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Tools for 3D Scientific Visualization in Computational Aerodynamics

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ABSTRACT

The purpose of this paper is to describe the tools and techniques in use at the NASA Ames Research Center for performing visualization of computational aerodynamics, for example visualization of flow fields from computer simulations of fluid dynamics about vehicles such as the Space Shuttle.

The hardware used for visualization is a high-performance graphics workstation connected to a super computer with a high speed channel. At present, the workstation is a Silicon Graphics IRIS 3130, the supercomputer is a CRAY2, and the high speed channel is a hyperchannel.

The three techniques used for visualization are post-processing, tracking, and steering. *Post-processing* analysis is done after the simulation. *Tracking* analysis is done during a simulation but is not interactive, whereas *steering* analysis involves modifying the simulation interactively during the simulation. Using *post-processing* methods, a flow simulation is executed on a supercomputer and, after the simulation is complete, the results of the simulation are processed for viewing. This is by far the most commonly used method for visualization of computational aerodynamics. The next two methods are much more desirable, yet much less common given the current state of supercomputer and workstation evolution and performance. Both of these are more sophisticated methods because they involve analysis of the flow codes as they evolve. *Tracking* refers to a flow code producing displays that give a scientist some indication how his experiment is progressing so he could, perhaps, change some parameters and then restart it. *Steering* refers to actually interacting with the flow codes during execution by changing flow code parameters. (Steering methods have been employed for grid generation pre-processing as well to substantially reduce the time it takes to construct a grid for input to a flow solver). When the results of the simulation are processed for viewing by distributing the process between the workstation and the supercomputer, it is called distributed processing.

This paper describes the software in use and under development at NASA Ames Research Center for performing these types of tasks in computational aerodynamics. Workstation performance issues, benchmarking, and high-performance networks for this purpose are also discussed as well as descriptions of other hardware for digital video and film recording.

A new software environment, FAST, is introduced that is currently being developed at NASA Ames for implementation on workstations that will be procured in the latter half of 1989. This modular software environment will take advantage of the multiple processor and large memory configurations and other features as specified in the NASA RFP for these workstations and is a natural evolution of the techniques described in this paper.

1. INTRODUCTION

Using computational aerodynamics, scientists are now able to model complex fluid mechanics problems using supercomputers and new numerical algorithms. To gain a better understanding of these complex flow fields, scientists use high-performance computer graphics workstations to view and in some cases animate these simulations. This paper describes this application, the hardware, the software, and the techniques used by the Fluid Dynamics Division of the NASA Ames Research Center.

2. DESCRIPTION OF THE APPLICATION

The simulations involve visualizing flow field solutions generated on supercomputers. The raw data from these simulations consists of density, momentum vector, and total energy per unit volume specified at each grid point in the computational domain. A typical computational domain may contain 1 million grid points. This raw data must be converted to a scene depicting the physics in a manner the scientist can easily interpret. Color and visual cues (shading, animation, etc.) are used to demonstrate the physics of the particular result. PLOT3D, GAS, SURF, RIP and a new software environment FAST (currently under development) are visualization tools described further in this paper.

3. VISUALIZATION REQUIREMENTS

The views of the simulation portrayed by the computer graphic workstations must be 3D because visualization of the inter-related flows of all three dimensions simultaneously is important. The displays must be dynamic in order for the time-variant features of the flow fields to be understood. Although the motion need not be real time, the motions must be rapid enough to gain a proper understanding of the dynamic features of the flow. The flow fields typically have a large range of scales; therefore, the scientist must be able to zoom into a region of small scale features and zoom back out to view the overall flow field. Furthermore, the displays should be high definition to contain adequate detail at all scales. The displays should simultaneously contain solid body objects, such as an aircraft (with hidden surfaces removed), and points or lines (such as lines representing the paths of tracer particles inserted into the flow field). As the displays evolve in time illustrating the flow dynamics (e.g., the movement of tracer particles) the viewing position must be simultaneously changeable in real time (as the flow is evolving) in order to maintain the best view or to get a different perspective. Dynamic change of the viewing position is one of the best cues for enhancing the 3D aspects of the display. In addition, new visualization effects such as ribbon traces, smoke, shading of function mapped parts, anti-aliasing, variable transparency, volume visualization and stereo are being requested by the scientists studying the flow fields.

4. OVERALL APPROACH

At the current time, no workstations costing less than approximately $100K have been available that can meet the requirements described above for dynamic viewing of complex solids embedded in flow fields. Therefore, the approach has been to obtain workstations with the highest performance available at the time of the procurement, and to augment these workstations with equipment for recording on video tape and 16mm film to permit dynamic viewing of complex scenes that could not be viewed dynamically on the workstations.

The next generation workstation is expected to be procured in approximately the third quarter of 1989. The performance of the Silicon Graphics 4D/240 GTX is given in the table below, and it is the approximate expected performance of the next generation workstation. These workstations are expected to meet most of the requirements for dynamic viewing listed above. A more complete description of the features expected in the next generation workstation is given in reference 2. Phong lighting, material maps, alpha blending, and a windowing system in a parallel programming environment are additional features of this next generation workstation.

Benchmark software has been developed at NASA/Ames to test, among other things, what kind of

Table 1: Features of Current and (typical) Next Generation Workstations

Feature	**IRIS 3130**	**IRIS 4D/240 GTX**
	CPU	
CPU performance	1 MC 68020 0.1 MFLOPS/16MHz	4 x R3000 (RISC) 16 MFLOPS/25 MHz
FPU performance	1 MC 68881	4 x R3010 (RISC)
RAM	16MB	128MB
disk storage	474 MB	9.6 GB
Computations	0.1 MFLOPS	40 MFLOPS
	GRAPHICS	
Resolution	1024 x 768	1280 x 1024
Image memory	24 bitplanes	48 bitplanes (+overlay,alpha)
Z-buffer	12 bits	24 bits
Pixel rate	1,000,000 pixels/sec	8,000,000 pixels/sec
3D coordinate transformations	80 K/sec	400 K/sec
polygon transformation*	16 K/sec (flat, not z-buffered)	100 K/sec (Gouraud, lighted, and z-buffered)

(*polygons are 400 pixel quadrilaterals) graphics performance can be expected from these next generation workstations (Note: the numbers quoted in the table above are NOT measured with these benchmarks, but are published numbers from Silicon Graphics Inc.) The graphics capabilities emphasized by the benchmark include color, simultaneous vector and polygon display, double buffering (ref. 7, p.84), hidden surface removal, smooth shaded polygons and coordinate transformation rates. The benchmarks also test display list operation (creating an object in a application program and displaying it) and frame buffer performance. This software can be obtained through the authors from NASA/Ames Research Center.

5. HARDWARE CONFIGURATION

The hardware configuration is shown in figures 1, 2, and 3. Figure 1 shows the hardware configuration for creating and viewing flow field solutions. Figure 2 specifies the hardware for creating video tapes, and figure 3 specifies the hardware for creating 16mm film.

The calculations to generate the flow field solutions are done on the supercomputer. The conversion from these solutions on 3D grid points to scenes depicting the physics (e.g. particle traces about the body) can be done in three ways. The first way is to transfer the whole solution file (containing the solution at each grid point) to the large disk on the workstation and generate the scene on the workstation. The second way is to produce graphics files on the supercomputer (and transfer these graphics files to the workstation). The software for creating and viewing scenes using these two methods is described below in the **software** section. The third way is to create the scene using the supercomputer interactively while viewing the scene on the workstation. The software for this method includes tasks that run simultaneously on both the supercomputer and the workstation. This concept involves separating the computationally intensive portion of the processing on the supercomputer from the graphics on the workstation and having the two processes communicate over a high speed network. One scenario involves sending pre-computed display list (ref. 7 p 348) information to the workstation using a remote graphics library developed for just such a purpose (this graphics library allows a graphics program to be implemented on a supercomputer). Other scenarios involve more standard networking schemes, where subroutine and/or interprocess communication are utilized. The bottleneck in those types of schemes can often be the large amount of data that has to be transferred from one computer to another. Existing software and techniques being utilized at NASA/Ames Research Center are described further in references 3, 5 and 6.

The key features of the workstation are its rapid 3D transformation speed (for changing the viewing position), its high definition display, and its rapid display creation speed. 3D coordinates can be transformed at a rate of 80,000 coordinates per second. The display has high spatial resolution (1024 pixels horizontally by 768 pixels vertically) and high color resolution (24 color planes giving more than 16 million simultaneous colors). (The color planes can be divided into two buffers with 12 color planes each to obtain the double buffering required for most dynamical displays. This reduces the number of simultaneous colors to 4096.) Displays with a very simple solid object and thousands of lines or points can be generated at a rate of more than 10 per second — a rate that provides satisfactory motion for understanding dynamics. The Space Shuttle illustrated in

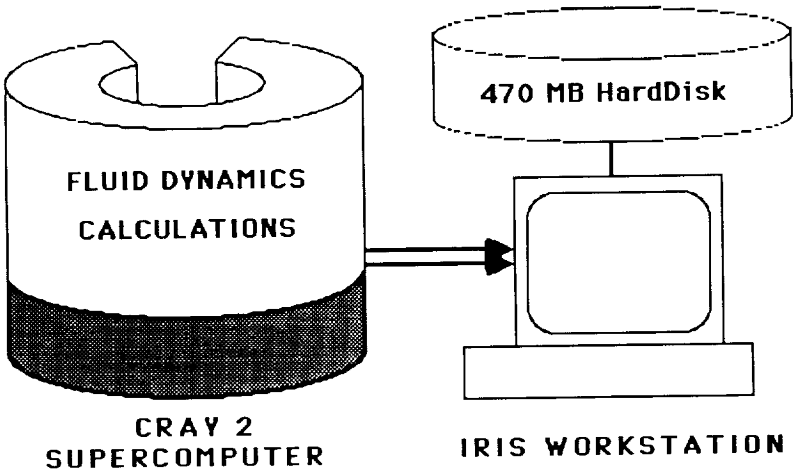


Figure 1. Hardware configuration for creating and viewing flow field solutions

the video tape represents a maximum display complexity for studying dynamics directly with the workstation, as the time to create each display (frame for film) is approximately 1/2 second — a rate that is marginal for viewing dynamic motion. For this display, the Space Shuttle is represented by approximately 8000 polygons (ref. 7 p. 87) and the painter's algorithm was used for hidden surface removal.

The workstation contains a Z buffer (ref. 7, p. 560) for hardware implementation of hidden surface removal. In addition, the Gouraud shading (ref. 7, p.498) calculations get an assist from the workstation hardware. However, many seconds are required to create displays of typical aerodynamic vehicles if the Z buffer and Gouraud shading are used. Therefore, these displays must be recorded on video tape or 16mm movie to view the dynamics satisfactorily.

The hardware used to record the displays on video disk is shown in figure 2. The high definition display is digitally sampled by a scan converter to a lower resolution RS170a format that can be encoded by the encoder into the standard single NTSC (National Television Standards Committee) signal used by standard video recorders and players. (The loss in spatial and color resolution during this conversion is described later in the section "**Discussion**".) A time base corrector must be inserted into this system prior to the 1" video recorder to generate the precision signal timing required for "broadcast" quality signals (necessary for broadcasting over the air). The Abekas A62 video disk recorder is controlled via a standard RS232 interface. As each frame is displayed, control information tells the Abekas to record. It then stores the frame as digital NTSC. This process occurs at standard video rates; that is the digital video system

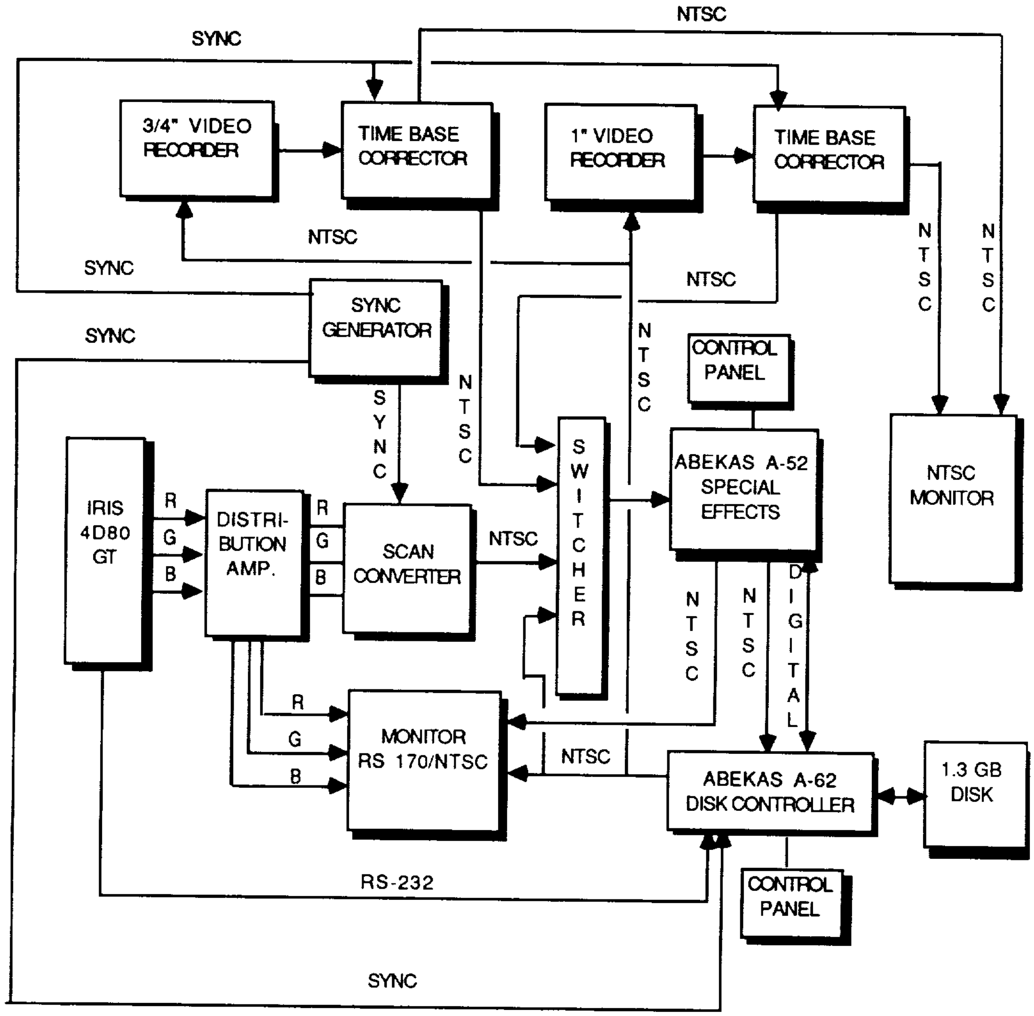


Figure 2. Hardware configuration for digital video disk recording

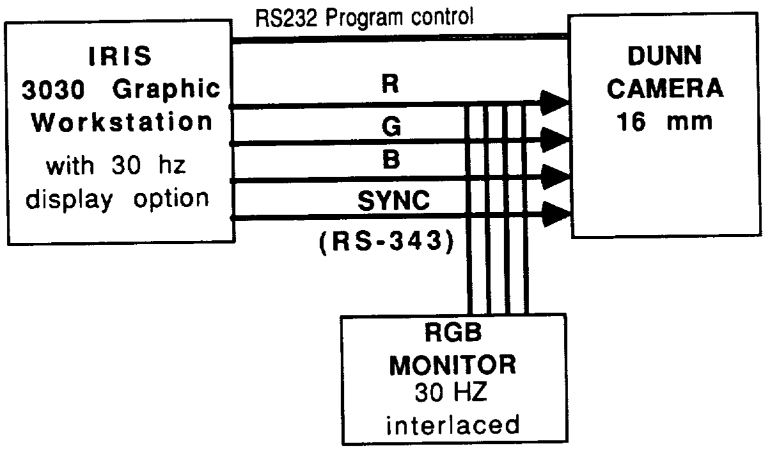


Figure 3. Hardware configuration for 16mm film recording

has the capability to record analog NTSC at real-time rates so the time required to record a computer workstation frame is limited by the time it takes to render it. The workstation then continues on with the next frame, and repeats the process until the animation is complete. The Abekas uses Winchester disk technology (1.3 gigabytes storing 100 seconds of video), allowing stored video to be edited (using the A52 special effects) or the disks to be re-recorded. There are no generation losses within the system due to the digital formatting.

The hardware for recording the displays on 16mm film is shown in figure 3. The Dunn Camera is controlled from the workstation using an RS232 hardware connection and the GAS software described later in this paper.

6. SOFTWARE

The three techniques used for visualization are *post-processing, tracking, and steering.* Using post-processing methods, a flow simulation is executed on a supercomputer and, after the simulation is complete, the results of the simulation are processed for viewing. This technique is by far the most common for visualization of computational aerodynamics, given existing computing resources. The following are examples of post-processing software packages in use at the NASA Ames Research Center:

PLOT3D accepts as input the flow field solutions from the supercomputer and creates as output a variety of displays that can be viewed dynamically with the workstations (or statically from other graphical display devices). The software makes extensive use of color and 3D cues (such as shading and perspective: ref. 7, p. 269). A very popular display is path lines of particles released at selected points inside the flow field. An example of particle paths in the flow field is shown in figure 4. A second example of displays from PLOT3D is color mapping on a vehicle surface representing the magnitude of some scalar property on the surface, such as pressure. A third example is a shock surface within the flow field (or some other surface of constant scalar value) represented as a partially transparent surface so the vehicle creating the shock can be seen through the shock. PLOT3D software can be run on the workstations, the Cray supercomputers, and on a VAX 11/780 minicomputer.

SURF(Surface Modeller) allows scientists to input grid and solution files and interactively build a 3D model consisting of wireframe, shaded, and function mapped parts. These parts can be interactively viewed, edited, and output to ARCGRAPH files which can then be loaded into GAS and then animated. SURF has a mouse driven interface (similar to GAS). Gouraud shaded parts can have their color and specular highlighting adjusted interactively. Shaded parts are created based on user specified lightsources (up to 20), a viewpoint, and an ambient light level. The function mapped parts can also have their color spectrum adjusted interactively. Legends can be created to show the correlation of color and normalized function values. Also, function mapped parts can be "clipped" so that they only show areas within a specified range of function values (e.g. normalized pressure between 1 and 2). SURF computes the following functions: pressure, density, temperature, Mach Number, and custom (user defined) functions.

GAS(Graphical Animation System) permits the scientist to interactively and dynamically view the 3D displays created by PLOT3D (or several other graphical packages) while simultaneously changing the viewing position within the 3D space. In addition,

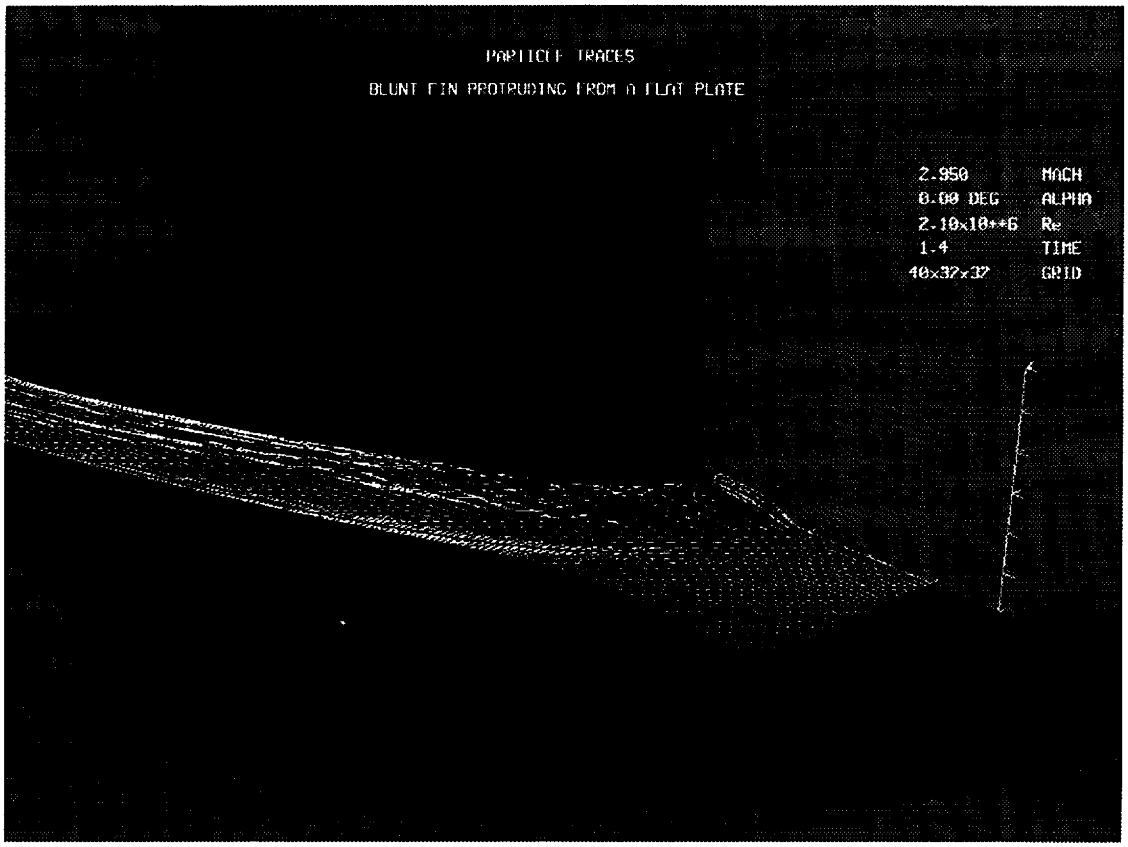
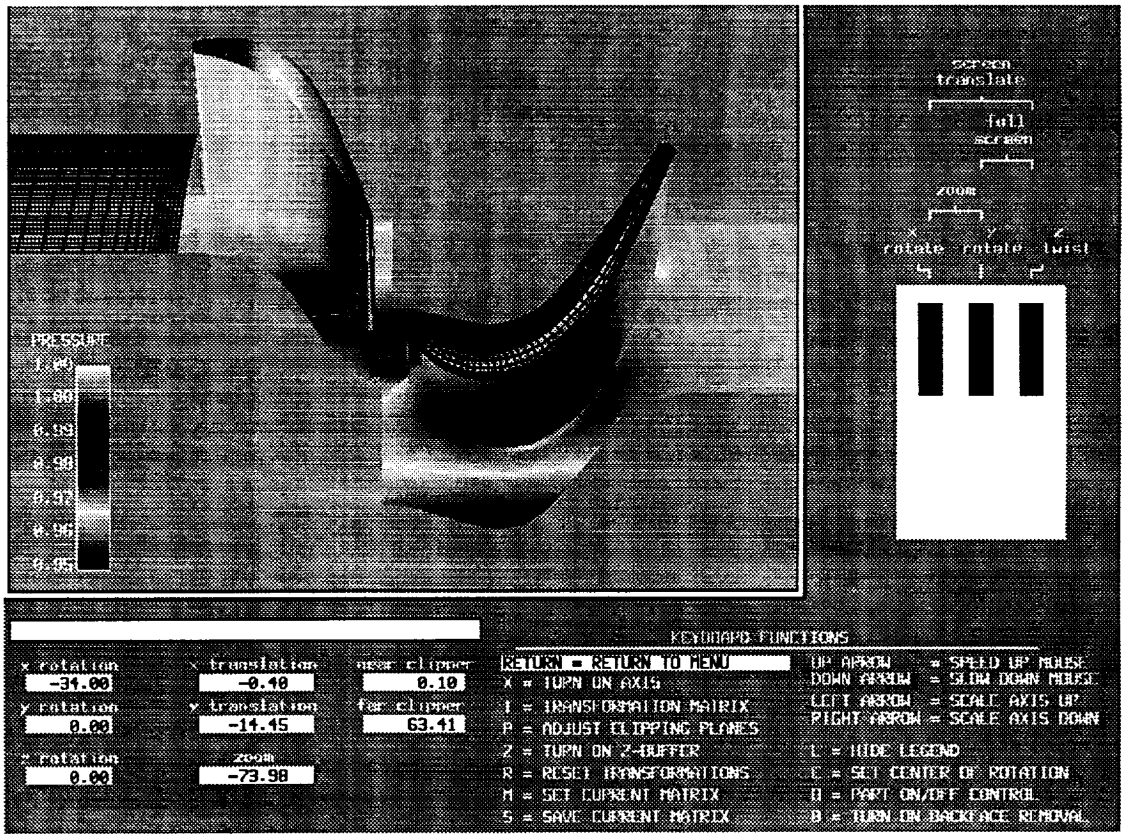


Figure 4. Example of figure created with PLOT3D.



x rotation -34.00
y rotation 0.00
z rotation 0.00
x translation -0.40
y translation -14.45
zoom -73.98
near clipper 0.10
far clipper 63.41

KEYBOARD FUNCTIONS

RETURN = RETURN TO MENU
X = TURN ON AXIS
T = TRANSFORMATION MATRIX
P = ADJUST CLIPPING PLANES
Z = TURN ON Z-BUFFER
R = RESET TRANSFORMATIONS
M = SET CURRENT MATRIX
S = SAVE CURRENT MATRIX

UP ARROW = SPEED UP MOUSE
DOWN ARROW = SLOW DOWN MOUSE
LEFT ARROW = SCALE AXIS UP
RIGHT ARROW = SCALE AXIS DOWN
L = HIDE LEGEND
C = SET CENTER OF ROTATION
O = PART ON/OFF CONTROL
B = TURN ON BACKFACE REMOVAL

Figure 5. Example of figure created with SURF.

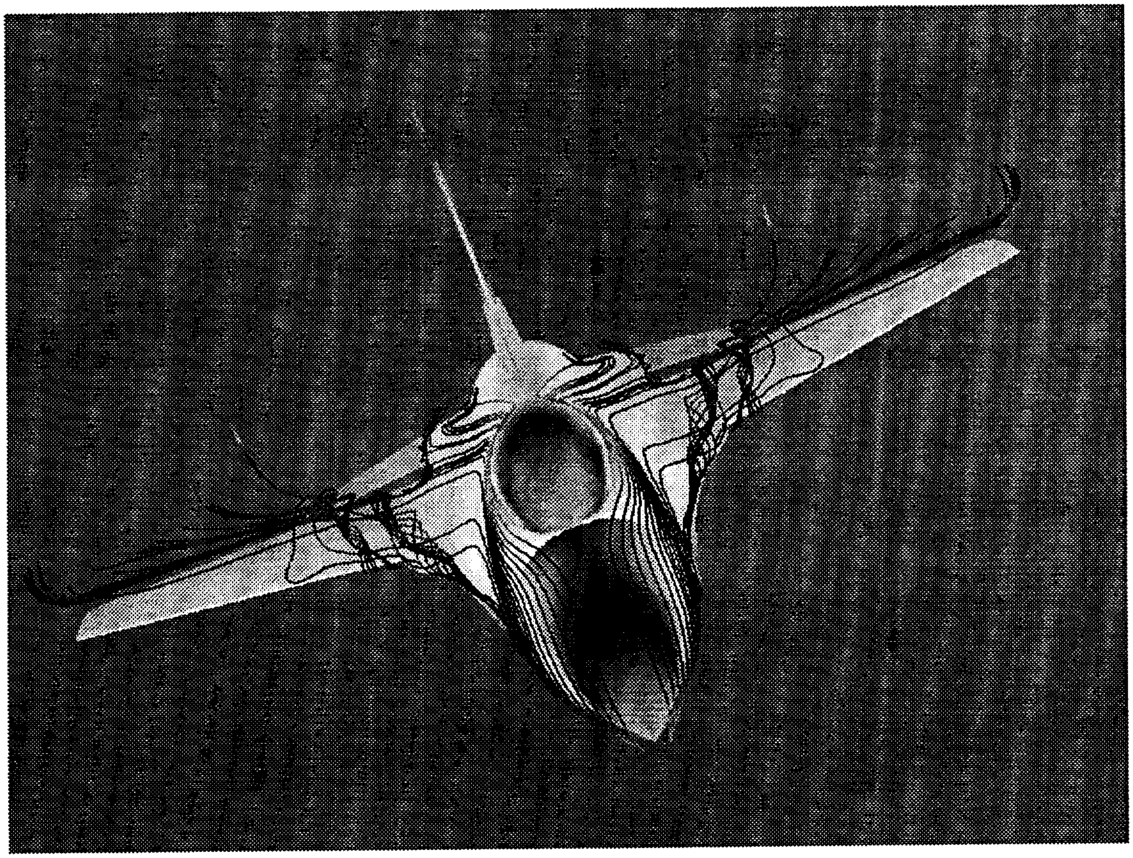


Figure 6. Example of figure created with GAS.

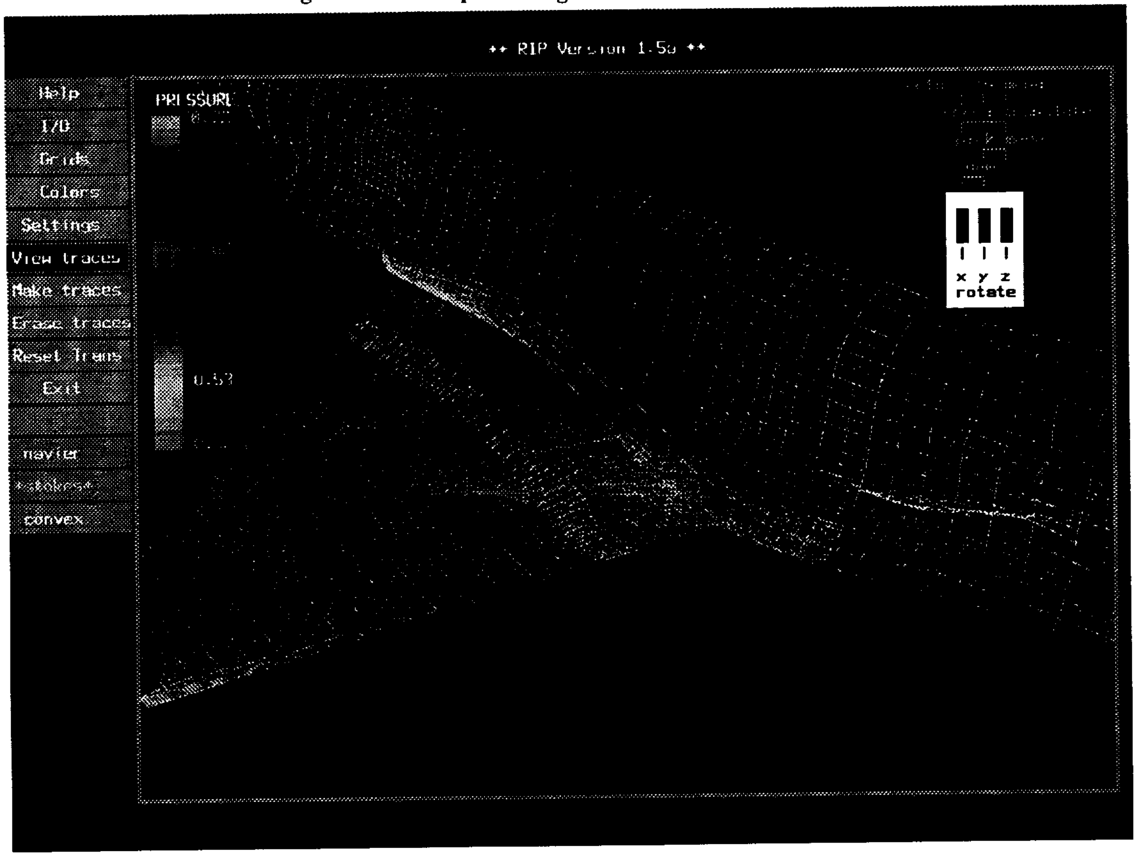


Figure 7. Example of figure created with RIP.

it permits the scientist to generate an animation sequence with smooth 3D transitions between a series of specified positions. Both the animation speed and the number of "tweening" steps (automatically added to give smooth transition between specified positions) are under user control. Titles can be inserted, and the resulting "movie" can automatically be recorded by the video equipment or the 16mm film recorder which are under control of the GAS software. This software is device specific and runs only on a Silicon Graphics IRIS Workstation. It was written in the C programming language under the UNIX operating system.

FAST(Flow Analysis Software Toolkit) is a new proposed standard fluid-dynamics graphics environment. The purpose of FAST is to provide the scientist with a single software environment for handling many graphics needs (some functionality exists in the programs described above) in a way that is quick, powerful, and easy to use. The programs above were designed and built for the current Silicon Graphics IRIS 3130 workstation, whereas the FAST environment is being designed for the capabilities of the next generation workstation (see Table 1.). The new capabilities of these machines warrant a new approach to building graphics tools. The goal is to allow a scientist to quickly and easily perform fluid dynamics scientific visualization from this environment. Initial software features include (1) a standardized user interface, (2) data sharing, communication and memory management between modules, (3) high quality rendering and advanced animating capabilities, (4) new ways for viewing and interpreting fluid dynamics. The five initial modules are (1) the main FAST module to load and unload the other modules and manage data structures, (2) The MODELLER module to read grid and solution data and create models, (3) The FLOW TRACER module for illustrating the flow field in a variety of ways (tracers, ribbons, smoke), (4) The TITLER module for titling and labelling, and (5) The ANIMATOR for advanced animation and recording.

RIP(Real-time Interactive Particle-Tracer) is an example of a distributed graphics tool and actually consists of two programs that communicate over a high-speed network. One program computes the flow traces from raw data on a supercomputer and the other program renders these traces for interactive viewing on a workstation. Particle tracing is then interactive, where a scientist selects a trace or rake of traces for display and the traces are computed and then drawn in most cases almost instantaneously, much like a smoke wand in a wind tunnel.

There are other codes in use at NASA Ames that employ tracking and steering methods, although these codes are typically in more prototype use than part of day-to-day simulation efforts. Versions of **ARC2D** (Ames Research Center 2-d flow solver), a code in use at NASA Ames, exist that "track' the progress of a simulation. Simple examples of 'steering' a flow code exist as part of the interactive grid generation program **IZ** (Interactive Zoner). In this example of 'steering', you can generate a grid and then run a flow solver on it using the distributed graphics techniques discussed earlier. This example is only 2-d because workstations have not had the resources (until recently) to allow 'steering' a 3-dimensional flow solver.

7. DISCUSSION

Of the three visualization methods discussed in this paper (post-processing, tracking, and steering), post-processing is by far the most common. Current supercomputer and workstation performance make this the most practical method for viewing solutions of computational aerodynamic solutions. Probably 90% of all simulation is performed in this manner, with the remaining 10% made up of scientists using tracking codes, and, to an even lesser extent, scientists using steering codes.

Post-processing techniques include (1) dynamic, interactive viewing on the workstation, (2) recording and playback on video disk and then to tape, and (3) recording and playback on 16-mm film. These techniques have greatly improved the ability of scientists at NASA Ames to conduct fluid dynamics research, although these techniques necessarily mean a loss of interactivity, take a long time to record, and, for video, mean a loss of spatial and color resolution.

With direct viewing on the workstation, the capability to **interactively** manipulate the viewing position and the animation sequence was found to be very effective in providing a quicker and more complete understanding of the flow field solutions. This capability is lost if the displays are so complex that they must be recorded for playback. A solution for this problem is to increase the performance of the workstation. As mentioned earlier, the display creation speeds of workstations are projected to increase an order of magnitude over the next year. This will permit many complex displays that now must be recorded for satisfactory motion analysis to be viewed directly on these newer workstations. Nevertheless, there will still be displays that are too complex to view with adequate rates of motion on the new workstations;

recording will still be required for these displays. (In addition, recordings are required for group presentations.) Therefore, it is important to improve the recording techniques also.

Recording on the Abekas video disk or Dunn film recorder with the hardware shown in figures 2 and 3 requires a much longer time than simple viewing on the workstation — a typical recording time is 1/2 to 1 hour for every one minute of playback time (based on 30 frames per second video playback and 24 frames per second film playback). The film medium takes longer due to the nature of the recording process. The Dunn film recording system requires cycling of red, green, and blue filters for each frame (or exposure). The Abekas system records each frame essentially instantaneously, so the length of recording time is determined by the time it takes to render each frame, which is determined by the rendering techniques being used for the simulation (1 sec to 2 minutes).

Recording on video disk also causes a loss in picture quality (a loss in picture definition and shifting in colors). The initial spatial resolution must be cut nearly in half (down to 512 x 512) for the conversion to RS170a RGB format, and the further encoding to the single composite video signal (NTSC) causes another substantial reduction in quality. Analog recorders that rewind and pre-roll also cause some loss in quality. The digital video system mentioned above provides a partial solution to the loss in picture quality. There is no loss of resolution or shifting of colors in the editing because the pictures are stored digitally. The loss of quality during recording is also reduced by using continuous recording rather than a frame at a time and by using the larger 1" tape format rather than the 3/4" tape format used in older analog recording systems. The capability to record individual "fields" of video is also an important feature of the digital process. Animation sequences can be separated by fields (instead of by full frames of video). The effect on playback is very smooth motion, as the eye cannot detect or distinguish between these fields. This technique is borrowed from commercial television computer graphics applications where it is used often.

Recording on video disk and tape could be substantially improved with the addition of real-time digital video output from a workstation frame buffer. Certain digital video component manufacturers are already standardizing on the D2 (Sony, Ampex) composite digital video format and, although many workstation manufacturers have discussed such an option, the authors are not aware of it being available at the time of this writing. Not only would this option eliminate the need for much of the outboard equipment necessary for video recording, it could potentially improve the video quality by eliminating numerical sampling error going from digital to analog and back to digital again.

Recording on film requires a long time primarily because film processing at NASA/Ames is done off-site. This processing time could be reduced from days to hours if a film processor were placed on-site.

The need for these recording techniques arises from the current capacity and performance limitations touched on earlier in this paper and summarized in table 1.

While there will always be a demand for presentation videos, partially reducing the dependence on these recording techniques would require ultimate performance in a computer graphics workstation. A spatial resolution of 1280 x 1024 requires 100,000 polygons/sec updated at 10-12 frames/sec for baseline performance (with hidden surfaces removed, antialiasing and interactive, advanced lighting models).Workstations that approach this level of performance are discussed in this paper. Other possible configurations NOT discussed in this paper include fast frame buffer configurations utilizing a very high speed network interface to a supercomputer (100 mbyte/sec) or an RGB digital video system (although this would NOT be interactive).

As further advances are made in supercomputing, parallel architectures, networks and workstation graphical performance, the authors predict development of more and more software environments where tracking and steering techniques are employed. At the time of this writing state-of-the-art resources allow for only minimal examples of these types of scientific visualization of computational aerodynamics (see Table 1).

8. CONCLUSIONS

The high resolution, high performance 3D graphical workstation combined with specially developed display and animation software has provided the scientists conducting fluid flow simulations with a good tool for analyzing flow field solutions obtained from supercomputers. A video tape recorder or 16mm film recorder, and the controlling animation software, are needed in addition to the workstation for very complex displays that cannot be created rapidly enough with at this point in time to yield satisfactory dynamics on the workstation alone.

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