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# SHIVA: A Unix-Based, Menu-Driven, Color Image Processing Software Package

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## NOTICES

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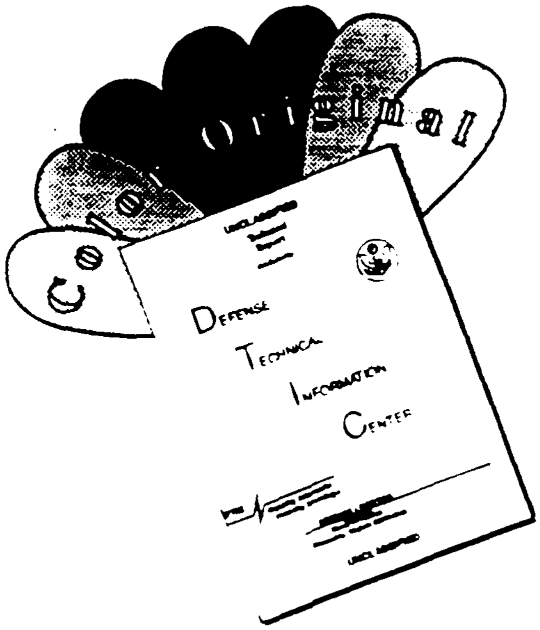


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A user-friendly "point and click" program named SHIVA has been developed to facilitate processing and analysis of digital color images. SHIVA, an acronym for Simple Heuristic Interactive Visualization and Animation, provides access to a full range of image processing and analysis tools via a graphical interface and with minimal instruction. This technical report describes the main hierarchy and functionality of SHIVA. The program has been used to process color images of burning monopropellant sprays illuminated by a copper vapor laser. Though SHIVA was developed to support our spray research effort, it should be useful in a wide range of U. S. Army Research Laboratory (ARL) research applications where color image processing and analysis is employed.

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## 1. INTRODUCTION

Simple Heuristic Interactive Visualization Analysis (SHIVA) is a software package that was developed to facilitate color image processing and analysis of digital color images. The impetus for developing SHIVA was the need for a powerful, but easy to use, program for analyzing experimentally visualized combusting sprays. When SHIVA was conceived, the only commercially available package for color image processing that approached our requirements was a suite of tools (Wyndham Hannaway Image Processing [WHIP], W. H. Hannaway & Associates) which required the user to know the UNIX operating system, hundreds of commands, and thousands of flags for the commands. To avoid the intensive user training (and retraining after a usage lapse) that would be needed to apply these tools, we decided to develop a user-friendly "point and click" shell program to run the package. SHIVA is the result. It allows users access to a full range of image analysis tools via a graphical interface and with minimal instruction.

This technical report describes the main hierarchy and functionality of the SHIVA software package. In addition to facilitating the use of image analysis tools, SHIVA provides an efficient file management system and animation ("movie-making") capability. The modular structure of SHIVA facilitates its expansion to accommodate the addition of other commercial image processing and/or analysis packages which run in the OSF/Motif and X Window systems. Though SHIVA was developed for our spray research application, it should be useful in any U. S. Army Research Laboratory (ARL) research application where color image processing and analysis are employed.

## 2. BACKGROUND

SHIVA is the final phase of an ongoing, evolutionary effort to establish a strong image analysis capability to supplement the ARL spray research effort. The present configuration of the image processing system is a result of decisions dating from June 1989. These decisions have been driven in large part by the state of existing technology and capital cost considerations. The first decision involved selecting the Silicon Graphics Personal Iris 4D20 workstation as the operating platform. At the time, it was the highest performance platform offering 24-bit color in our price range. It also had the advantage of being a popular platform within the BRL* for scientific visualization. When the workstation was acquired, WHIP was the only sufficiently complete, color image processing and analysis package actually on the market

* The U.S. Army Ballistic Research Laboratory was deactivated on 30 Sept 1992 and subsequently became a part of the U.S. Army Research Laboratory (ARL) on 1 Oct 1992.

for this platform. It was apparent that additional programming would be required in order to make full use of this package. However, it was uncertain that a more complete product would become available within a reasonable time period.

A feature of WHIP which made it attractive was its provision of a "virtual" imaging environment. In a virtual environment, the image may reside and be processed in local or shared random access memory (RAM). The memory dedicated to an image is called a "framebuffer." The virtual environment avoids input/output (I/O) bottlenecks once the image has been loaded from the disk, and allows the chaining of processing operations without the necessity to create temporary images to hold intermediate results. Finally, the framebuffer concept does not require additional hardware support. Thus, RAM availability is the only limitation to the size and number of working images. Working with images in RAM greatly facilitates the production of animation sequences.

WHIP provides a number of color and monochrome image processing tools such as edge detection and noise reduction routines. (Both color and monochrome image processing routines may be accessed through SHIVA.) WHIP also provides pull-down menus for some image morphology and analysis functions which can be accessed from on-screen displays. These provide measurements for attributes such as shape, color, and size. Finally, there is a set of routines for image labeling.

As capability and complexity with which WHIP could be applied expanded through the development of SHIVA, an upgrade in the speed and capacity of the operating platform became necessary to more fully take advantage of the package. Furthermore, the original system did not provide a direct path to transfer the processed images to videotape. Accordingly, when funding became available, the Silicon Graphics Personal Iris was upgraded from a 4D20 to a 4D35, a 767-MB hard disk and 32 MB of RAM were added, and a Genlock board witn an NTSC encoder was installed. The Genlock board enables the toggling of the screen output between the Silicon Graphics monitor and a conventional NTSC video monitor or VCR. About the same time that the upgrades were installed, Silicon Graphics released an upgraded operating system for the Personal Iris. This moved our programming effort to the more portable X Window and OSF/Motif systems.

## 3. IMAGE DIGITIZATION AND TRANSFER

The WHIP software is designed to work with RGB-based *.pic format image files. To obtain such a representation of high-speed film records, an image transfer and digitization system had to be developed.

The system assembled was based on choices driven primarily by cost considerations, and the transfer procedure described is specific to the hardware selected. It is presented as an example of obtaining digital images from an image in an analog format—a potential consideration for users of this system.

The first step of the film transfer procedure employed involved projecting film images onto a screen and recording the projection to a video tape (S-VHS format) using a professional video camera (JVC, Model BY-10). The image as recorded on tape was grabbed and digitized using a PC-AT-based framegrabber (Truevision Inc., ATVista). The framegrabber produces a *.tga format image file. Like *.pic format, *.tga files are based on RGB values. These files are then ported to the Silicon Graphics workstation via a dedicated local area network (Ethernet). Finally, a WHIP subroutine facilitates the conversion from the *.tga format to the *.pic format. After the completion of an image processing session, newly created images can be converted back to the *.tga format and returned to the PC via the same dedicated Ethernet, if desired.

We note that the virtual image handling environment provided by WHIP does not require specific hardware support. Therefore, SHIVA/WHIP can be used to process any image which can be converted to a *.pic file. As currently configured, SHIVA supports conversion between (Silicon Graphics) *.rgb, *.tga, and *.pic formats. Silicon Graphics bundles 15 other image conversion utilities with the workstation, and adapting SHIVA to import any of these formats would require only a small programming effort.

## 4. SHIVA HIERARCHY AND FUNCTIONALITY

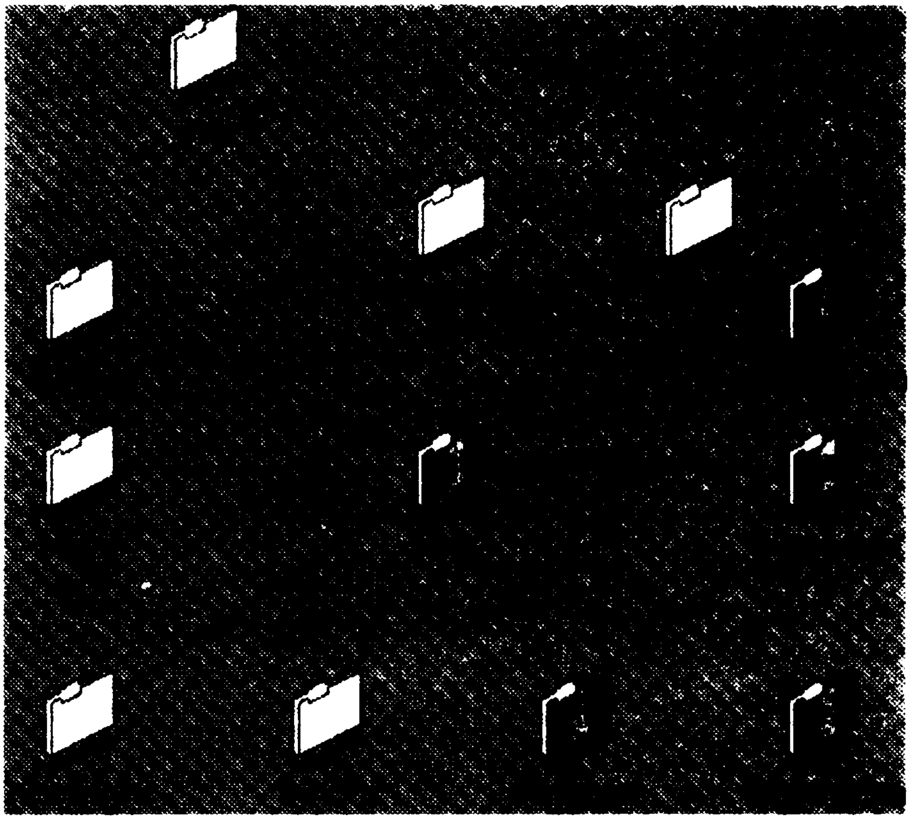
4.1 Directory Structure and File Handling. SHIVA is set up within a directory called **whip**. The structure of this directory is shown in Figure 1. Files to be processed must initially reside within the **whip** subdirectory called **pic**. In the interest of keeping things as simple as possible, it was decided that all image processing should take place in a subdirectory of **pic** called **WorkingPics**. This structure minimizes the chance of accidentally operating on the wrong file, prevents the saving of a processed file over top of the original, and simplifies the search procedures created to help automate our system. If the **pic** directory or any of its subdirectories contains any *.pic image files, the icon for that directory is painted red, green, and blue to remind the user that such files are present.

Because of the capability for automatic saving of image files, and because of the frequent transferring of image files between three different formats, an automatic file naming algorithm was incorporated into the program. This simplifies the tracing of the image through various image processing applications.

4.2 User Interface. Silicon Graphics workstations come with a demonstration program called "buttonfly." "Buttonfly" opens a window with a labeled button prominently displayed at its center. Positioning the cursor over this icon and clicking the mouse button ("point and click") causes the icon to change color, flip over, and display more options. Pointing and clicking the cursor in the black background causes the button field to return to the previous level of buttons. For every level of the "buttonfly" hierarchy, there are user-configurable menus that label the buttons and cause some action to be taken. The graphical interface employed in SHIVA is modeled after this demonstration program. To provide feedback on the operations selected in the graphical environment, the commands and written program output are echoed in the console window. Twenty-eight menus, 170 UNIX shell scripts, and 98 C programs were created to obtain the user interface.

4.3 SHIVA Functions. SHIVA is accessed by typing "shiva" at the prompt in the console window displayed upon logging in as a WHIP user. The first button displayed is a title button (Figure 2). When this button is selected, a field with three new options is displayed: *Restore Previous Session*, *New Session*, and *Return to Present Session* (Figure 3). *Restore Previous Session* returns the user to where he or she last exited the program. This only works if the user has exited the previous session in a specified fashion that is covered later. (Otherwise, the button is inactive.) *New Session* resets all program flags for a fresh start. *Return to Present Session* was created in case the user returned through the option hierarchy to this level and wanted to return to the main level of the program without resetting flags or losing unsaved work.

The main menu level has 15 options which correspond to the primary areas of the program (Figure 4). The selection of any of these options reveals a new field with two buttons. The first of these is labeled *Help#*, with # corresponding with the position of the button in the main menu field. The second button is labeled *Proceed*. Choosing *Help#* opens a full-screen on-line help package on the relevant topic(s). These run as long as three full screens and are illustrated as necessary to more fully explain the choices that will be available at the next level down in the menu. Once *Proceed* is chosen, the user is led through the options needed to specify the implementation of the function. This will primarily involve making choices from successive button menus. If input from the keyboard is required, the user is prompted for the appropriate information. In addition to the processing options and help screens, there are also a few shortcuts placed within the shell so that the user does not have to toggle through multiple levels.



NOTE: The directories that are colored red, green, and blue contain *.pic format image files. This color coding is updated every time SHIVA is exited.

Figure 1. The directory structure relevant to image processing.


Figure 2. The title button that initiates the program

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Figure 3. The session control field.

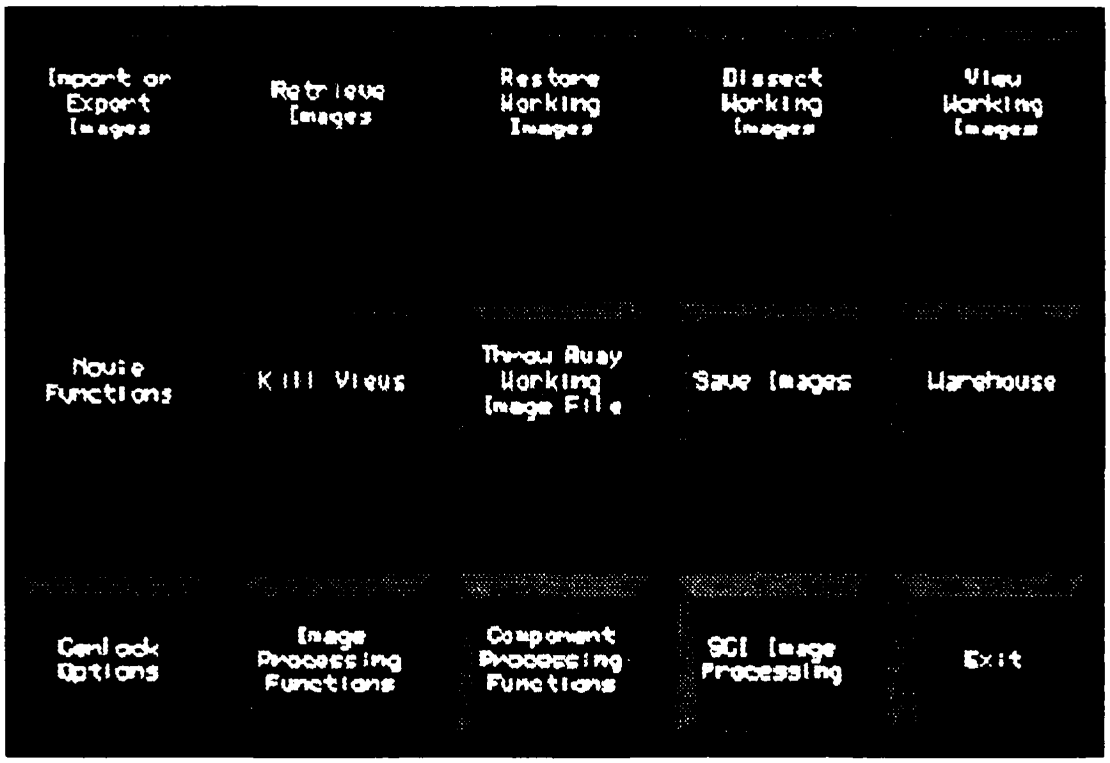


Figure 4. The primary buttons (also referred to as the main level)

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4.3.1 Import or Export Images. As the name implies, this option facilitates various file conversion and transfer subroutines. Choosing *Import or Export Images* and the following *Proceed* button leads to a field of five buttons. These buttons are *FTP Import*, *FTP Export*, *Convert PIC to TGA*, *Convert TGA to PIC*, and *Delete Imports or Exports* (Figure 5). *FTP Import* copies image files from a remote computer to the workstation subdirectory **TGAfromPC** using the FTP file transfer protocol. *FTP Export* sends image files in the workstation subdirectory **TGAtoPC** to a remote computer, again using the FTP file transfer protocol. The two *Convert* ... options facilitate conversion between the two image formats we commonly use: the *.tga format generated by the framegrabber used for image digitization, and the *.pic format used by WHIP. The *Convert TGA to PIC* conversion routine automatically loads the *.pic files into the **pic** directory. *Delete Imports or Exports* allows the selective pruning of files from the **TGAfromPC** or **TGAtoPC** subdirectories.

4.3.2 Retrieve Images. *Retrieve Images* transfers image files from the **pic** directory to the subdirectory **WorkingPics** where they become available for processing and analysis. The selected files are also transferred to the **Reservoir** subdirectory to facilitate the *Restore Working Image* subroutine discussed later. The user selects the images to be retrieved from point and click accessed lists containing all of the image files located in the **pic** directory.

4.3.3 Restore Working Images. *Restore Working Images* allows the user to restore a processed image to its original state; i.e., the image prior to being placed in the **WorkingPics** directory.

4.3.4 Dissect Working Images. *Dissect Working Images* allows the red, green, and blue components of an image file to be processed and analyzed separately. It is an important function, permitting the monochrome image processing functions to be utilized for color image processing. *Dissect Working Images* maps each primary color component map to a separate image file. The resulting image files are effectively 8-bit gray scale images with pixel element intensities directly related to the component intensity in the original image. The images created by *Dissect Working Images* are automatically named by appending an _R, _G, or _B as appropriate to the original filename. These files are then automatically placed in the **WorkingPics** subdirectory for subsequent processing.

4.3.5 View Working Images. *View Working Images* is used to place images in a window at a chosen screen location. As presently configured, eight screen locations are available. Once a screen location has been selected it is automatically deleted from the list of available screen locations. This was done because there is no intrinsic limit to the number of images that can be placed on top of one another, and it was desirable to minimize the workstation overhead devoted to maintaining images on the screen.

4.3.6 Movie Functions. In the course of this work, the need for a number of different movie types was identified. All of those that were identified are enabled through *Movie Functions*. There are ten options under *Movie Functions* (Figure 6). These are *Select Images for Movie, Process Entire Movie, Show Movie, Show Double Movie, Show Genlock Movie, Show Double Genlock Movie, Select Images for Sync Movie, Process Entire Sync Movie, Show Sync Movie,* and *Kill Movie*. *Select Images for Movie* displays, via *List#* buttons, the images available for animation. User selections are placed in a list in the **Movie** subdirectory. The images are implicitly numbered in the order selected. *Process Entire Movie* branches to the *Image Processing Functions* menu (discussed later) and applies any image processing function available in this menu to the images chosen using *Select Images for Movie*. *Show Movie* opens a window and animates the previously selected, and possibly processed, images in the order that they were selected. *Show Double Movie* operates like *Show Movie* except that the selections are displayed in a split screen format—the upper half of the window corresponding to odd-numbered selections while the even-numbered selections are displayed in the lower half. The split screen format permits comparison of image sequences "before-and-after" processing. *Show Genlock Movie* works like *Show Movie* except that the animated images are reduced to fit within a NTSC monitor. *Show Double Genlock Movie* is a split screen movie that is reduced to fit within a NTSC monitor. The various options referring to Sync Movies work just like the previous options, except they invoke an algorithm designed to reduce frame-to-frame variations (jitter) in the location of an object's centerline. (The jitter observed was introduced during the framegrabbing procedure.) The algorithm is applicable to images containing a primary object (a spray for example) which is nominally symmetric about a horizontal centerline. An "S" is appended to Sync image file names to differentiate them from the original *.pic image files. These files are made accessible to other portions of SHIVA through the *Save Images* option discussed later. *Kill Movie* clears the image selection in the **Movie** and **MovieSync** subdirectories. As currently configured, movies with up to 60 regular frames or 30 split screen frames can be conveniently processed using SHIVA.

4.3.7 Kill Views. *Kill Views* contains two options for closing down windows previously opened using *View Working Images*: *Kill All Views* and *Kill Specific Views*. *Kill All Views* closes down all view windows on the screen. Individual view windows may be shut down using *Kill Specific Views*.

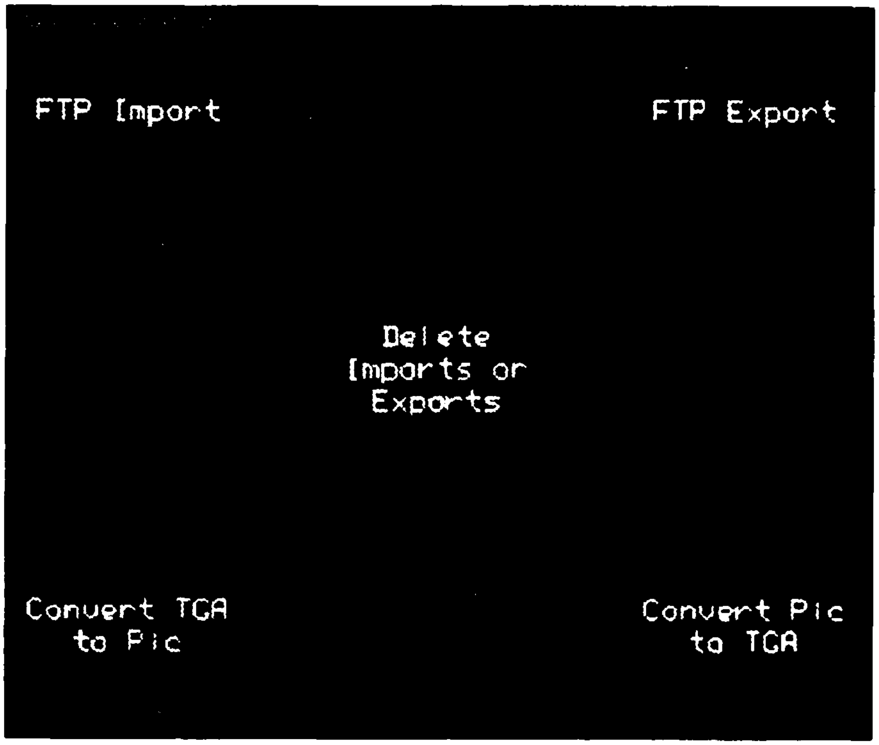


Figure 5. The Import or Export Images field.

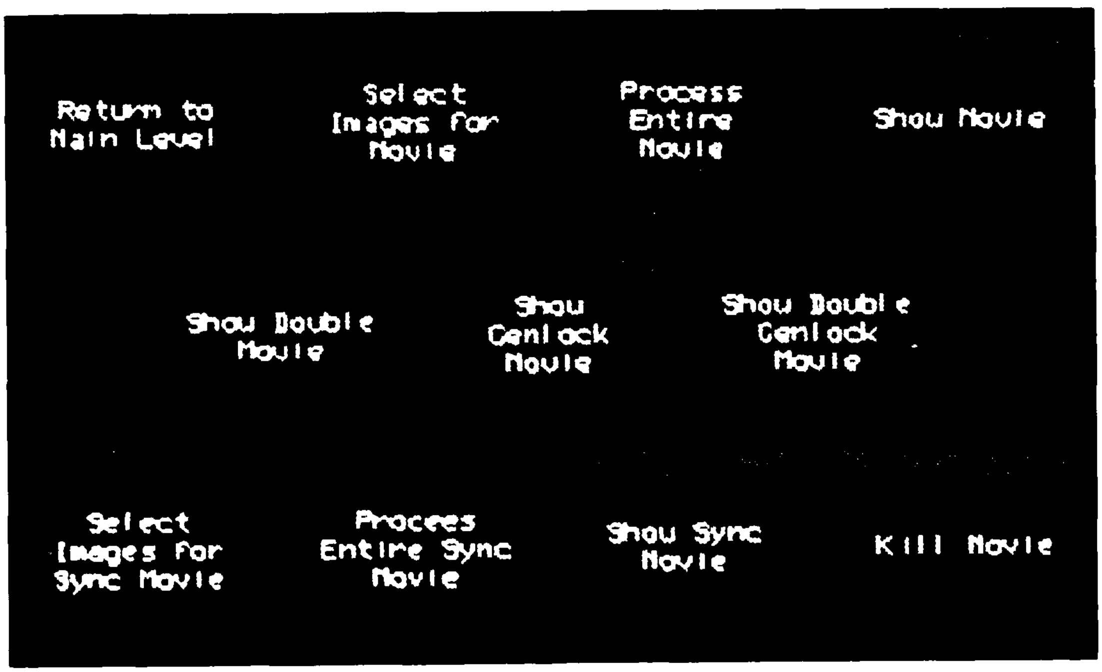


Figure 6. The Movie Functions field.

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4.3.8 Throw Away Working Image Files. *Throw Away Working Image Files* is a simple utility to reduce clutter and to eliminate hopelessly corrupted image files. It erases selected image files from the **WorkingPics** directory, closes down any open view windows associated with these files, and moves the originals (located in the **Reservoir** directory) back to the **pic** directory.

4.3.9 Save Images. *Save Images* transfers processed files in **WorkingPics** to the **pic** directory. This provides short term storage and overwrite protection. (Long term storage is best accomplished using the *Warehouse* option discussed later ) Two options are available: *Save Working Image* and *Save Sync Image*. The latter option refers to images produced for "sync" movies as explained in *Movie Functions*. When a processed image is saved, it is automatically named by appending a version number to the name of the original file.

4.3.10 Warehouse. *Warehouse* is a utility that facilitates long term storage of image files. The "warehouse" is a directory which is divided into 32 "aisles," providing a structure for organized, user-specified downloading of files. There are three options within *Warehouse*: *Store Images*, *Fetch Images*, and *List Inventory* (Figure 7). *Store Images* removes user-selected image files from the **WorkingPics** subdirectory and archives them in a compressed format to a user-specified aisle in the warehouse. It also closes any view windows associated with the file which may be open. *Fetch Images* retrieves image files previously placed in the warehouse. It decompresses archived files and places them in the **pic** directory for subsequent processing or analysis. *List Inventory* opens a window on the left side of the screen that lists, by aisle, every image file in the warehouse.

4.3.11 Genlock Options. The Genlock board enables toggling of the workstation's video output between the SGI monitor and a conventional NTSC video monitor or a VCR. Control of the Genlock board is provided through SHIVA using *Genlock Options*. There are three options under this menu: *Open Genlock Window*, *Show Working Image*, and *Kill Show and Window* (Figure 8). *Open Genlock Window* opens a window in the lower left corner of the screen. Anything placed in this window can be seen on a conventional monitor or captured by a VCR. *Show Working Image* opens a window whose size and location is user specified. This option permits the user to obtain a magnified image in the Genlock window. *Kill Show and Window* closes the Genlock window and all show windows.

4.3.12 Image Processing Functions. *Image Processing Functions* contains two lists of color image processing subroutines: *Functions Menu 1* and *Functions Menu 2*. *Functions Menu 1* contains nine WHIP subroutines and six subroutines designed for processing images of combusting sprays illuminated with a copper vapor laser. *Functions Menu 2* contains 23 subroutines, 17 of which prompt the user for further input. The application of several of these functions is detailed in the next section.

4.3.13 Component Processing Functions. This menu contains 26 routines for processing monochrome images. Twenty-three of these routines are directly analogous to color processing routines found in the *Image Processing Functions* menu. Used on the component images created by *Dissect Working Images*, they offer a means of separately processing and analyzing each color component.

4.3.14 SGI Image Processing. This menu facilitates user access to the image-filtering routines and hard copy device drivers bundled with the SGI software. It is an example of the flexibility available through SHIVA for adding more image processing, analysis, and production capability to the system. There are four options within this menu: *WHIP to SGI Conversion*, *SGI to WHIP Conversion*, *imgworks*, and *showcase*. The *WHIP to SGI Conversion* option converts user-selected images to the format required by SGI programs *imgworks* and *showcase* (Figure 9). The *SGI to WHIP Conversion* option converts the user-selected images back to *.pic. The *imgworks* button accesses the SGI image editing program of the same name. The *showcase* option accesses the SGI program which produces color hardcopy.

4.3.15 Exit. There are two options within exit: *Exit and Save Session* and *Exit Without Save*. *Exit and Save Session* enables the *Restore Previous Session* option previously discussed, resets all flags, shuts down all views and movies, and exits SHIVA. *Exit Without Save* resets all flags, removes all unsaved component images, moves all remaining images back to the **pic** directory, shuts down all views and movies, and exits SHIVA. Both options also update the WorkSpace window and a window outside of SHIVA that displays the current available (and used) disk space.

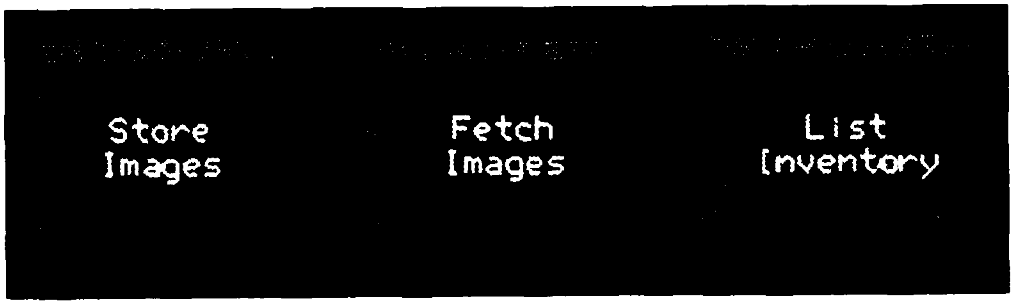


Figure 7. The Warehouse field.


Figure 8. The Genlock Options field.

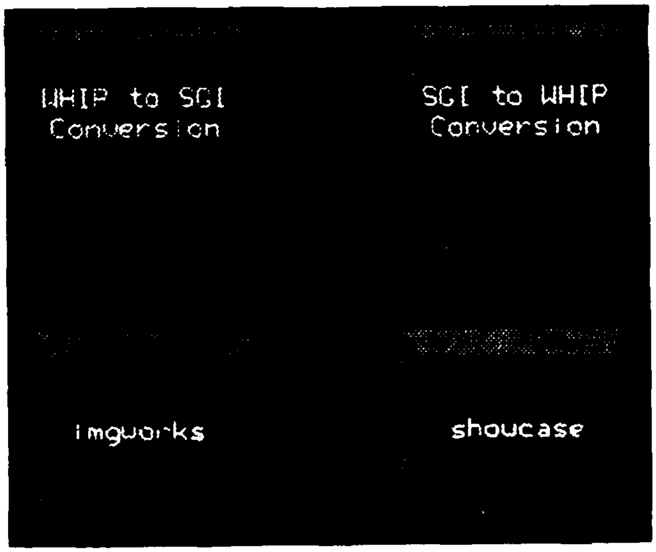


Figure 9. The SGI Image Processing field.

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## 5. APPLICATION OF SHIVA

We have utilized SHIVA in analyzing high-speed cinemagraphic records of combusting HAN-based liquid propellant sprays. Two of the techniques employed for visualizing the spray were (1) sidelighting the spray with a pulsed copper vapor laser light sheet and (2) seeding the propellant with $LiNO_3$ and/or $NaNO_3$ to enhance flame luminosity. It was found that the images were effectively the result of just four narrow wavelength band color sources—(1) 510.6-nm and 578-nm radiation associated with scattered copper vapor laser light and (2) 589-nm and 671-nm emission associated with Na ($3s^2S$-$3p^2P$) and Li ($2s^2S$-$2p^2P$) atomic transitions. It was then shown that laser scatter at 510 nm was the only color source that could produce blue primary content (B), while red primary content (R) was predominantly due to emission from lithium. Thus, the color content of the images provided a basis for identifying contributions from flame and laser scatter in regions where radiation associated with these two sources was coincident. Through the use of color processing and analysis techniques, color content served as a basis for characterization of spray dynamics beyond that possible through simple observation.

Figure 10 shows a typical original image (as digitized and printed) of a combusting spray recorded using high-speed cinematography. The greenish-blue color of the spray is a result of the film's exposure to laser light scattered from liquid particles. The yellow and orange regions are a result of optical emission from combustion. Figures 11a–11c show the component maps of the R, G, and B primaries of Figure 10. Each primary has an 8-bit dynamic range; i.e., integer values from 0 to 255. These component maps were obtained using the *Dissect Working Images* routine. The intensity and extent of the green component are due to the fact that the magenta-forming layer of the film (which results in a green projected image) is sensitive to all of the color sources radiating from the spray. The smaller extent of the B color map is a result of a significant decrease in liquid density downstream of the orifice in the reactive spray. Since the film's yellow-forming layer (which results in a blue projected image) is sensitive only to the 510.6-nm radiation from the copper vapor laser, the decrease in laser scatter corresponds to a decrease in liquid density. For a more detailed description of this analysis, see Birk, McQuaid, and Bliesener (1992).

Figure 12 shows the application of the z5A function in *Functions Menu 1*. This is a custom processing routine which was designed for noise reduction and image enhancement based on the characterization of the color sources in the image. This filter achieves noise reduction by mapping to black (R=G=B=0) any pixel element which does not meet a threshold criterion ($B \geq 40$ or $[R+G+B \geq 60]$). Image enhancement is produced by mapping the color of each pixel element based on its R/B ratio. Several other custom routines of this nature are included in *Functions Menu 1*.

Figure 13 shows the result of applying to Figure 10, the Sobel edge detection algorithm provided in the WHIP package. This routine was helpful in measuring the spray angle—a parameter commonly used as a basis for characterizing spray attributes. The sharpened edge produced by the Sobel convolution provides a better defined angle for making this measurement. The angle measured can be used to validate the measurement obtained from the original image and establish error limits. This routine is also useful for identification of particles outside the spray envelope. WHIP routines for Roberts and Kirsch edge detection algorithms are also available through SHIVA.

In addition to the functions previously mentioned, which were applied with a defined objective, we have experimented with a number of processing routines without attempting to quantify the results. This was done to obtain a change of perspective in the hope of obtaining new insight into the spray dynamics. Among those routines producing interesting results were *rgbrev*, which produces a color negative of the original (Figure 14), and *fatter*, which applies a 3×3 convolution algorithm based on a "logical or" (Figure 15). Routines yielding qualitatively interesting results can be analyzed to determine if a quantitatively useful correlation exists. The ease with which different processing routines can be applied through SHIVA facilitates such an approach.

## 6. CONCLUSIONS

A color software package which enables even the marginally computer literate to perform full-featured color image processing and analysis has been developed. A novice can exercise full control of SHIVA after just a few hours of casual experimentation, rather than several weeks of intensive study. People who may only need to use SHIVA at very long intervals will find that relearning the program is intuitive. Additionally, the modular structure of SHIVA facilitates its expansion to accommodate any further desired image processing, analysis, or production tools.

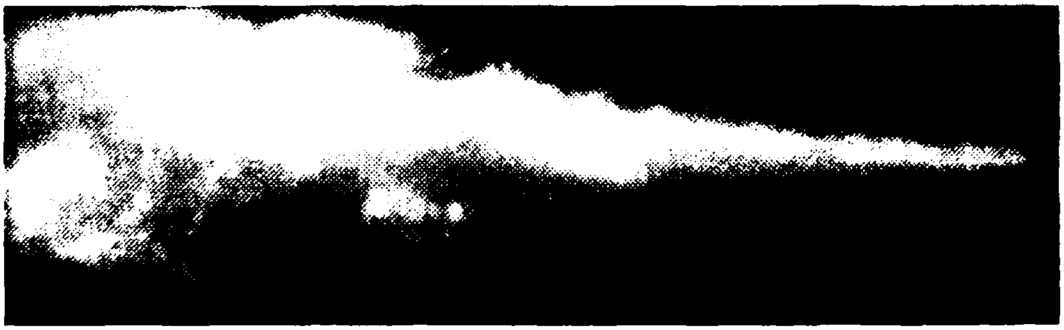

Figure 10. Image from a spray combustion experiment.

Figure 11a. Dissected red component of image in Figure 10.

Figure 11b. Dissected green component of image in Figure 10.

Figure 11c. Dissected blue component of image in Figure 10

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Figure 12. Application of z5a function.

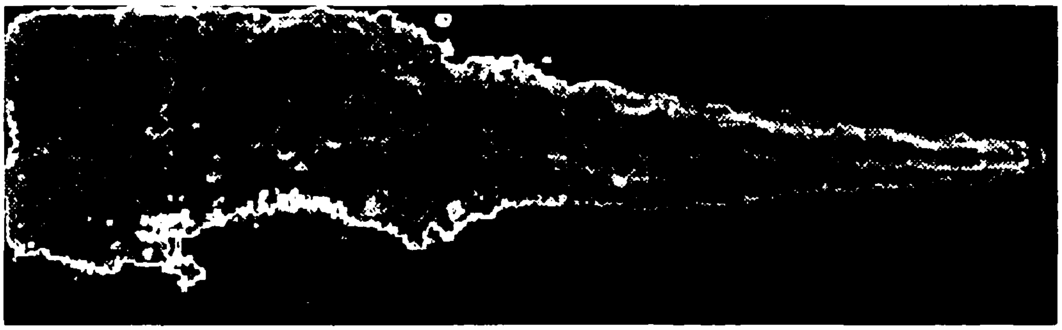

Figure 13. Application of edge - Sobel function.

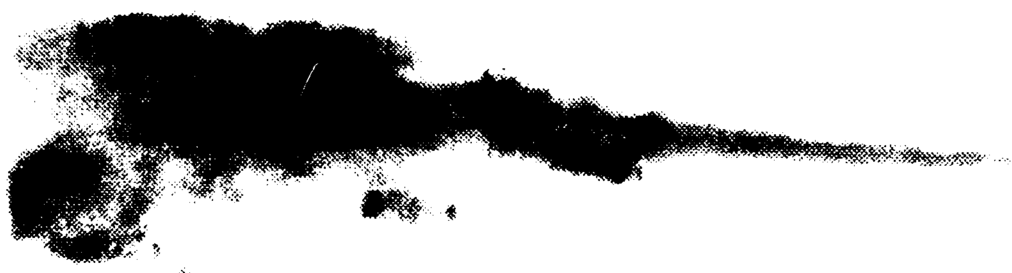

Figure 14. Application of rgbrev function.

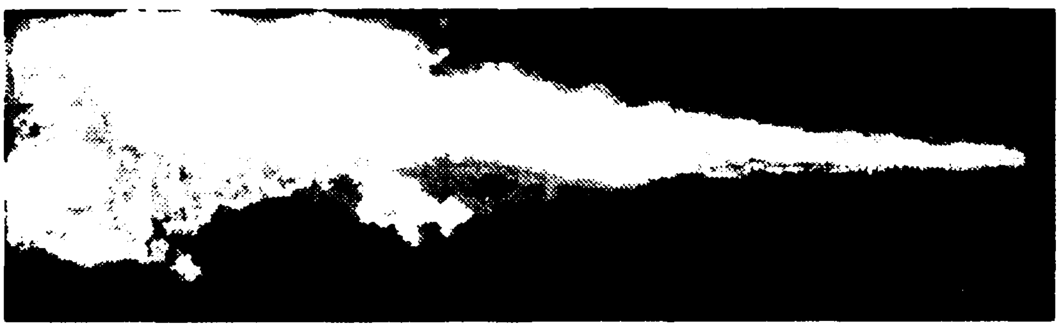

Figure 15. Application of fatter function.

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## 7. REFERENCES

Birk, A., M. J. McQuaid, and G. G. Bliesener. "Reacting Liquid Monopropellant Sprays - Experiments with High Velocity Full Cone Sprays in 33 MPa, 500° C Nitrogen." ARL-TR-17, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, December 1992.

Rogers, D. F. Procedural Elements for Computer Graphics. New York: McGraw-Hill, 1985.

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