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Haptic Rendering Techniques for the Interactive Exploration of CFD Datasets in Virtual Environments

T. van Reimersdahl[1], F. Bley[2], T. Kuhlen[1], and C.H. Bischof[1]

[1] Center for Computing and Communication, Aachen University (RWTH), Germany
[2] Department of Technical Computer Science, Aachen University (RWTH), Germany

Abstract

In pure CFD visualization tools, some flow features are hard to visualize such as the properties of a local flow probe. Haptic rendering techniques offer an intuitive understanding and allow more detailed insights than the visual perception solely. In our application framework ViSTA FlowLib *for the interactive visualization and exploration of unsteady flows in virtual environments we implemented haptic rendering techniques as an add-on feature for the commonly used visualization algorithms for scalar and vector fields. We extended the ideas of Pao and Lawrence and developed new promising techniques.*

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [User Interfaces]: Haptic I/O; I.3.7 [Computer Graphics]: Virtual Reality; I.3.6 [Computer Graphics]: Interaction Techniques

1. Introduction

In the last decade, a variety of scientific visualization tools arose for the exploration of Computational Fluid Dynamics (CFD) data in virtual environments. Most of them are pure visualization systems and provide 2D and/or simple 3D human computer interfaces. Only a few of them offer multi-modal interaction techniques for the interactive exploration in virtual environments (e.g. The Virtual Windtunnel[2], COVISE[11], MSVT[7]). In most of these tools, haptic perception is not supported.

However, the haptic rendering of flow visualizations is a promising approach to support the visual exploration process by representing additional details of the multi-dimensional CFD datasets. Some flow features are hard to visualize such as the properties of a local flow probe. In such cases, the haptical assistance can facilitate and accelerate the exploration process of the flow properties.

In the following, we introduce the haptic rendering subsystem of *ViSTA FlowLib*[12], which is a highly scalable and extendable software framework for the interactive visualization and exploration of unsteady flows in virtual environments. The haptic rendering algorithms are an add-on feature which can be enabled if a force feedback device such as the PHANToM Haptic Device from SensAble, Inc. is available.

The remainder of this paper is structured as follows. In the next section we give an overview of the related work, followed by a description of the haptic rendering concept within *ViSTA FlowLib*. In section 4, we present the haptic rendering techniques for scalar and vector fields. In section 5, we describe the initial evaluation of these techniques. In the last section we conclude and give a short overview about our future work.

2. Related Work

In 1990, a research group from the University of North Carolina led by Prof. F. Brooks, presented the first system which is able to provide a 6DOF force display[1]. Their so called Project GROPE used a feedback device to render forces that would occur in a simulation where molecular structures have to be manipulated. The first interface that displays abstract data is described 1993, when Iwata et al. from the University of Tsukuba introduced a system for volume haptization[5]. An important conclusion gathered from probing volumes with different densities and simple vector fields is the increased user acceptance for pure torsional forces opposite to combinations of torsional and translational forces. Haptic exploration of a streamline is proposed 1998 by Johnson et al. from the University of Utah in the context of the SCIRun project. Beside the visualization of streamlines, the method of the Relative Drag is implemented to enhance the data display[3]. One year later, Infed et al. from the University of Colorado describes a system, which uses an especially-designed device to align a stylus in the direction of a streamline[4]. The test results indicate, that graphical and haptical information need to be displayed well-balanced to prevent from confusing the user.

Until now, the most active researchers in this field are D.A. Lawrence and L.Y. Pao from the University of Colorado. In 2000, they presented in [6] a combined visual/haptic interface for shock and vortex visualization. In 2002, they proposed in [8] an advanced interpolation algorithm for a near real-time haptic probing in unstructured tetrahedral meshes. The visual rendering in their prototype is done with AVS/Express and the haptic rendering on a dedicated haptic device with 5 degrees of mechanical freedom.

3. Haptic rendering concept in *ViSTA FlowLib*

In *ViSTA FlowLib* we integrated haptic rendering techniques as an add-on feature, which can be enabled if a force feedback device such as the PHANToM Haptic Device from SensAble, Inc. is available. The concept of this component is illustrated in Figure 1 showing the sequence diagram of the haptic simulation. The visualization application runs on a visualization host and the haptic rendering server application on the haptic server host.

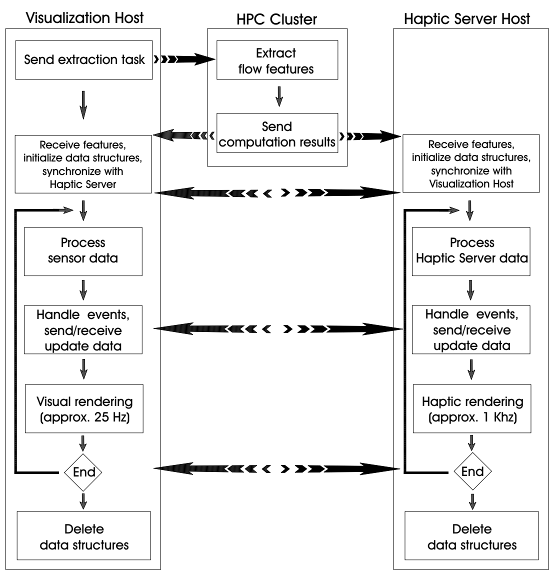

Figure 1: *Sequence diagram of the haptic simulation in ViSTA FlowLib.*

In a typical exploration session, the user interacts with the application and initiates visualization tasks. Such tasks consist of the visualization technique type and its individual parameters which are configurable via menu interaction. In presence of a high performance computing (HPC) host, the calculation is done there in parallel (e.g. on a HPC cluster). If no HPC host is connected, the computation is done locally on the visualization host. Once a haptic rendering technique is selected via the geometry-based 3D menu in Figure 2, the computation results are forwarded to the haptic server host as a local copy for the haptic rendering. In the haptic update loop, the force vector is computed on the local data in accordance with the chosen rendering technique. Using this local model we gain a haptic rendering frequency of nearly constant 1 kHz.

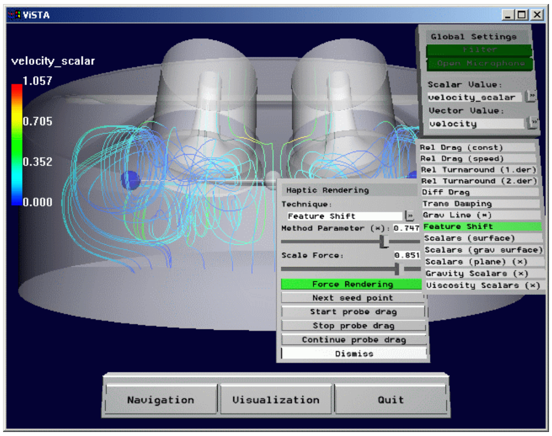

Figure 2: *The geometry-based menu for selecting the different haptic rendering techniques and theirs parameters.*

4. Haptic Rendering Techniques

In pure flow visualization systems, some local flow properties are only assessable with much attention. Haptic rendering techniques offer an intuitive understanding and allow more detailed insights of the flow. We implemented haptic rendering techniques for the commonly used visualization algorithms. We extended the ideas presented in [9] and developed new promising techniques. In the next subsections, we describe the implemented haptic rendering algorithms for scalar and vector fields.

4.1. Scalar Fields

Flow properties like for instance pressure, density, temperature, and scalar functions of vector fields are represented by real numbers. In common practice, such values are visualized by color-coded cut planes or isosurfaces. For a haptical representation, the scalar values can be mapped to force vectors. In the following, techniques are described how to perform this mapping.

4.1.1. Warp Scalars / Topography

When the user has visualized a cut plane he can get additional support of this technique. In addition to the visual presentation of the plane, the values of the current scalar (or another available scalar) are mapped as heights of a virtual surface, that can not be seen, but felt through the haptic output device. A large value will result in a large height of the surface. In this fashion, local extrema can easily be distinguished. To calculate the amount of force that has to be generated, the depth of penetration of the probe into the surface has to be determined. The deeper the penetration, the greater the force vector will be. The direction of the force vector is always perpendicular to the cut plane.

One drawback of this method is the absence of information about positive and negative scalar values since no information about the height of zero is given. A modification of this technique generates forces that pulls the PHANToM's stylus upward or downward respective to the sign of the scalar.

4.1.2. Gravity Scalars

The *Topography* method can only map the values of a sliced plane. A substantial amount of information is lost. To represent a complete three dimensional dataset, a mass can be assigned to each point of the computational grid. A large scalar value results in a high mass and therefore a highly attracted force. When the user moves the probe through the dataset, the probe will be attracted by regions with high scalar values. Regions with small values will reject the probe. Since a repeatedly computation of all grid points would be too time consuming, an extraction algorithm is used before the haptic rendering starts. This algorithm determines e.g. the positions of minimal and maximal scalar values and stores them for subsequent use. During the rendering loop, the spatial difference between probe and stored position is calculated and the amount of force is appointed inverse to the difference such that a small spacing results in a high attracted force. The resulting force vector is a superposition of the separate vectors generated by every position that has been stored previously.

4.1.3. Viscosity Scalars

In contrast to the assigned mass in *Gravity Scalar*, this method assigns kinematic viscosity to the grid points according to the magnitude of the scalar value on that point. When moving the probe through the dataset, the user will feel a damping impedance that slows down the probe in regions with large scalars. Regions with smaller values will appear less viscous. This method proves useful for a fast and qualitative exploration of a complete dataset. To calculate the force for the output device, the current speed of the probe, its position and the scalar value that takes effect has to be taken into account. In consideration of these factors, a force vector is determined that points opposite to the movement direction, therefore slowing down the probe motion.

4.2. Vector Fields

The vector fields of CFD datasets like for instance velocity fields or gradients of scalar fields are usually visualized by a set of arrows, glyphs, particles, and integral objects (e.g. stream- or pathlines) segments. Although an immersive virtual environment provides stereoscopic depth perception, the visualization can get cluttered rapidly. In addition, it is difficult to track local flow properties of the vector fields and to understand 3D vector directions. The haptic perception is better suited for such tasks. In an intuitive manner, the output device can be attached to the local flow probe, thus feeling the behavior of it.

In the following, we describe haptic rendering techniques for vector fields. The *Relative Drag* and *Transverse Damping* techniques are adapted from [9].

4.2.1. Relative Drag

The purpose of this method is to render the forces that would be applied to a particle which is moving along an integral object (e.g. a streamline). While the graphical representation of the interaction device (the probe) moves along the line, the user can feel the appropriate forces through the device. The position of the stylus is of no importance so that the user only has to concentrate on the force output. To calculate the direction of the force output of the device the spatial difference between the two adjacent points is calculated and rendered as force vector (see Figure 3). In addition to the directional information, the flow velocity can be used to scale the force vector.

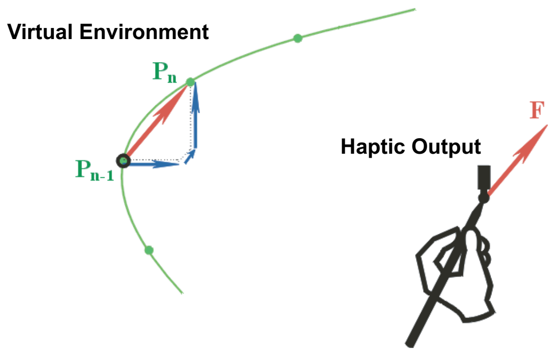

Figure 3: *Relative Drag*

The position and direction of the users viewpoint has to be taken into account while calculating the force vector, so that the haptical output occurs in accordance with the graphical movement with the graphical movement of the probe (e.g. while the probe is moving to the left, the stylus is being pulled to the left). This method proves useful, when the probe is moving mainly toward the user or away from him, so that the amount of longitudinal movement can hardly be estimated visually.

4.2.2. Relative Turnaround

This method renders the changes in the movement direction of the probe. When the probe is changing its movement from a straight line to a rising curve, the tip of the stylus is pulled upwards. When the twist of the line is changing from a left turn to a right, the force output displays a change of sign. The user can control the movement of the probe along the integral object through the pointing direction of the stylus. Turning the stylus clockwise results in a movement in direction of the flow, turning it counterclockwise will inverse that direction. This method renders information that is sometimes hardly noticeable when using visual rendering alone, like the alternation of the twist.

4.2.3. Transverse Damping

Here, the location and shape of an integral object is presented haptical to the user. The movement of the probe is restricted onto the line and movement transversal to the integral object results in a motion damping of the stylus, that surges with increasing displacement between probe position and the line. The user is able to touch the line and to feel its shape this way. To calculate the force, the spatial difference between the current probe position and the next point on the line is determined (see Figure 4). Since the line is stored in a discrete form in the data structures, the intersections of the complete integral object are interpolated with straight lines. The force, that is rendered by the output device pulls the stylus and therefore the probe back into the ideal position on the integral object. Movement on the line itself is not damped in any way, so that its form can be felt easily. This method proves to be a very intuitive tool to present the shape of integral objects.

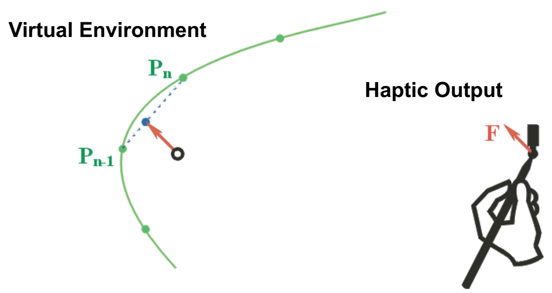

Figure 4: *Tranverse Damping*

4.2.4. Differential Drag

This method adds a force to the method of *Transverse Damping* in a way, that the user feels an additional drag of the probe onto the integral object into the direction of the flow. The stability of the output device is very difficult to control in both of these methods. Due to the small area in which the probe movement is permitted, forces can occur that hurl the probe from one threshold of the motion area to the opposite one. This deficiency is overcome with the use of an critical damped filter of second order.

4.2.5. Gravitational Line

Using this rendering method, the integral objects in the virtual scene emit a gravitational force field that pulls the probe towards them. Unlike in the two previously described methods, the probe can be moved freely around the whole dataset, but the user is able to position the probe onto one line and feel its shape. With the application of enough force to snatch the probe away from the line, the user can select the next line and continue his exploration. The calculation of the forces is handled similarly to the one in *Transverse Damping* and *Differential Drag*, but all integral objects, that are present in the scene, are taken into account. The resulting force is a superposition of the forces emitted from all integral objects, that are rendered visually.

4.2.6. Feature Shift

To compare the spatial differences between two similar integral objects, this method renders forces to display the spatial shift. While the probe is moving automatically along one of the two lines, the stylus is dragged into the direction of the temporarily equivalent point on the other line while the amount of force decodes the spatial length between the two points. To calculate the force, the vector between the two points is determined (see Figure 5). The viewpoint direction of the user onto the dataset is taken into account and the rotated vector is rendered as output. Since the probe is moving automatically along the line, the user does not need to concentrate on the position of the stylus and can divert his complete attention to the force output.

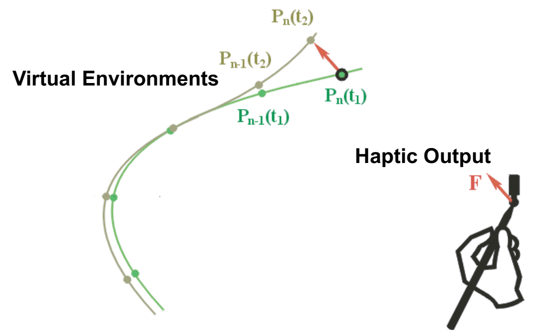

Figure 5: *Feature Shift*

5. Initial Evaluation

The evaluation of explorations and interactions in virtual environments can be divided into three issues[10]: the effect to the subjects, the cognitive translation of the involved information and the motor operation of the interaction devices.

The visual and haptical perception are evaluated by questionnaires after the completion of experiments. During the experiments the subjects form a mental image of the data. In contrast to the haptical perception which contributes to a sequential exploration of the features, the visual perception leads probably to another cognitive translation of the presented data. Thus, the subject's cognitive structure of the dataset should be asked and checked. The motor issues in the operation of the interaction devices are evaluated by time measurements. Additionally, user acceptance is to be investigated.

The initial evaluation of the haptic rendering techniques was carried out with four participants as follows. The procedure started with a training process for each participant, followed by a short description of the experimental task. Then, the subject had to process the task as fast and accurate as possible. After the task completion the subject had to complete a questionnaire. At the end of all experiments, the experiences and difficulties were discussed in order to optimize the approaches in future work.

In our study we used the PHANToM 1.5 from SensAble, Inc., allowing a six degrees of freedom input and a simple force vector as output. The PHANToM was connected to an off-the-shelf PC running the haptic server of *ViSTA FlowLib*. The network connection between both hosts was a 100 MHz Fast Ethernet connection. The visualization host was a SGI Onyx2 driving a TAN HoloBench projection system.

Because the prototype system is primarily designed for a multi-disciplinary exploration of flow features, we concentrated on the common issues of each technique. Thus, we tested the techniques with a steady CFD dataset. In the questionnaires we asked for the degree of difficulty of the task, the agreement of visual and haptic rendering and to what extent they trust in their estimation.

In the following, we describe the investigated experimental tasks for the scalar and the vector fields techniques and their results.

5.1. Scalar fields techniques

In the scalar fields techniques we focused on the tasks to find minima and maxima scalar values and to locate their positions. Comparing the experimental results, the *Gravity Scalars* approach was the best regarding to user acceptance and accuracy expectedly. The two minima and two maxima of the scalar values were pre-computed and rendered visually as colored spheres and haptically as attracted or rejected forces. The users rated this assistance as very intuitive. The *Warp Scalars/Topography* technique also led to acceptable accuracy results. However, the subjects were a little less certain with the exact agreement of visual and haptic presentation. In the *Viscosity Scalars* approach the subjects reported not being able to locate certainly any relevant position. Instead, they rated this technique beneficial for finding candidate regions.

5.2. Vector fields techniques

In the vector fields techniques we concentrated on probing the shape of integral objects. The mental image of the subjects was asked and checked at distinct samples.

The haptic rendering techniques *Transverse Damping* and the similar *Differential Drag* gained the best user acceptance. In comparison to the *Transverse Damping* approach, the additional drag into the direction of the flow is rated as beneficial if the integral object is not visualized. In both techniques the agreement of the mental image and the visualized image led to the user acceptance. The *Relative Drag* was rated as an intuitive approach. Here, the subjects recognized that their mental image was fragmentary. Thus, visual rendering is definitely needed in this techniques to gain a profit. The *Gravitational Line* was rated as a helpful approach to switch the integral objects to scan. The *Feature Shift* approach illustrating the spatial differences between two similar integral objects showed how indispensable the combined visual and haptic rendering is. Without the visual rendering, the subject could feel the spatial difference vector, but the mental image of the two lines was not built completely. With the visual rendering, the subjects statements matched at the samples. The technique *Relative Turnaround* led to a confusion, at first. The transition of a left turn to a right turn is hardly visible. In the haptic rendering method, it results in a change of the sign of the force vector. The subjects reported that the turnaround felt was not intuitive to understand. Knowing the details, they valued this technique as beneficial - to feel a flow property that they could not immediately notice visually.

6. Conclusion and Future Work

In our initial evaluation, the *Gravity Scalars* approach gained the best user acceptance for scalar fields. In the case of vector fields, the *Transverse Damping* and the *Differential Drag* approaches showed the best agreement of visual and haptical presentation.

The evaluation results approve that haptic rendering as an assistance to visual rendering is a very promising approach to facilitate the exploration process of CFD simulation data.

In our future work, we will perform continuative evaluations to optimize the techniques. We plan to integrate some observer automatism of the haptic probe for quantitative evaluation studies.

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