Invited Paper

Scientific Visualization in computational fluid dynamics

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While visualization of flows in experimental situations has a long tradition, numerical flow solutions may be presented using easily understandable images only since fast computer graphics techniques are available. During the recent past a number of software systems appeared, some developed at universities or research facilities, others being commercially available. When studying those systems different designs become obvious which make a given system more or less suited to a particular application. An overview about some of the most relevant software packages illustrates their differences and advantages.

Most of the available visualization software offers a common set of visualization techniques. The methods used by established software systems largely determine the way how numerical flow simulations are presented today. Nevertheless some activities may be identified which try to develop new methods for flow visualization in computational fluid dynamics (CFD). These new techniques will add more variety to the methods for creating images of flows and thus allow a better communication of results, concepts and understanding of fluid dynamics.

In many cases easy and fast visualization is a necessary condition for the discovery of structures and phenomena in flow fields. The reason for this are the vast amounts of data which are produced during a numerical simulation of flows. By visualizing these data one can make efficient use of the capabilities of the human brain to detect structures even in partly obscured or incomplete images. Once a particular, may be unexpected structure has drawn the attention of the researcher, he may follow this trace using a fast interactive visualization system until finally he eventually discovers a new unknown feature. Automatic data reduction algorithms, however, would find only structures for which they are designed to detect.
FEATURES OF CFD DATA

Numerical simulation of flows becomes easier to understand when data are mapped to graphical presentation. Since these flow calculations are created using computers the use of computer generated graphics is highly desirable. Thus early visualization of numerical results frequently presents the state of the art in computer graphics. The technique chosen to illustrate the data depends on the methods which are easy to implement in computer codes and the output is determined by the quality of existing hardware. While in experimental fluid mechanics a significant amount of research work is put into the development of visualization apparatus for specialized applications, a specialized flow visualization computer does not exist. Software in use offers visualization methods which are generally applicable in the wide area of scientific visualization rather than tackling the special problems of fluid dynamics. Direct comparison between the visualization of real flows and their numerical simulation is rarely possible.

Data Types

Numerical simulations of flows essentially produce a limited set of data types which are very frequent in engineering sciences. This makes it easy to apply mapping techniques which are commonly used. Such visualization will often be sufficient and satisfying. In some cases however, additional methods dedicated to fluid mechanics will be required. Typical data types are:

- location, a vector quantity which defines a location for a data value in a space or in a space-time frame
- scalar quantity which describes a selected physical quantity
- vector quantity, for example the flow velocity
- tensor quantity

Data structure

Besides the data type, the structure of how the data are accessed within the computer's memory plays an important role for the visualization. There are mainly two reasons for that. Often visualization software will be designed to operate on the same data structures without any necessary conversion or generalization of the data in order to benefit from possible advantages in processing speed. On the other hand the user may want to avoid any data conversion or interpolation in order to avoid artefacts introduced by the visualization scheme being visible on the display, while they are not present in the data. Some flow data may be reduced to single numbers or discrete representations of functions. Since computational fluid dynamics today deals with two-dimensional data fields at least, most often however with three-dimensional data or even time-dependant data in 3D-space, these data are organized using computational meshes. These meshes define a certain ordering of the location in space and time where the governing partial differential equations of the problem are solved numerically. All flow
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data is stored at these discrete locations. Frequently these locations are visual-
ized by connecting them with straight lines which gives the illusion of a mesh.
The data may be stored at the node of the mesh, in some cases as well in the
centre of the cells of the mesh. Four major types of meshes or grids are used in
CFD:

- structured grids
- multi-blocked structured meshes
- unstructured meshes
- hybrid meshes

The unstructured mesh is the most general but at the same time most memory
consuming way to store data.

COMPUTER GRAPHICS TECHNIQUES

Some data requires only moderate visualization techniques which are readily
available on most computers today. This holds for example for the problem of
visualizing discrete functions of one independent variable. Such data are fre-
quently displayed using x-y-charts. Besides a large number of commercial soft-
ware packages which serve this purpose there are some excellent programs to
be found in the public domain. One example is the well known xvgr tool by P.
Turner [1].

In the two-dimensional domain the use of various techniques is known for
the visualization of scalar quantities:

- iso-contours
- pseudo-colours
- height maps

All these methods are easy to understand for most users since they are known
from cartography and serve well for their purpose.

For the display of vector quantities two techniques are most common in
CFD:

- arrow or hedgehog plots
- streamlines or particle paths

In order to create an arrow plot the direction of the arrow encodes the direction of
the vector quantity, the length of the arrow will encode the magnitude of the
vector quantity. To avoid visual clutter the magnitude may be encoded by the
colour of the arrow as well while all arrows are drawn using an equal length. If
different visual idioms [2] rather than classical arrows are used these plots are
commonly called hedgehog plots.
Streamlines are a numerical simulation of the experimental flow visualization techniques which results from the recording of particle paths through a flow field. It is important to notice that particle paths turn out differently if a flow field is considered independent of time or not. A review of streamline tracking algorithms was recently given by Kenwright and Mallinson [3]. While in fluid dynamic streamlines, that are trajectories of the velocity vector field, may be the most common use of this visualization technique, these methods are not restricted to velocity vector fields. The same technique may be applied to the wall shear stress vector or any other vector field. Nevertheless the computation of trajectories in the velocity field of a flow in order to display streamlines or particle paths is probably the most often used visualization technique which tries to mimic the visualization of real flows.

Figure 1. A planar cut through a numerical flow field. The Mach number distribution is displayed in pseudo-colours on the planar section. The computational mesh which holds the data is presented in black. The planar section cuts through the cells of the mesh in an oblique fashion.

In three-dimensional space the visualization of flows becomes much more difficult since the techniques known from the 2D case are no more applicable or misleading. The use of height maps, iso-contours and pseudo-colouring is not directly usable in a 3D field of scalars. However these techniques may still be applied to surfaces in a 3D-domain. Therefore they can often be found in visualization of CFD results in 3D space. This requires some data reduction process to have taken place beforehand. Typical data reduction methods to be applied in order to create surfaces in a three-dimensional domain for which then 2D visualization techniques may be applicable are:
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- subsampling of surfaces according to identifiers or grid indices
- interpolation of data upon planar cuts
- thresholding of surfaces to limit visibility to a scalar interval

After this data reduction, scalar quantities in space may be visualized on selected significant surfaces using height maps, iso-contours and pseudo-colouring. Of course, it is possible to display arrow plots of vector quantities or streamlines on surfaces, however the resulting images are often misleading and if at all need to be used with special caution. Streamlines, if displayed as simple lines, are not really easy to understand in a three-dimensional domain since the depth information is easily lost.

![Figure 2. Iso-surface of the vorticity within a wall shear layer during transition from laminar to turbulence. This visualization of a numerical simulation exhibits the lambda shaped structures which are known from experimental visualizations of such flows.](image)

As there is no effective method for rendering scalar quantities within a volume of space, much emphasis needs to be put on the interactive selection or creation of surfaces inside the volume onto which the desired quantities may be mapped for display. If the data is stored using structured grids, surfaces of constant index often provide a significant location such as a wall, a plane of symmetry or a domain boundary. In other cases, it may be necessary to create surfaces using a special data processing and to use these artificial surfaces for display. Any quantity which is mapped onto such a surface may be visualized at that location.

Frequently, surfaces within a volume of data are created using an iso-surface method. This powerful mechanism allows to spot locations where a selected
quantity takes a certain value. In arbitrarily shaped data meshes the same algo-
rithm may be used to create planar cuts through a volume. In such meshes a pla-
nar cut is nothing but an iso-surface where a linear combination of the
coordinates takes a constant value.

Iso-surfaces are a very powerful technique to illustrate internal structures in
data fields. In order to be able to create meaningful services which reveal some
information from the data, one needs to interactively adjust the parameter
which defines the surface carefully. Since this process may require a large
number of loops, an effective algorithm for the calculation of such surfaces is
needed. Due to the effect that shaded surfaces can exaggerate any kink or
unsmoothness iso-surfaces are extremely sensible to numerical wiggles or noise
in the data. Therefore they may be of great help when looking for the quality of
numerical simulations.

Figure 3. Streamribbons illustrate the vortical flow near a turbine blade.
Increasing width of the ribbons visualizes the flow divergence.
The transparent blade geometry allows to visualize the flow on
both sides of the blade.

Many systems have implemented an algorithm suggested by Lorensen and
Cline [4]. This algorithm which was originally designed to process medical
imagery data has been thoroughly discussed in the literature and improvements
have been suggested (see for example: [5]).

For the visualization of vector quantities within a volume of data several
techniques are widely used:
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- streamribbons
- stream surfaces
- particle traces
- particle advection
- topological analysis of vector fields

There are various methods to generate the surface elements of stream ribbons from the information of particle traces. Some modern extendable software systems allow to implement a choice of methods [6]. A simple technique is achieved by connecting adjacent streamlines by surfaces obtained from triangulation. This method may be used to create streamsurfaces as well.

![Figure 4. Streamsurfaces in a wall shear layer. In order to illustrate how the surface is created by connecting adjacent streamlines, these lines are drawn upon the surface. While the left and right streamsurface is selected properly to display the vortical behaviour of the flow, the surface in the centre was intentionally composed of a diverging set of lines to illustrate the need for a careful selection of lines in order to avoid unrealistic folds.](image)

Even more information about the velocity field may be seen in images of particle systems which move along with the flow. These images can display not only the local flow direction but also the velocity magnitude as well as the local shear in the flow field. This becomes visible in particular by using animations. Some very interesting research work concerning motion of particles has been described by Stolk and van Wijk [7]. Another technique which is useful especially for vortical flows and three-dimensional flow separation is the extraction of topology information from the flow field. The visualization system FAST [8] which is in use at NASA has incorporated some algorithms reported by Helman and Hesselink [9] for that purpose.
SURVEY ON VISUALIZATION SYSTEMS

A survey on visualization systems conducted recently at DLR examined more than 30 systems which are commercially available or known to be in use at various universities or research establishments. About one third of these systems was installed on our computers for a serious testing. Other systems have been tested at different sites of cooperative partners. A technical report [10] is available which summarizes the results of this survey.

Most of the systems offer a good selection of the present state of visualization techniques as presented in the previous chapter. However the particle system technique as well as the extraction of topology information from the flow field is still not available in these systems.

Architecture of visualization systems

All systems examined during the study can be ordered according to their internal architecture into three groups.

- turn-key systems with traditional single program architecture
- application builders with data flow driven user interfaces for visual programming
- modular systems

Most of the research systems and some of the commercial visualization systems have a software architecture which combines data storage mechanisms, all the different visualization algorithms and the user-interface within one single program. These turn-key systems are most easy to design and have some advantages due to the fact that once loaded into the system all data is accessible at any time. This advantage allows easy implementation of feedback mechanisms such as probes or picking devices to select data within the image and trace back to the related input data. This architecture as well has advantages in processing speed as long as the amount of data to be processed does not exceed the available memory of the computer by far.

Unfortunately CFD tends frequently to tackle problems which are large even for the biggest available computer. Therefore the advantage of processing speed is often lost due to the need of swapping data to the disk which is in general not done with an optimal strategy.

Another severe disadvantage of this architecture is the well known tendency of such programs to become very complex. This makes them difficult to maintain and extend. Even if the source code is available to only a limited amount of people, if not only the designer of the program, they will have a chance to customize the system and implement new visualization technologies.

Several commercial systems such as AVS [11], apE [12], Khoros [13] and Explorer offer a visual programming interface. This interface allows to select algorithms from a toolkit and program the data flow between those modules visually by drawing connecting lines. Further customizing a system to deal with a
given application becomes easy. To a certain extend new algorithms may be implemented by using a combination of existing modules. Some systems like AVS offer facilities to create user designed modules and therefore allow in principle to include any future visualization technique. In practice it may turn out that these extensions require significant knowledge about the system and unexpected effort [14].

Due to the fact that all modules communicate using pipes or socket connections they are loaded into the computer simultaneously once they are required for a programmed sequence. Since they all allocate memory to hold their data a significant duplication of data is unavoidable, which makes such systems very memory consuming.

Whereas the turn-key systems are a good choice in a production environment where a given class of visualization has to be produced frequently, the visual programming systems have their advantages when developing new visualization technology or processing very different types of data.

**Modular systems, the best of two worlds?**

The third class of visualization systems are the modular systems. SUN’s visualization and image processing package SUNVISION [15] may be considered to be in this group as well as the system designed at DLR named HIGHEND [16]. As our own software is mentioned here the heading of this paragraph may be provocative, indeed. In fact, modular systems can combine some of the benefits of the two other known architectures but they certainly show their own particular drawbacks. Note, that depending on the computing environment and the application any of the three architectures may turn out best suited for a user.

The modular system HIGHEND consists of a large number of programs which each perform a comparatively small task of the visualization process. Data is passed between those modules by writing or reading files. These files are created and accessed automatically. Therefore, the user does not have to bother with this data system. In order to keep things comfortable all modules have a similar, consistent user interface. In the modular system SUNVISION the user interface is even combined in one special program which communicates with all modules using a parameter management system.

For both systems holds that by invoking modules in a desired sequence many different visualization tasks may be performed. Much like in the visual programming systems even new effects which have not been considered during the design of the system are possible due to the flexible arrangement of the modules. Since the data may be easily retrieved from the intermediate files, new algorithms may be added to extend the system. This is even possible if the source code of the visualization system is not available. By creating a simple program which may be used in between two of the existing modules data from the visualisation may be captured and undergo additional user-defined processing. Afterwards it will be feed back into the visualization system.

The HIGHEND system presently offers a large selection of state of the art
visualization technology. Besides generally applicable algorithms a number of features is dedicated explicitly to fluid dynamics. Presently the following features are available:

- structured, body-fitted grids
- multi-blocked grids
- unstructured grids in 2D and 3D
- display of gridlines
- display of surfaces, flat shaded and Gouraud shaded
- display of poly-lines and single points
- extraction of subvolumes from unstructured grids according to markers
- extraction of surfaces of constant grid index including subregions
- extraction of surfaces from unstructured grids according to markers
- extraction of lines from unstructured grids according to markers
- calculation of aerodynamics quantities on all data structures
- location of shock positions
- gradient calculations
- 3D interactive rotation with mouse input
- OPEN LOOK compliant user interface
- reusable layout definitions
- pseudo-coloured encoding of scalars on any surface or line
- hedgehog plots
- isocontours, isosurfaces
- planar cuts through structured and unstructured grids
- calculation of streamlines, trajectories, vorticity lines
- streamribbons, streamsurfaces
- triangulation of surfaces between sets of lines
- triangulation of arbitrary polygons
- thresholding of polygons and lines
- conversion of data formats, import and export converters
- interactive control of all processes and parameters
- multi-lingual user-interface selectable at run-time
- open data interfaces for user designed extensions
- definition of keyframes for calculation of animations
- on-line help facility
- modular structure
- remote visualization and cooperative working facilities

This makes HIGHEND a competitive system even compared to commercial visualization systems. In particular, HIGHEND turns out to be very effective in environments with relatively poor computer hardware and large amounts of data. Due to the build-in need for disk I/O the system is less effective, once the problem size fits well into the computer.
FUTURE DIRECTION OF VISUALIZATION RESEARCH

Improved rendering technology
Modern hardware provides the necessary processing speed for enhanced rendering techniques. These allow to include visual aids such as:

- shadows
- atmospheric attenuation
- transparency
- texture mapping

Such visual aids will provide a more rapid and more intuitive understanding of images to persons who were not involved in the process of the visualization or which are not trained in understanding and interpreting simplified computer graphics. Visualized data will be presented in a way much closer to human viewing experiences and thus be less difficult to perceive.

Figure 5. Shock visualization around a hypersonic transport aircraft. The position of the shock is extracted from a numerical solution of the flow field. The transparently rendered shock surface allows to see the details of the complex shock pattern near the wing.
Improved data reduction and mapping techniques
Visualization requires to transform data which is essentially not visible into some kind of visualizable objects. Since these objects frequently do not have much in common with real objects the human mind has to draw conclusions from often very abstract structures. Once visualization techniques are readily available additional effort may be spent by customizing visualization towards specific applications. Therefore, some of the pattern recognition task which are normally performed by the human mind may be transferred into the computer. Structures may be localized and identified within the data and then displayed on the screen using a dedicated method for those structures. This is why today visualization systems in fluid mechanics are equipped with topology analysis systems [9] or shock wave analysis algorithms [17].

The shock wave localization method provides a polygonal representation of the three-dimensional shock systems in supersonic flow fields. These may be displayed in a way which is quite close to some experimental visualization techniques in real flows. Researchers which have experience with optical methods of flow visualization in experimental setups will thus more easily compare their images to numerical results.

Another final goal may be to simulate experimental visualization methods on numerical data in order to obtain a direct comparability of images.

Animation and Digital Video
Today, workstations offer sufficient processing capabilities to display animated graphics. However in general, the amount of information within a scene as well as the choice of rendering methods is limited to those techniques which are supported by the specialized graphics hardware. High quality visualization may on the other hand require more effort. Still, excellent animations may be created on small computers by calculating single images in advance which are afterwards assembled to make up the required animation scenes.

There is a low cost possibility to record such scenes frame by frame to a video tape [18]. However new technology developed for multi-media applications offers opportunities to create and store even long animations on a disk in a compressed fashion. Real-time decompression software is then used to run the animation on any workstation screen. The new SUN XIL [19] software for example was found to be fast enough to perform this task even on a low cost SPARCstation II computer. This software offers decompression without loss of image quality. The processing speed is even fast enough to include audio with the animation. This technique is an excellent method to document and transport animations. It may be used as a preview method during video production as well [18].

Remote visualization and cooperative visualization
Computer networks provide a mechanism to visualize data remotely from a distant site. This makes it easy to bring different data to a display for comparison. Multi-media technology today offers the possibility for researchers at distant
locations to visualize the same data simultaneously and discuss about the images using telepointers, audio and video communications [20]. All these communication mechanisms may be integrated within one single software system which uses a standard computer network to transfer necessary information. The feasibility of such cooperative system was already demonstrated on local networks. A wide area connection will be built in the near future in the course of a european project.

Figure 6. The cooperative visualization facility built upon the HIGHEND visualization system

Besides providing all standard visualization techniques the system offers a bi-directional audio communication, a low speed video connection over standard Ethernet networks and a remote pointer to enhance human discussion about the data in display. For demonstration purposes video cameras were directed towards the computer screen in order to illustrate the synchronous visualization on both workstations.

By the use of networked visualization systems, scientific visualization faces the chance to become an integrated part of communication in modern science.
CONCLUSION

The lack of visualization software about 6 years ago led to a large number of software systems being developed in European research establishments. Today there is a choice of systems as well as several commercial visualization packages available. These software may be sorted into three groups depending on the software architecture. Each type of architecture turns out to be best suited for a certain application environment. Turn-key systems work best for production purpose, visual programming provide high flexibility for varying visualization demands. Modular systems while still very flexible show smaller appetite for computer memory and processing speed.

A common set of standard visualization technique may be found in most systems. Future developments direct towards improved rendering quality, enhanced data abstraction and recognition of structures and phenomena in the data as well as the use of multi-media techniques for animation and communication purposes.

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