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Visualization of Post-Processed CFD Data in a Virtual Environment

Abstract

This paper discusses the development of a virtual reality (VR) interface for the visualization of Computational Fluid Dynamics (CFD) data. The application, VR-CFD, provides an immersive and interactive graphical environment in which users can examine the analysis results from a CFD analysis of a flow field in three-dimensional space. It has been tested and implemented with virtual reality devices such as the C2, head mounted display (HMD) and desktop VR. The application is designed to read PLOT3D structured grid data and to display the flow field parameters using features such as streamlines, cutting planes, iso-surfaces, rakes, vector fields and scalar fields. Visualization Toolkit (VTK), a data visualization library, is used along with OpenGL and the C2 VR interface libraries, to develop the application. Analysts and designers have used VRCFD to visualize and understand complex three-dimensional fluid flow phenomena. The combination of three-dimensional interaction capability and the C2 virtual reality environment has been shown to facilitate collaborative discussions between analysts and engineers concerning the appropriateness of the CFD model and the characteristics of the fluid flow.

Keywords

VRAC

Disciplines

Computer-Aided Engineering and Design

VISUALIZATION OF POST-PROCESSED CFD DATA IN A VIRTUAL ENVIRONMENT

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ABSTRACT

This paper discusses the development of a virtual reality (VR) interface for the visualization of Computational Fluid Dynamics (CFD) data. The application, VR-CFD, provides an immersive and interactive graphical environment in which users can examine the analysis results from a CFD analysis of a flow field in three-dimensional space. It has been tested and implemented with virtual reality devices such as the C2, head mounted display (HMD) and desktop VR. The application is designed to read PLOT3D structured grid data and to display the flow field parameters using features such as streamlines, cutting planes, iso-surfaces, rakes, vector fields and scalar fields. Visualization Toolkit (VTK), a data visualization library, is used along with OpenGL and the C2 VR interface libraries, to develop the application. Analysts and designers have used VR-CFD to visualize and understand complex three-dimensional fluid flow phenomena. The combination of three-dimensional interaction capability and the C2 virtual reality environment has been shown to facilitate collaborative discussions between analysts and engineers concerning the appropriateness of the CFD model and the characteristics of the fluid flow.

INTRODUCTION

In various diverse areas such as aeronautical, chemical, civil and mechanical engineering, meteorology, naval architecture, oceanography and others, the analysis of fluid flow is central to research, design, and testing of facilities and products. A typical example would be the study of fluid flow around an airplane, which would be vital in determining its structural stability in flight. An understanding of the fluid flow around automobiles, aircraft and underwater vehicles can be used to alter designs to

reduce drag which in turn reduces fuel consumption. Engineers study the flow inside machinery like turbines, compressors and propellers to develop and improve the design of these machines. In each of these application areas, analysts are interested in examining scalar parameters of the flow such as temperature, pressure and density, as well as vector parameters, such as velocity.

Fluid dynamic analysis can be performed using actual parameter values obtained through experimentation or by theoretical computation. Computational fluid dynamics (CFD) is a technique for calculating approximations to the fluid flow and is commonly used in industry today to predict flow behavior (Munson, et. al., 1994). The CFD results are generally displayed using desktop monitor systems. Existing CFD software tools provide limited VR capability. Ensign and Fieldview provide for stereo viewing, but not for three-dimensional input devices or multiple window synchronized displays.

In 1992, Steve Bryson and Creon Levit developed the first virtual reality (VR) application designed to allow users to examine fluid flow characteristics using immersive visualization and three-dimensional user interaction (Bryson and Levit, 1992). This application is called the Virtual Windtunnel and is used to examine the airflow characteristics surrounding various aircraft. Bryson continues to develop the capabilities of that application and intends to make a public release available in the near future (Bryson, et al., 1997). In 1995 Sterling Software Inc. and the Ford Motor Company developed a VR interface to FAST (Bancroft et al., 1990) (Mahoney, 1995). This capability was used by Ford engineers to examine the air flow around the engine of a vehicle.

In 1997, Brad Kohlmeyer, working under the direction of Jim Oliver at Iowa State University (Oliver et al., 1997), developed a VR application to examine CFD data which modeled the air flow from the air conditioning unit in the interior of a tractor cab. They used the C2 device at Iowa State University as the virtual environment. Kohlmeyer's application was developed as a demonstration of the use of VR for CFD and was not intended to be a general purpose VR CFD program. This paper outlines the capabilities of the VR CFD program developed at Iowa State University and presents initial user reaction of engineers and analysts who have used the application.

MOTIVATION

Bryson and Levit's "Virtual Wind Tunnel" was developed to provide an interface where the results of CFD analysis on unsteady three-dimensional flow could be examined. Each time step represented a new flow pattern. These flow fields were pre-computed and a virtual reality interface was used to display these results. The hardware consisted of a BOOM visual display, VPL dataglove II with a Polhemus 3Space tracker, and a Silicon Graphics Iris 380 VGX computer. The Sterling Software/Ford application was implemented using the BOOM visual display, CyberGlove with a Flock of Birds tracker, and Silicon Graphics computers.

One motivating factor concerning the work presented here was the desire to explore other virtual reality interface devices and environments for CFD analysis in order to facilitate collaborative design and discussion. The application discussed in this paper was developed for display in a head mounted display, on a stereo capable monitor and also in the C2 virtual reality room.

The C2 at Iowa State University is a room where stereo images are projected on three walls and the floor. Position tracking with the Flock of Birds is used to track one person's head and hand position allowing one person to act as a guide for the other participants investigation of the data field. Up to 12 people can be in the room comfortably at the same time. Each person wears CrystalEyes stereo glasses in order to see the stereo images being projected on the screens. Sound capabilities enhance the immersive nature of this device. The C2 is powered by two Silicon Graphics Onyx racks, each with 2 Infinite Reality Graphics pipes and 12-R10,000 processors. This device is most similar to the CAVE which was originally developed by Carolina Cruz-Neira (Cruz et al., 1993). Although the correct viewing perspective is only projected for the one person wearing the tracked stereo glasses, others in the environment rarely notice the small distortions viewed from their individual perspectives. Interaction within the C2 is provided by a wand or the Pinch Gloves. In the application developed here, the wand is used as the primary input device.

One key distinguishing characteristic of different virtual reality environments is the ability to immerse the user in the

computer generated images. When users feel immersed in a virtual environment they believe that the computer generated objects occupy specific locations in the virtual environment. This is accomplished through the use of head tracking and three-dimensional interaction. Field-of-view has also been shown to affect a person's sense of immersion in the virtual environment.

While the BOOM provides excellent tracking and presents a non-intrusive head tracked visual display, it remains a one person device. In a collaborative environment, with an external monitor attached, participants can only describe and discuss what the user of the BOOM cares to investigate. In addition, when using the BOOM, only the person viewing the data through the BOOM achieves any sense of immersion in the data. The head mounted display is similar to the BOOM in that it also is a single person device. Only through the use of an external monitor can others participate in collaborative discussions of the data and the only person experiencing immersion in the data is the person wearing the helmet. The stereo capable monitor allows all of the participants to view and discuss the image without the aid of an external monitor, however, the sense of immersion that is felt when viewing stereo data captured on a desktop monitor is very low. The C2 provides an environment where multiple users are immersed in the data field and can easily discuss and investigate the entire flow field. The wide field-of-view and user controlled viewing allows multiple users to individually look around at the data and examine individual areas of interest.

The goal of this research was to provide a virtual environment for post processing CFD data which would allow stereo viewing and three-dimensional interaction in a collaborative environment. VR-CFD, a program that can be implemented using a variety of VR hardware, was built to meet these objectives. The following sections outline the structure and capabilities of VR-CFD.

SOFTWARE and HARDWARE

VR-CFD was developed using OpenGL, Visualization Toolkit (VTK), and the C2 library. The C2 library provides the virtual reality framework by providing functions which synchronize the four viewing walls to display one environment, display the correct viewing perspective based on the head tracked position of the one pair of tracked glasses and allow interaction with the computer images through an input device. This library was developed by Carolina Cruz-Neira. OpenGL and the Visualization Toolkit are used to provide the graphics framework for this application. The VTK library provides functions for the calculation of fluid flow parameters and renders the output as OpenGL graphics (Shroeder et al., 1998). This software is downloadable from the web at <http://www.kitware.com/vtk.html>. In cases where geometry display is needed and few calculations are required, OpenGL alone is used as the graphics software framework which provides faster

rendering than the VTK software. Implementing VTK into the C2 library was fairly straightforward since both software libraries render graphical output using OpenGL. To get VTK output to display in the C2 environment, the VTK window widget is replaced with the X11 window widget of the C2 library. VR-CFD can be displayed using either the C2, the HMD, or a standard monitor with stereo display. Head and hand tracking exist in all these environments. Figure 1 shows a person interacting with the data in the C2 facility.



Figure 1. User interacting with data in the C2

SOFTWARE FEATURES

Interaction

Wand: This device is a joystick with a six degree of freedom position tracker attached such that the position and orientation of the wand can be determined at all times. The three buttons on the wand are configured to enable the user to perform functions such as translation, rotation, and scaling of the entire scene, and toggling between different modes of interaction for manipulating flow entities. The buttons are also used for interaction with a menu system which provides for selection of various tasks.

Menu System: The menu is an array of texture mapped 2D polygons that are attached to the front wall of the C2. Red buttons are used to open menus, close menus and switch between menus. Blue buttons either lead to further menus or activate functions. The menu organization was patterned after the Fieldview post-processing software so that users of Fieldview could easily navigate within the menu. Fieldview is a commercial post-processing software package. Interacting with the menu is accomplished by pointing the ray that extends from the wand at a button on the menu. Once the intersection of the ray with the button has been detected, the button is highlighted and can be selected using the trigger of the wand. See Fig. 2 for a picture of a sample menu and wand cursor. When a button is

selected, a sound is produced indicating positive selection.



Figure 2. Menu system

Data format

At present the application supports two types of data, PLOT3D and Fieldview particle tracer format. PLOT3D is a standard data type for CFD applications.

Entity visualization

Streamlines: Streamlines in the flow indicate the path that a particle in the flow would take if placed in the flow at the seed point. The users have the ability to place seeds in the flow and create streamlines by moving into the flow and using the wand to indicate the seed position. Integration of the velocity vector field can be performed forward, backward or in both directions through the flow field from the seed point. Figure 3 shows two rakes of streamlines. Rakes are a set of streamlines originating from a source line. The streamlines can be displayed as either lines, tubes or ribbons. Scalar parameters such as pressure or temperature can be color mapped onto the streamlines. Multiple streamlines and multiple rakes can be placed in the flow.

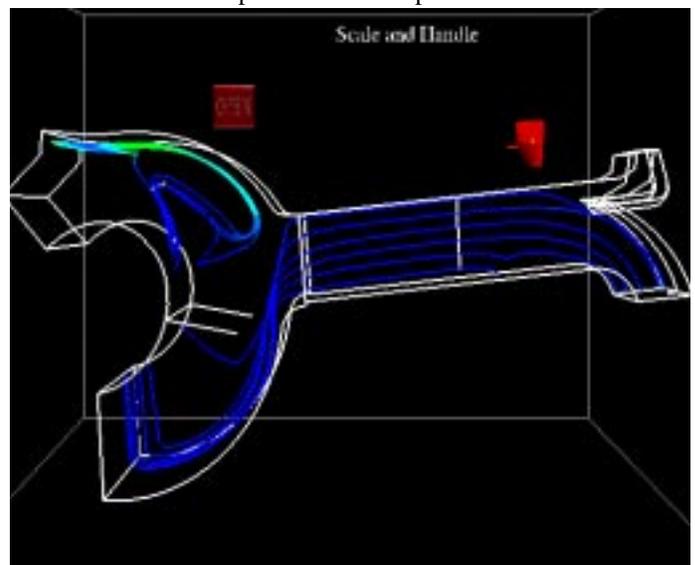


Figure 3. Rakes of streamlines

Animated flow particles: Bubbles placed on the streamlines can be animated to better show the path of particles in the flow (Figure 4). The streamlines are set as the paths for tracer particles. If multiple streamlines are selected as paths, bubbles start out on each streamline at the same time. These bubbles, however, travel at the instantaneous speed of the streamline as they move along the streamline. Examining the movement of bubbles on multiple streamlines gives the user an indication of the relative velocities of areas of the flow. The bubbles can be animated forward and backward.

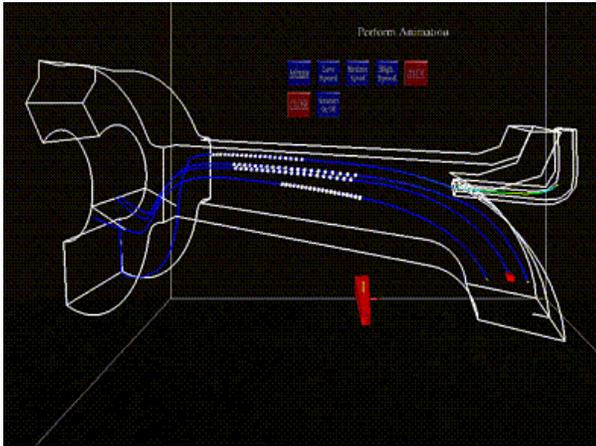


Figure 4. Animated bubbles along streamlines

Cutting Planes: Cutting planes can be oriented according to the local x, y, and z axes or interactively placed at any orientation. The planes can be color mapped according to the chosen scalar value. The default color mapping selects a range based on the maximum and minimum values of the scalar. Often, the area of interest is contained in a narrow range of scalar values. In order to more clearly visualize different areas of interest, the user can adjust the color mapping maximum and minimum values. All areas below and above the range are set to the maximum and minimum values of the range respectively. The range of values can be interactively defined using a slider mechanism. In this way, the user can more clearly differentiate the data in the range of values of interest (Figure 5).

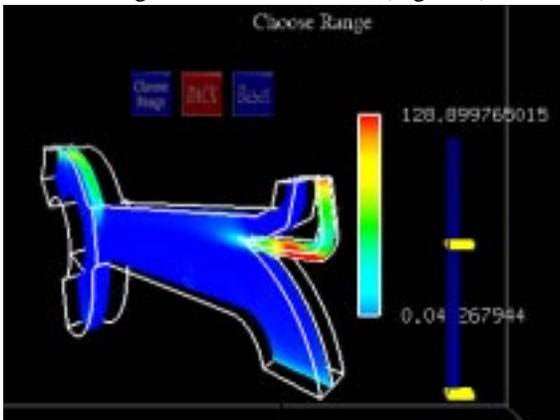


Figure 5. User-defined color map ranges

In-plane vector values can also be mapped to the cutting plane (Fig. 6).

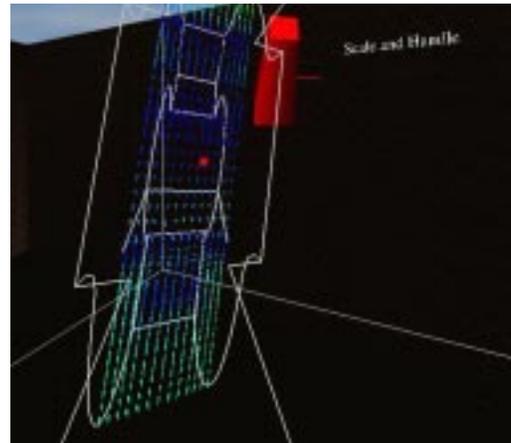


Figure 6. In-plane vectors

Vector Field: Capability has been provided for visualizing the full vector field. Lines are drawn at every point and are oriented along the direction of the vector at that point. The field is color mapped according to the vector magnitude. See Fig. 7.

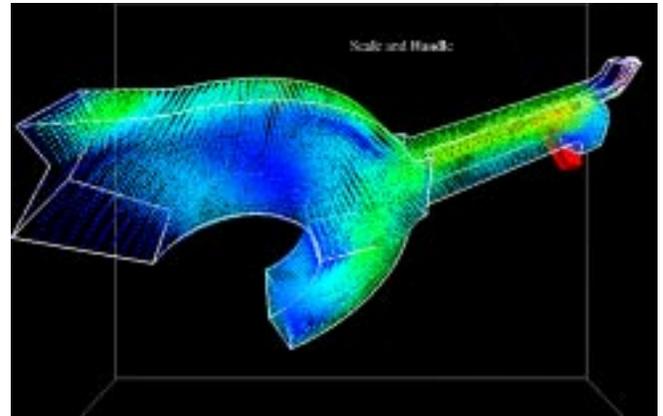


Figure 7. Full field velocity vectors

IsoSurfaces: Isosurfaces are surface contours of points having the same scalar value. Users can visualize isosurface pairs at a minimum and a maximum value. The pair values can be changed and defined by the user. The user can also switch between scalars, with the maximum and minimum range values as the defaults. See Fig.8

Mixing: In flows that involve mixing of two or more streams, it is helpful to visualize the amount of mixing between two streams. In Fig. 9, the first fluid is shown as green and the second fluid is red. As the two streams mix, they form areas of dominant red, green, or yellow as well as tints of reddish and greenish yellow depending on the degree of mixing. This color identification enables the users to locate areas of interest where the mixing is good, unequal etc. For example, in Fig. 9 it can be observed that there is an almost equal mixing of the red and

green streams in the upper central region of the geometry.

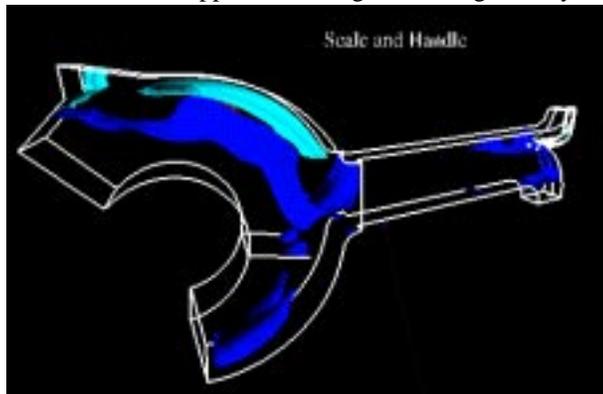


Figure 8. Two isosurfaces of scalar parameters

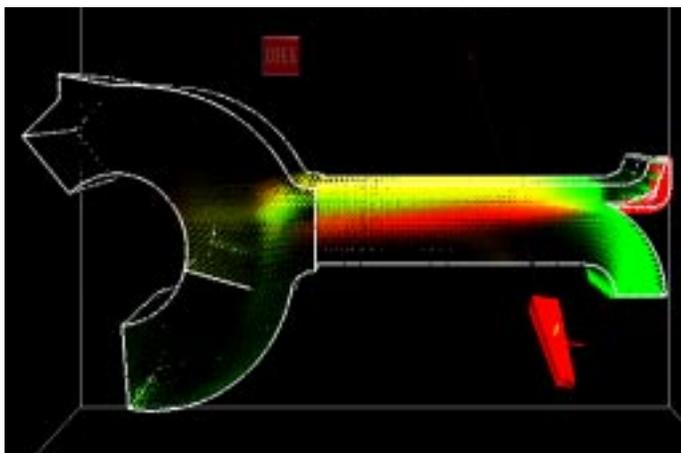


Figure 9. Mixing of two or more streams

Multiblock data

It is usually not possible to generate a single structured grid for a complex flow field. Different areas of the flow require finer meshing. Unstructured grids can be used in these cases, but the computation time for creating flow entities while using unstructured grids is quite high. To overcome this difficulty, it is common to divide the flow field into several smaller structured grids of varying sizes. Each division is called a block and the flow field data is stored as multiblock data. This allows flexibility in modeling while providing for faster computations.

The VTK software does not specifically support multiblock data format. For entities such as cutting planes and isosurfaces, a given entity most likely will span several blocks of data and can be calculated in each block independently. However streamline generation presented the problem of creating continuous streamlines extending from one block to another. The data that was supplied to us was multiblock data. One approach to overcoming this limitation with generating streamlines in multiblock data using VTK was to append together all of the structured grid blocks and store the result as one unstructured grid data file. Theoretically it should be

possible to generate all the visualization components with the resulting unstructured grid. But VTK software has an error which prevents the formation of streamlines when there are coincidental points making up flat hexahedral cells, which result at the common surface of two blocks of data when they are appended. This approach to dealing with multiblock data was abandoned.

RESULTS

Over the course of the development of this software several meetings were held with the sponsors of the research. Typically these meetings involved five people: two of the co-authors of this paper, a manufacturing process engineer, a CFD analyst, and a CFD code developer. User response to the VR CFD application paralleled results reported by Bryson, et al. (1995) which states that users were enthusiastic about the capabilities that VR provided for examining fluid dynamics data. Bryson reports that users who viewed known data sets found flow phenomena which hadn't been recognized before. It was our experience that in addition to this, users were able to more fully reconfirm their understanding of the fluid flow while working in the virtual environment. The C2 virtual environment provided a fully immersive environment in which to examine the results of the data analysis. Users were comfortable moving in and out of the flow to examine the flow characteristics. It was common for the team to spend up to 3 hours at a time in the C2 and up to 6 hours per day examining the data. Interaction with the wand was very natural and easy to learn. The menu hierarchy was familiar because it was organized similar to the Fieldview menu organization.

During one visit, the application was demonstrated on both the stereo monitor and in a head mounted display. The user interaction with the wand was the same in all three environments and head tracking was also implemented in all three environments. Feedback from the users indicated that the head mounted display was intrusive and did not encourage collaboration in examining the data flow. The stereo monitor's lack of ability to provide the user with a sense of immersion greatly reduced the advantages of implementing this application using virtual reality. The use of the C2 encouraged collaboration and was a comfortable interface in which users could work for an extended period of time.

FUTURE WORK

There are many ways to improve this application. The following avenues are currently being explored:

- *Generality:* The generality of this application as a post-processing tool can be further improved to be able to specify a larger number of data formats, and to take in a larger number of scalars and vectors.
- *Computation speed:* This is a key issue in CFD post-processing. CFD grids can easily become very large and trade-offs must be made between displaying all of the data and

maintaining real time display speed for VR on the order of 12-15 frames per second as a minimum. The application presented here contained 50,000 cells. When the full velocity field was displayed, the frame rate dropped below 10 frames per second. Displaying multiple rakes with a cutting plane also reduced the frame rate. Researchers at the National Center for Supercomputing Applications are developing an interface where VTK and Iris Performer are combined in an effort to increase display performance (Leigh et al., 1998). Bryson and Gerald-Yamasaki (1992) have investigated implementation of a distributed architecture for the Virtual Windtunnel. Both of these approaches will be investigated in the near future.

- *Calculation of new scalar and vector properties:* This capability will allow users the ability to define more parameters by using the given scalar and vector data.
- *Flow field approximation:* Since CFD simulations take a long time to generate, approximating, interpolating or extrapolating the flow fields using intermediate existing flow fields would be an effective way of obtaining an understanding of the flow behavior with changes in parameters such as geometry and time. This approach has been successfully applied to finite element results (Yeh and Vance, 1998) and similar methods will be pursued as they relate to CFD data.
- *Multiple usage and VR networking:* This development will enable different users in different locations to interact with the application at the same time. At present, the application can only run in one location. In the future, several users at different locations in different parts of the world will be able to work with the same data.
- *Menu system:* Currently, the menus are stationary. There are many different menu paradigms possible in VR. Different options such as the VUI developed by Daniel Heath (1998) will be investigated.

CONCLUSIONS

A virtual interface tool (VR-CFD) for the visualization of CFD data was developed. Features for creation and manipulation of flow visualization entities, and for interacting with the geometry were provided. These entities include streamlines, rakes, cutting planes, isosurfaces, and vector fields. Interaction was provided using the wand and through a menu hierarchy. Other features included visualization of full field vectors, mixing streams and animating tracer particles. Data formats supported include PLOT3D and Fieldview particle data. The flow visualization functions of VTK were used for calculations and rendering along with OpenGL. The VTK library was integrated with the C2 library which was used as the virtual reality platform.

The C2 virtual reality environment provided a comfortable three-dimensional immersive environment for the examination of the results of CFD analysis. This virtual environment

facilitated collaboration between various members of the design/analysis engineering team.

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