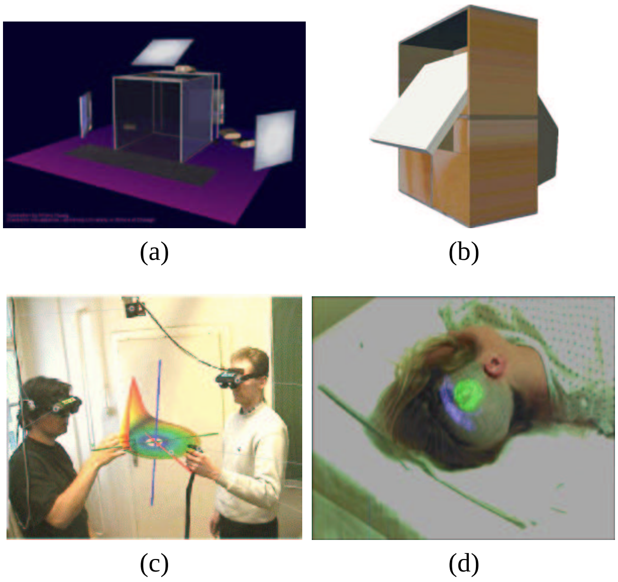

(a) (b)
(c) (d)

Figure 2: (a)CAVE technology. (b) Immersadesk device. (c) Dynamical System analysis through AR devices. (d)AR for image guided surgery.

In these examples, the user is (fully or partially) immersed in a virtual world. Another possibility would be to mix the reality with virtual objects. In this case multiple collaborating users can be simultaneously studying a three-dimensional scientific visualizations that is combined with the user's surrounding environment. The "STUDIERSTUBE" project is an example. As pictured on Figure 2.c, each participant wears an individually headtracked see-through HMD (Head Mounted display) (see section 3) providing a stereoscopic real-time display. Such a architecture was used for dynamical systems visualization [6].

For medical applications, AR can be applied so that the surgical team can see the CT (Computer Tomography) or MRI (magnetic resonance imaging) data correctly registered on the patient in the operating theater while the procedure is progressing (Figure 2.d). Being able to accurately register the images will enhance the performance of the surgical team and eliminate the need for the painful and cumbersome stereotactic frames that are currently used for registration [7]. For ultrasound imaging applications, the ultrasound technician using an optical see-through display (section 3) can view a volumetric rendered image of the fetus overlaid on the abdomen of the pregnant woman. The image appears as if it were inside of the abdomen and is correctly rendered as the user moves [12].

In a different way, we found the concept of the Luminous Room [17]: an interior architectural space whose surfaces have been made capable both of displaying visual information and of performing visual capture. By using this collocated pairing of optical input and output, each room surface - floor, walls, ceiling, tabletops, assorted furniture - becomes a potential site for interaction. Scientific visualization can be implemented in such paradigms by displaying computer-generated images over the optical inputs. For instance, in the ”seep” application, an interactive simulation system allows physical objects placed in a workspace to act as obstacles in a purely computational fluid flow. Then, the resulting vector field is visualized over a display surface of the system (Figure 3).

Figure 3: Flow visualization in the *seep* application.

The work [17] introduces the idea of composing scientific data with the real object simulated. However, we point out that we do not require that the workspace surfaces work like displays. Following AR in medical applications, we can just superimpose data and the view of a real object. Consequently, data analysis is improved because experts can view graphical representations of the data overlaid on the physical environment simulated. Henceforth, the computer-generated images can enhance the insights of scientists and engineers about the behaviour of real objects in their real working conditions. Moreover, insights about the validation of the mathematical model used in the simulation may appear. We are going to demonstrate these features in the next sections.

3 AR and Scientific Visualization

Let us present some fundamental points in AR and scientific visualization. From the following discussion, the main idea of this work will be highlighted.

The Augmented Reality technology has many possible applications in a wide range of fields, including entertainment, education, medicine, engineering and manufacturing.

When designing an AR system, three aspects must be in mind [1]: (1) Combination of real and virtual worlds; (2) Interactivity in real time; (3) Registration in $3D$.

To perform the combination of real and virtual objects we must have a scene generator, which is the device or software responsible for rendering the synthetic objects. These objects will be in a view of the real scene. Users must be allowed to interact with the resulting scene. Things work fine if the objects in the real and virtual worlds are properly aligned with respect to each other; that is, if the registration was accurately performed [1].

The technology for AR is still in development and solutions depend on design decisions. When combining the real and virtual world two basic choices are available: optical and video technology. Each of them has some tradeoffs depending on factors like resolution, flexibility, field-of-view, registration strategies, etc. [1].

Among the possibilities for display devices pictured on Figures 4 and 5 - Optical See-Through HMD, Virtual Retinal Systems, Video See-Through HMD, Projection Displays and Monitor Based - the later one is basic for our work [15, 1].

Monitor Based AR uses merged video streams but the display is a more conventional desktop monitor or a hand held display. It is perhaps the least difficult AR setup, as it eliminates HMD issues.

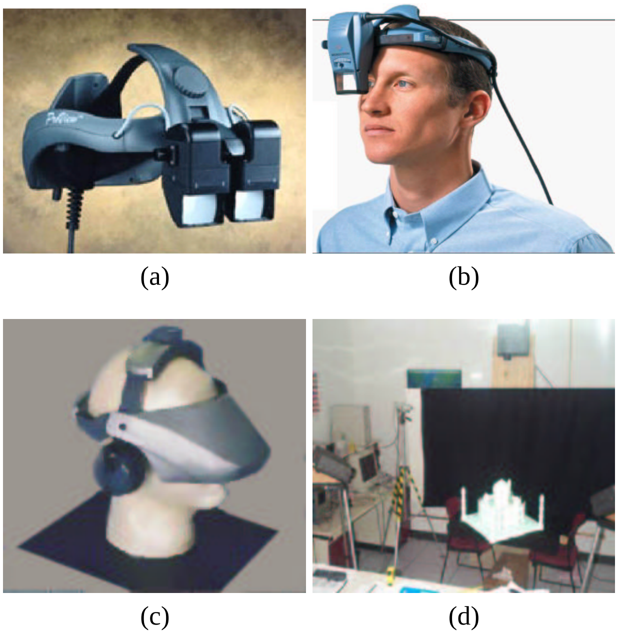
The techniques in scientific visualization can be classified according to the data type they manage. *Scalar fields* ($F : D \subset \Re^3 \rightarrow \Re$), vector fields ($F(x)$ is a vector, $x \in D \subset \Re^3$) and *tensor fields* compose the usual range of data types in this field.

Henceforth, we have methods for scalar fields visualization (isosurface generation and volume rendering, colormap, etc.), vector fields visualization (field lines generation, particle tracing, topology of vector fields, LIC, among others) and techniques for tensor fields (topology and hyperstreamlines) [11].

In the case of particle tracing methods, used in the next section, they can be mathematically defined by an initial value problem [11]:

$$\frac{dx}{dt} = F(x,t), \quad x(0) = P_0, \tag{1}$$

where $F : \Re^3 \times \Re_+ \rightarrow \Re$, is a time-dependent vector field (velocity, for example). The solutions for a set of initial conditions gives a set of (integral) curves which can be in-



(a) (b)

(c) (d)

Figure 4: (a) Optical See-Through HMD. (b) Virtual Retinal HMD System. (c) Video See-Through HMD. (d) Projector Based AR.

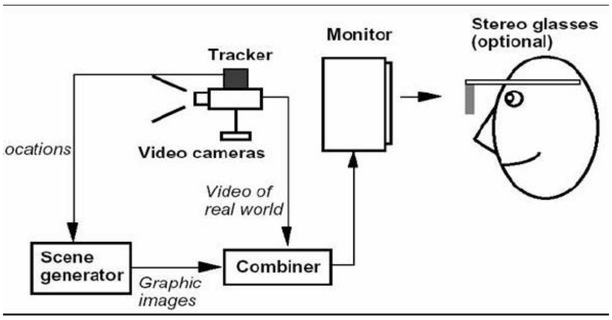


Figure 5: Scheme for Monitor Based AR System.

terpreted as the trajectory of massless particles upon the flow defined by the field $F(x,t)$. Other tracing methods can be used (streamlines, streaklines, etc.) through slight modification of the equation (1) [11].

For all these methods, the result is a bi-dimensional image out of the three-dimensional data. This computer-generated image can be usually displayed in $2D$ devices or in a VR system. The main proposal of this paper is to mix that computer generated-image (or sequence of images) with a video stream, or an user's view in the case of See-Through HMDs, to enhance scientific behaviours. This will be demonstrated next.

4 Experimental Results and Discussion

In this section we present two experiments in which we combine real and synthetic objects for scientific visualization purposes. Our AR system is a monitor-based one (Figure 5) composed by a Logitech QuickCam, connected to a Pentium III running Windows XP and ARToolkit 2.52.

The first experiment shows a setup in which we compare a virtual and a real pendulum. The mathematical model used is the simplest one given by:

$$\theta(t) = A\cos(\omega t + b), \quad \theta(0) = \theta_0, \quad \frac{d\theta(0)}{dt} = \dot{\theta}_0, \quad (2)$$

where $\theta_0, \dot{\theta}_0$ are the initial angular position and velocity, respectively (see Figure 6).

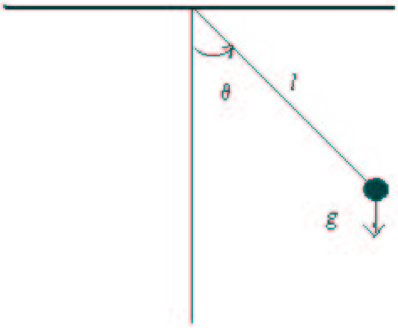


Figure 6: Scheme for a simple pendulum.

Besides the $3D$ registration, we have a *time synchronization*: the positions of the virtual pendulum must be updated according to the clock of the real one. Hence, if the camera's recording rate is $N frames/seconds$, the real movement will be captured at instants: $0, \Delta t, +2\Delta t, ..., M\Delta t$, where Δt is given by: $(1/N)$ $seconds$, and $M\Delta t$ is the final instant of observation.

Consequently, we must update the virtual system according to: $\theta(0), \theta(\Delta t), \theta(2\Delta t), ..., \theta(M\Delta t)$. Such time synchronization will be a requirement for all applications that mix virtual and real moving objects. For example, a virtual and a prototype of a plane could be aligned in a scene and the simulated velocity vector field displayed. If a non-stationary behavior takes place, that time synchronization must be performed also.

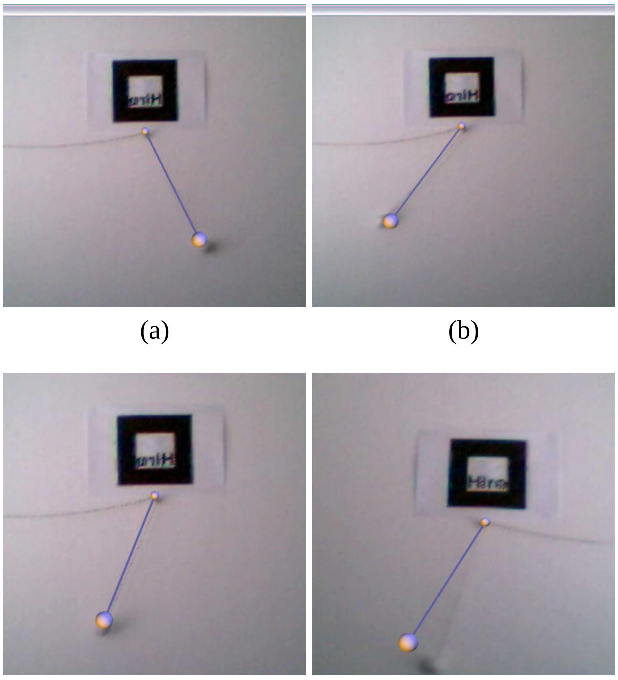

(a) (b) (c) (d)

Figure 7: (a)Initial instant. (b)-(c) Virtual movement reproduces the real pendulum at the initial instants. (d) Mathematical model does not agree with the reality after some time.

Another important point is that virtual objects follows mathematical models that in general can not completely reproduce the real behaviour. For instance, as expected, we observe in Figure 7.d that the movements of the virtual and real pendulum do not match after some time steps. Certainly, we could use a more realistic model or even track the real pendulum and, from the captured positions, estimate a more precise mathematical model. However, this is not the point in this paper. Besides, the field of vibrations capture has been done specific sensor devices with an accuracy impossible to be achieved by a tracking/camera system (as an interesting material, see http://www.patchn.com/plc_cont_sens.pdf).

In this paper, our proposal is to enhance experimental results through graphical representation of the numerical datasets. For a complex phenomenon, the experts could discuss if the source of the observed differences is the mathematical model or the experimental setup. Moreover, experimental measurements can be also visualized. Thus, visual comparisons between measurements and simulation can be performed bringing insights about the phenomenon.

In the next example, we use the particle tracing (equation (1)) to analyse the simulation of the air flow caused by a fan. The image sequence so obtained is mixed with a video stream showing the fan in rotation. Figure 8 pictures two time steps of the obtained sequence. To simplify the simulation, the flow was considered as a stationary one, and so, there is no need for time synchronization.

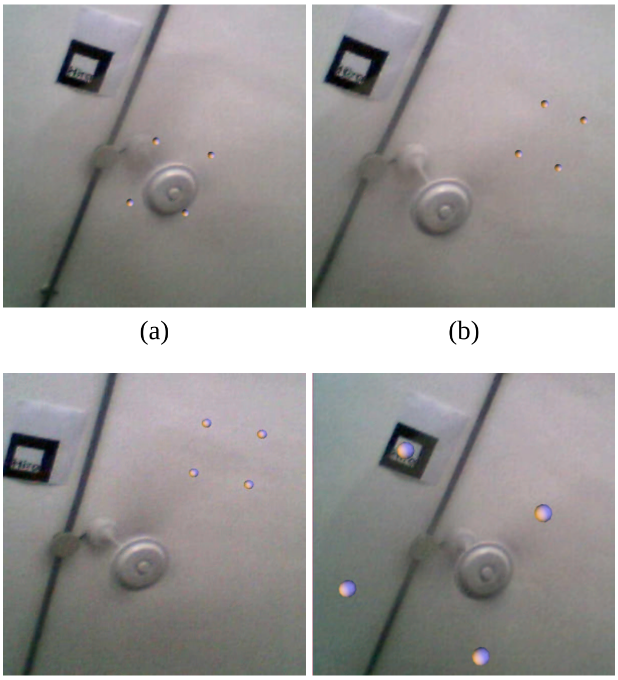

(a) (b) (c) (d)

Figure 8: (a) AR for displaying particle tracing. (b)-(d) Virtual particles enhancing air flow analysis.

The result can be used to analyse the distribution of the air inside the environment. When superimposing the real and the virtual all aspects of the real world will be present in the background (windows, doors, furniture, etc.). It makes easier for experts to understand and discuss about aspects that must be considered in the simulation in order to get a more realistic result. Such level of data analysis can not be achieved by usual visualization methods because, in that case, the background would be the synthetic domain used to set up the boundary conditions for the simulation.

In this case, two or more users, wearing a see-through HMD (Figure 4.a), could be analysing the air flow. When user moves around the real object, accurate registration must be dynamically re-established, which is still an open problem in AR [15].

An outdoor experiment would be even more challenging. For example, the measured location of an object in the environment may not be known accurately enough to avoid visible registration error. Under such conditions, one approach for rendering an object is to visually display the area in screen space where the object could reside, based upon expected tracking and measurement errors [8]. This guarantees that the virtual representation always contains the real counterpart. Moreover occlusions may happen. In this case, one approach is to use a probabilistic function that gradually fades out the hidden virtual object along the edges of the occluded region, making registration errors less objectionable [5]. Besides, allowing AR systems to go anywhere also requires portable and wearable systems that are comfortable and unobtrusive.

Improving the rendering quality of virtual objects could be important for our applications. For instance, Figure 8 shows the undesirable aspect that virtual elements may get too much the attention of the observer due to its rendering properties (color, texture, etc.). To avoid such effect, we need the ability to automatically capture the environmental illumination information [2] in order to avoid that virtual objects get over enhanced in the scene.

These are challenges in AR that we must address to completely explore our work.

5 Conclusions

In this work we propose the combination of AR and scientific visualization methods for numerical data analysis. The demonstrations presented show the potentiality of this idea as well as future drawbacks related to $3D$ registration, portability and rendering.

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