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David J. Kelly 7/14/97  
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## TABLE OF CONTENTS

	Page
Cover Page .....	1
SF 298 Report Documentation Page .....	2
Foreword .....	3
Table of Contents .....	4
Introduction .....	5
Body of Report .....	8
Conclusions .....	14
References and Background Literature .....	15
Appendix .....	17

## INTRODUCTION

We have developed a stereoscopic mammography system using state-of-the-art digital technology that enables a mammographer to view the internal structure of the breast directly in depth. Stereo mammograms are obtained by taking two x-rays of the breast from viewpoints separated by about 6 degrees, each view captured by a digital CCD camera. The two digital images are viewed on a stereo display workstation by a radiologist wearing stereo-viewing eyeglasses. The system provides the user with control over display parameters such as brightness, contrast, grayscale polarity, and inversion of depth.

The primary aims of this project are to further develop and refine this system and then to evaluate its effectiveness in increasing the accuracy of diagnosis of breast cancer relative to the diagnostic accuracy afforded by standard, non-stereo film views. The expected increase in diagnostic accuracy could increase the yield of biopsy substantially by allowing the radiologist to more confidently recommend accelerated follow-up of truly benign disease and biopsy of truly malignant disease.

One of two final goals in this project is to conduct a reading accuracy study with a group of mammographers. Each will rate the probability of malignancy for each of a set of cases acquired during the project, first reading only the conventional planar films, then reading the films supplemented by non-stereo viewing of the digital mammograms, and finally reading the films supplemented by stereo viewing of the digital mammograms. We will use ROC methods (Swets, 1979, 1986a, 1988) to evaluate the increase in diagnostic accuracy due to the addition of the digital non-stereo views, and the increase due to addition of the stereoscopic view.

Our second goal is to determine the further improved accuracy that is attainable by use of a feature-based aiding system. In a second, separate study, readers will read each case and assign a numerical value to each of a set of stereo and non-stereo mammographic features on a checklist. A statistical prediction rule will be trained on those feature sets and evaluated, using ROC methods, as a diagnostic aid to further increase the accuracy attained by stereo mammography (Getty et al., 1988; Seltzer et al., 1996; Getty et al., 1997).

Three preliminary steps are necessary before conducting these studies: (1) to further develop and refine the user control interface of the stereo display system, (2) to acquire a large case set of standard films and digital stereo mammograms from consenting patients about to undergo breast biopsy, and (3) to identify new stereo features, and features that may be seen better in stereo, with the aid of expert mammographers and to develop quantitative rating scales for each.

### *Advantages of stereo mammography over standard non-stereo film mammography*

Mammography is known to be one of the most difficult and demanding of the image-based examinations conducted by radiologists. Focal abnormalities are often difficult to detect because of obscuration by superimposed normal parenchymal tissue, particularly in the dense breast. Moreover, once detected, a focal abnormality is often difficult to diagnose -- first because

of the difficulty of separating it perceptually from superimposed parenchymal tissue, and second because of the subtlety, even if unobscured, of the visual features distinguishing benign and malignant lesions. We believe that stereo mammography will significantly help with both of these problems, by providing the mammographer with much more precise information about the three-dimensional properties of each abnormality and by visually segregating the abnormality from the parenchymal context in which it resides.

With a conventional two-view mammographic study, the volumetric locus and the volumetric properties of a focal abnormality can only be determined through a rather demanding and imprecise cognitive process. The abnormality must first be localized, and its two-dimensional, planar properties assessed separately in two views. Then, to determine its volumetric locus and volumetric properties, the two sets of planar information have to be merged cognitively, into what can only be a rough impression of where the abnormality lies and how it would look if it could be seen in the volume. With the stereo display, the mammographer does not have to rely on such a demanding and imprecise process. He/she can look directly into the volume and, via a very natural and effortless perceptual process, see precisely where the abnormality is and what it looks like. Moreover, the perception is a global one that can reveal in a rich and precise way how the abnormality relates to the surrounding parenchymal structure as well as to other possible focal abnormalities. These gains in the richness, precision and global nature of the volumetric information that can be obtained from a stereo display have implications for potentially large improvement both in the detection and diagnosis of focal abnormalities. In this project, the focus is on improvements in accuracy of diagnosis.

#### *Prior Work Developing a Prototype Stereoscopic Digital Mammography System*

In earlier work, we developed a prototype stereoscopic digital mammography system which consists of two components: the first, a mammography unit modified to capture stereo direct-digital mammograms, and the second, a workstation to display the stereo mammograms.

The system for capturing direct-digital mammograms was developed by team members in the Department of Radiology at the University of Massachusetts Medical Center (UMMC). The prototype laboratory system consists of a standard GE Senographe, Model 500TS, as the x-ray source. The film tray of the unit was replaced with a high resolution fluorescent screen to which was attached an experimental CCD (charge-coupled device) camera, developed by Dr. Andrew Karellas (Karellas et al., 1989, 1992a). We designed and built a special mounting system to hold the compression table, fluorescent screen and camera fixed while the gantry and x-ray tube were allowed to rotate, enabling the capture of correctly imaged stereo pairs.

At BBN, we developed a stereo display workstation that permits the radiologist to view a pair of images stereoscopically and to control various aspects of their presentation. Left and right eye views are presented alternately at 120 Hz, in non-interlaced mode, on a single, high resolution monitor. The viewer's two eyes are alternately occluded in synchrony with successive images displayed on the monitor by a pair of StereoGraphics liquid crystal shutters mounted as eyeglasses. By synchronizing the shuttering of the glasses to the display, the left eye always sees the appropriate left-eye-image and the right eye the right-eye-image. We developed software that gives the user control over the brightness and contrast of the displayed stereo image, the ability

to move a cursor in depth within the displayed volume, and the ability to invert the displayed grayscale and the displayed depth.

Using this prototype system, we collected a set of stereo images of 39 breast biopsy specimens. For many of these specimens, we were able to obtain multiple images spaced apart at 2-degree angular increments. From those multiple images, we determined that the optimal angular separation for stereoscopic viewing of the specimen tissue was about 6-degrees. We expect that the optimal separation for stereo views of the compressed, intact breast will be no greater than 6-degrees, and possibly slightly less. This will be determined from cases imaged early in this project and then fixed for the remainder of the project.

We also conducted a diagnostic reading study using 27 of the 39 cases for which we had complete materials, including digital stereo images of the specimen, localization films, specimen radiographs, and pathology reports. The cases were read blind, in a random order, by one expert mammographer, who first rated the probability of malignancy after viewing the two orthogonal localization mammograms, and then re-rated the probability of malignancy after being shown the stereo mammogram. We conducted an ROC analysis of these data and obtained an accuracy measure,  $A_z$ , of 0.725 when the mammographer viewed the standard pair of nonstereo views. Accuracy increased dramatically to 0.939 when the stereo mammogram was added.

## BODY OF REPORT

In the body of this report which follows, we discuss progress during Year 1 in three major areas: (1) improvements made to the stereo display workstation, (2) installation and testing at UMMC of a new GE full-field-of-view digital mammography, and its first use in acquiring stereo mammograms from several patients prior to biopsy, and (3) work on identification of visual features of lesions and normal breast tissue which can be seen uniquely, or better, in depth.

### 1. Improvements to the Stereo Display Workstation

We have completed a substantial amount of control software for the stereo display workstation during this first year of the project. This work has included (1) reorganization of the system's graphical user interface, (2) addition of new functionality to give the user control over zooming, panning and scrolling of the stereo image, (3) development of a database structure for storing the stereo images and parametric display information, and (4) implementation of speech control over many aspects of the display system. We discuss each of these developments below.

#### 1.1 Reorganization of the Graphical User Interface

In this first year, we have begun moving from an interface designed with the needs of the developer as a primary concern to one in which the convenience and needs of the mammographer as user take center stage. In particular, we have moved the essential controls required by the mammographer to the primary window for immediate accessibility, and moved secondary controls, needed infrequently, to hidden windows accessed from items on the menu bar. While we will continue to seek to make the graphical interface as convenient and logical as possible for the mammographer, we expect that much of the commonly-used functionality will be better implemented using speech control or by use of a joystick, thereby avoiding the need to look over at the system control monitor. These issues are discussed at greater length below.

#### 1.2 Addition of New Control Functionality to the Stereo Display System

We have added zoom, pan, and scroll capabilities to the stereo display during Year 1. When looking at tissue containing very fine detail, such as a dense cluster of very small microcalcifications, we have found that it is very helpful to be able to zoom in on the finding at either 2X or 4X magnification. Although, there is no gain in absolute information in a zoomed image, since pixels are merely replicated, visual perception is often significantly improved. Also, when a stereo image is magnified by zooming, perceived depth is magnified by the same scale factor. Since only a portion of the original image is visible when the mammogram is zoomed (1/2 of each dimension at 2X and 1/4 at 4X), the ability to pan and scroll within the larger available image becomes important. We have implemented routines that allow the user to carry out continuous panning and scrolling of the visible display window within the larger stored image.



As we begin to acquire a large database of stereo mammograms, it becomes important that we develop software to manage this database. In Year 1, we have developed capabilities of storing stereo images as linked pairs which define a case. In addition, the database stores particular information about each case that allows the stereo image to be displayed initially with optimized grayscale windowing, optimal image registration, and, optionally, with a description of the case.

### 1.3 Implementation of Speech Control over the Stereo Display System

We have incorporated speech recognition technology into the stereo display workstation during this first year. This technology gives the user control over most aspects of the stereo display using voice commands. A primary advantage of using speech to control the display is that the user is not distracted from his/her viewing of the mammographic images. Without speech control, the user must look over at the control monitor screen and use a mouse or the keyboard to manipulate controls displayed on the monitor. With speech control, the user can command changes to the stereo display and immediately see the resulting effects on the stereo mammogram.

The speech subsystem includes a hardware card and driver software developed by Speech Systems Inc. We have written software routines and speech syntaxes that implement a range of control functions by speech. The user wears a lightweight headset that includes a boom microphone, and holds a small control incorporating a push-to-talk button. Although the system can be run with voice-activated input, we have found that use of the push-to-talk device is preferable since it allows the user to carry on other conversations intermixed with control commands.

The speech commands implemented so far fall into four categories: (1) case selection, (2) windowing of the display grayscale, and (3) inversions of depth and grayscale, and (4) 3-D cursor control. The full set of speech commands is given in the Appendix. Case selection commands allow the user to choose a particular case to be displayed. Windowing commands permit the user to slowly (or rapidly) increase or decrease image brightness or contrast and to halt the change when an appropriate setting is reached. The system will also allow the user to specify particular brightness or contrast settings, and to save current settings as defaults for the case. Inversion commands allow the user to invert depth in the displayed mammogram and to invert grayscale. Inverting depth is very useful in bringing tissue at the back of displayed image to the foreground where it is perceptually more salient. Inverting the grayscale causes denser tissue to be displayed as darker rather than lighter. This gives the image the appearance of being backlit rather than frontlit, which can make fine detail such as thin spicules easier to perceive. The cursor commands turn a displayed cursor on or off, and determine whether it can change its position in depth.

### 1.4 Plans for Year 2

In Year 2, we plan three activities related to further refinement of the stereo display workstation. The first concerns an investigation of a three-dimensional joystick as an alternative

means to control grayscale windowing (brightness and contrast), to control movement of a cursor in the displayed volume, and to control panning and scrolling of the visible image window within the stored image. It is likely that a joystick will provide a user with a more natural and sensitive control over these functions than either speech control or use of the mouse. In the current system, grayscale windowing is controlled either by voice commands (e.g., "increase brightness" or "decrease contrast slowly") or in the graphical interface by moving a cursor over either a contrast or a brightness button and using the two mouse buttons to control changes. The joystick would allow brightness and contrast to be controlled by separate directions of movement. We will also explore use of the joystick to control positioning of a cursor in the displayed volume, using a three-dimensional joystick to permit control of position in depth as well as in the frontal plane. Finally, we will examine the use of the joystick to control panning and scrolling of the visible display window in normal and magnified images.

The second activity will be ongoing refinement of the user interface. As we gain experience with the use of the display workstation during Year 2, we will incorporate improvements to the interface based on comments and suggestions made by mammographers using the system. We expect that the most efficient and natural interface will involve a combination of manual and speech control, with categorical or discrete-state commands most naturally assigned to speech and continuous, graded commands controlled manually with a joystick.

The third activity will be a study to determine the feasibility of porting the stereo display system from the current Matrox Image-1280 display card, and supporting Matrox library, to a different display card and imaging library. The Image-1280 card, with a modification to enable stereo display, is no longer available from Matrox. We will explore other means of displaying stereo images using currently available imaging cards, one of several available image-processing libraries, and StereoGraphics current external stereo-enabling adapter. The goal will be to configure a new system that will duplicate the current system's functionality with minimal rewriting of our software. Our interest in developing this alternative display workstation is both to provide a backup for our current system and to make a stereo display system available to the mammographers at UMMC where the stereo images are being acquired.

## 2. Installation and Testing of a New Digital Mammography Unit at UMMC

The original mammographic detector for stereoscopic imaging was intended to be a small CCD-based digital imager covering an area of approximately 6 x 6 cm. This sensor would provide relatively high contrast and spatial resolution in a confined area which would be adequate for the stereoscopic studies. Although we have made very significant progress with this small CCD detector, some new developments have prompted us to make an adjustment in our plan which will result in a vast improvement in our technique. Earlier this year we were able to install a full-field digital mammography imager (General Electric) which is integrated with a GE DMR x-ray machine. We intend now to make use of this new device to acquire stereo images from patients enrolled in our study.

## 2.1 Acceptance Testing of the New Imaging Unit

Initial testing of the physical characteristics of the new full-field imager have revealed that the radiation dose with this device can be even lower than with typical small-field CCDs, and the contrast resolution and overall detectability is outstanding, perhaps the best that we have seen with any digital mammographic device. This is due to the direct contact of the scintillator with the photosensitive material without any intermediate fiberoptic plate or taper. Measurements of the modulation transfer function with this imager have revealed a significantly higher modulation at low to mid frequencies which is exactly what radiologists need to enhance the contrast resolution. This objective evaluation was followed by imaging to the standard ACR phantom, and the overall detectability in the phantom features appears to be significantly better than that of film screen systems. It appears, therefore, that this new full-field digital device is perfectly capable and, in fact, nearly ideal for stereoscopic imaging.

## 2.3 Modifications and Testing for Stereoscopic Imaging

We have proceeded to modify the system by enabling it to take exposures from 0 to +/- 15 degrees angulation without moving the compressed breast or the image sensor. Further, we have attached a high precision electronic goniometer, which provides a digital readout of the angle in better than 0.5 degree increments. Moreover, the x-ray collimation can be adjusted to close in to the area of interest and acquire two images from two slightly different angles for stereoscopic fusion. After acquisition, the digital images are sent to the Radiology Research Laboratory where they are either written on a CD ROM or electronically forwarded to BBN. Stereoscopic images of specimens already obtained with this new system suggest a dramatic improvement in image quality after stereofusion as compared to our original images with the prototype CCD camera.

## 2.4 Plans for Year 2

This new system has been installed in a very convenient area in the clinical part of the Department of Radiology. Acceptance testing of the unit and modifications for stereo imaging are complete. In the past several days, we have acquired stereo mammograms from the first four patients enrolled in our study, prior to scheduled breast biopsies. We expect to enroll and acquire stereo mammograms on approximately 125 patients during Year 2.

## 3. Identification and Development of Stereo-based Visual Features

The basic task has been to refine and extend our present list of 2-D diagnostic features to cover features newly or differently visible in the stereo display. The original plan for this beginning stage of the work was to conduct interviews and studies with three expert mammographers, but that presumed the availability of a reasonably large number of stereo-imaged cases. We still intend to do that as soon as possible in Year 2.

The limited time we have spent on feature exploration in this first year has been devoted to examining carefully each of our existing set of specimen cases, as well as new ones as they

have become available, manipulating the stereo display parameters individually and in combination to bring out aspects of interest. We have considered it important to do each of these examinations first with our relatively unschooled eyes to bring as fresh and unbiased a perspective as possible to the exploration, and only then to sit with one of our expert mammographers, first to review our findings and then to conduct a detailed study from his trained perspective. This has allowed us to develop a good platform for the full activity with all three of our experts on the large set of cases in Year 2.

Though our exploration to date has been limited, it has been quite informative, first in clearly confirming the promise of the stereo display, and second in providing several very interesting specific findings. With respect to the general promise of the stereo display, we have found it to be remarkably sharp and clear, and to convey very powerful perceptions of the substance and structure of the lesions in depth. There is much that is seeable and much to be visually explored in these richly structured scenes.

### 3.1 Stereo-based Features of Masses

We are not in a position at this point to offer anything of an overview of what the display can provide with respect to specific new features. It will take the study of the larger set of specimens in Year 2 to develop one. What we can report now is our discovery of several features, particularly of masses, that we think are indicative of much more to come. The first of these is the discovery in one of the lesions of very clear nodules at the tips and at intervals along the length of many of its spicules. To our knowledge, this feature has not previously been reported, possibly because it has never been discernible in standard 2-D mammographic displays or in standard pathology preparations. The second discovery in another of the specimens is the apparent proclivity of its spicules to emanate from the center of the lesion, and not, as generally appears to be the case in 2-D silhouettes of masses, to grow out from the surface. It suggests that some lesions that look like masses in 2-D might actually be very dense forms of architectural distortion. The stereo display enables tracing the paths of individual spicules from end to end, and it is clear in this particular specimen that they emanate from a point in the middle of the lesion. Another striking finding, with a specimen showing a cluster of small masses, is how the spicules bridge the masses, as if one mass spawned the next as an outgrowth of one of its spicules. It suggests to us that the nodes visible on the spicule in the case mentioned above, though not visible here, might be the sites of such proliferation. These, of course, are very loose speculations, but they nicely illustrate the richness of what can be seen and the potential for new information and insights to be gained with the stereo display.

### 3.2 Stereo-based Features of Calcification Clusters

The few cases we have studied where the lesion is seen as a cluster of calcifications have also been revealing, mainly of the richness of information that is conveyed. The stereo display enables seeing the calcifications arrayed in distinctly separate groups, some obviously following ductal branches. The branches can be seen to go in different directions. Individual calcifications that in a conventional 2-D display would be seen all in one undifferentiated group can be perceptually segregated in depth into distinct sub-groups and branches, each with its own

distinguishable size, shape and orientation. Moreover, the global pattern of the subgroups in combination can be perceived, potentially revealing the ductal structure that has been occupied by the lesion. Several new and potentially diagnostic features can probably be farmed from this elaborate new information, e.g., to reveal the anatomical locus of the lesion in the parenchyma and how it has insinuated itself there.

### 3.3 Plans for Year 2

This limited exploratory effort has provided strong verification that the stereo display will provide a rich new set of diagnostic features. It has also enabled us to become familiar enough with the display, and with the domain of the new features to proceed at an accelerated pace at the remainder of this work in Year 2.

As soon as we have accumulated a sufficiently large number of cases to begin it, and we expect that to be the case within two or three months, we will pursue the originally planned approach of systematic review and study with our three expert mammographers. We anticipate that we can conduct the consensus meeting that will produce the final list of new stereo features by Month 20. We expect that we can then accelerate development of the feature checklist by Month 24.

## 4. Presentations of Research During Year 1

At the invitation of Dr. Susan Blumenthal, Deputy Assistant Secretary for Health (Women's Health), Dr. Getty participated in a meeting, the *Federal Technology Transfer Workshop on Breast Cancer Detection, Diagnosis, and Treatment*, held in Washington on May 1-2, 1997. He presented the research efforts of this project to the workshop, in a talk entitled "Stereoscopic Digital Mammography: Improving Detection and Diagnosis of Breast Cancer." Dr. Getty also presented a demonstration of stereoscopic mammography to individual participants, in the form of sample stereo mammograms captured on 35mm slides and viewed in handheld stereoscopic viewers.

## 5. Schedule and Level of Effort

The project ran at a level of effort and expenditure through Year 1 of close to 100% of budget. Because of the delays in acquisition and installation of the GE full-field-of-view digital mammography unit, we are behind our original schedule in accrual of imaged cases. However, we are confident that we will catch up in case acquisition during Year 2. All staff and consultants continue with the project as planned.

## CONCLUSIONS

All of the work proposed for the first year to improve the Stereo Display Workstation has been completed, including: reorganization of the graphical user interface; addition of new functionality to the stereo display system; and implementation of speech control over the stereo display station. Installation and acceptance testing of the GE full-field-of-view Digital Mammography Unit is now complete. Delay in delivery of the unit from the manufacturer put this work behind schedule, and caused attendant delays in the collection of case images and, in turn, a slowing of the feature development work. We have, however, been able to accomplish much of the feature development work planned for the first year by working intensively with available specimen images, and we expect that we can, therefore, accelerate the feature development work as cases are accrued with the new equipment. This optimistic projection is also justified by the fact that the pool of patients available for imaging has recently been greatly expanded due to the increased utilization of core biopsies at UMMC.

We can draw two general conclusions from this first year of work. The first is that the stereo display is all that we had expected and hoped it would be, and more. It provides displays that are easy to read and highly informative – sharp images of the fine features of lesions that have to be discriminated for diagnosis, and all perceived with remarkably strong impressions of position, separation and orientation in depth. Our initial explorations suggest that the display will provide rich new sources of diagnostic information. The second general conclusion is that the various aspects of development of the system we initially proposed to enable easy and versatile access to, and interaction with, the display system parameters were attainable, and most have proven to be quite necessary. We have found that to bring out the full richness and clarity of the display requires sensitive adjustment of the various parameters, and that it is important to make those interactions as natural and convenient as possible. Those interactive capabilities we initially proposed have been accomplished to very good and useful effect, and we plan further refinements for Year 2. All in all, this project is proving to be very productive and suggestive that some truly large gains in diagnostic accuracy will be obtained.

## REFERENCES AND BACKGROUND LITERATURE

- D'Orsi, C. J., Getty, D. J., Swets, J. A., Pickett, R. M., Seltzer, S. E., and McNeil, B. J. (1992) Reading and decision aids for improved accuracy and standardization of mammographic diagnosis. *Radiology*, 184, 619-622.
- D'Orsi, C. J. and Kopans, D. B. (1993) Mammographic feature analysis. *Seminars in Roentgenology*, 28, 204-230.
- D'Orsi, C. J. and Karellas, A. (1995) Digital mammography: Are we ready? *The Lancet*, in press.
- DuMond, J. W. (1932) The technique of stereofluoroscopy. *Radiology*, 19, 366-387.
- Getty, D.J., and Huggins, A.W.F. (1986) Volumetric 3-D displays and spatial perception. In E.J. Wegman and D.J. DePriest (Eds.), *Statistical Image Processing and Graphics*, NY: Marcel Dekker.
- Getty, D. J., Pickett, R. M., D'Orsi, C. J., and Swets, J. A. (1988) Enhanced interpretation of diagnostic images. *Investigative Radiology*, 23(4), 240-252.
- Getty, D.J., Pickett, R.M., Chylack, L.T., Jr., McCarthy, D.F., and Huggins, A.W.F. (1989) An enriched set of features of nuclear cataract identified by multidimensional scaling. *Current Eye Research*, 8, 1-8.
- Getty DJ, Seltzer SE, Tempany CMC, Pickett RM, Swets JA, McNeil BJ. (1997) Prostate cancer: relative effects of demographic, clinical, histologic, and MR imaging variables on the accuracy of staging. *Radiology*, in press.
- Huggins, A.W.F., and Getty, D.J. (1982) Display-control compatibility in 3-D displays. In D. Getty (Ed.), *3-D Displays: Perceptual Research and Applications to Military Systems*, Psychological Document 2570, American Psychological Association, 1200 17th St., NW, Washington, D.C. 20036
- Jarre, H. A. and Teschendorf, O. E. (1933) Roentgenstereoscopy: A review of its present status. *Radiology*, 21, 139-155.
- Karellas, A., Harris, L.J., and Davis, M.A. (1989) Design and evaluation of a prototype CCD-based imaging system for electronic radiography. *Medical Physics*, 16, 681.
- Karellas, A., Harris, L.J., and D'Orsi, C.J. (1990) Small field digital mammography with a 2048 x 2048 pixel charge-coupled device. *Radiology*, 177, 288.
- Karellas, A. and D'Orsi, C. J. (1992) Near real-time mammographic imaging with a CCD. *SPIE, International Working Group Newsletter*, 2(3).
- Karellas, A., Harris, L.J., Liu, H., Davis, M.A., and D'Orsi, C.J. (1992a) Charge-coupled device detector: Performance considerations and potential for small-field mammographic imaging applications. *Medical Physics*, 19(4), 1015-1023.
- Karellas, A., Liu, H., Harris, L. J., and D'Orsi, C.J. (1992b) Operational characteristics and potential of scientific-grade charge-coupled devices in x-ray imaging applications. *SPIE, Electron Tubes and Image Intensifiers*, 1655, 85-91.

- Karellas, A., Liu, H., Harris, L.J., and D'Orsi, C.J. (1994) Digital mammo delivers quick, reliable images. *Diagnostic Imaging*, Feb., 1994, 77-80.
- Liu, H., Karellas, A., Harris, L.J., and D'Orsi, C.J. (1993) Optical properties of fiber tapers and their impact on the performance of a fiber-optically coupled CCD x-ray imaging system. *Proc. SPIE*, 1994, 136-147.
- Liu, H. Karellas, A., Moore, S. C., Harris, L. J. and D'Orsi, C. J. (1994) Lesions detectability considerations for an optically-coupled CCD x-ray imaging system. *IEEE Trans. Nucl. Sci.*, 41, 1506-1509.
- Seltzer, S. E., McNeil, B. J., D'Orsi, C. J., Getty, D. J., Pickett, R. M., and Swets, J. A. (1992) Combining evidence from multiple imaging modalities: A feature-analysis method. *Computerized Medical Imaging and Graphics*, 16(6), 373-380.
- Seltzer SE, Getty DJ, Tempany CMC, Pickett RM, Schnall MD, McNeil BJ, Swets JA. (1997) Staging prostate cancer with MR imaging: a combined radiologist-computer system. *Radiology*, 202: 219-226.
- Swets, J. A. (1979) ROC analysis applied to the evaluation of medical imaging techniques. *Investigative Radiology*, 14(2), 109-121.
- Swets, J. A. (1986a) Indices of discrimination or diagnostic accuracy: Their ROCs and implied models. *Psychological Bulletin*, 99(1), 100-117.
- Swets, J. A. (1986b) Form of empirical ROCs in discrimination and diagnostic tasks: Implications for theory and measurement of performance. *Psychological Bulletin*, 99(2), 181-198.
- Swets, J. A. (1988) Measuring the accuracy of diagnostic systems. *Science*, 240, 1285-1293.
- Swets, J. A. (1992) The science of choosing the right decision threshold in high-stakes diagnostics. *American Psychologist*, 47(4), 522-532.
- Swets, J. A., Pickett, R. M., Whitehead, S. F., Getty, D. J., Schnur, J. A., Swets, J. B., Freeman, B. A. (1979) Assessment of diagnostic technologies. *Science*, 205, 753-759.
- Swets, J. A. and Pickett, R. M. (1982) *Evaluation of diagnostic systems: Methods from signal detection theory*, NY: Academic Press.
- Swets, J. A., Getty, D. J., Pickett, R. M., D'Orsi, C. J., Seltzer, S. E., and McNeil, B. J. (1991) Enhancing and evaluating diagnostic accuracy. *Medical Decision Making*, 11, 9-18.
- Warren, S.L. (1930) A roentgenologic study of the breast. *Amer. J. Roentgeneology Radium Therapy*, 1930, 24, 113-124.



## APPENDIX

### Description of the Stereo Display System

The Stereo Display System displays a pair of digitized x-ray images stereoscopically and provides the user with control over various aspects of the display through both a graphical and speech interface. Most commands can be invoked both through a menu item and/or button on the graphical user interface (GUI) or through a voice command.

When the GUI is used, the graphical system by its nature provides visual feedback about which command the user selected. For voice commands, the system provides auditory feedback through a headset about which command it will execute based on what it thinks the user said. Except for the "Save" command, the user is not required to confirm the command before it is executed.

The commands fall into five general categories:

1. Case selection
2. Grayscale manipulation
3. Image display
4. Cursor control
5. Speaker gender

This appendix describes the commands in each of the categories and how they are implemented in the GUI and VOICE interfaces.

### Conventions

The following conventions are used in describing the VOICE commands:

1. Words in parentheses () are optional and are included for naturalness or to improve recognition.  
Example: "Report (settings)"  
Here the user can say either "Report" or "Report settings".
2. Words or phrases separated by commas in square brackets indicate alternative items that can be said at that point in the text.  
Example: "Invert [grayscale, depth]"  
The user can say either "Invert grayscale" or "Invert depth".  
The user should not say "Invert".
3. Italicized words in angle brackets indicate a range of items that can be spoken at that point in the text.  
Example: Case (number) *<a number from 1 to 299>* "  
The user can follow either "Case" or "Case number" with a number between 1 and 299.

## Stereo Display Windows

The Stereo Display application has a startup window whose function is to call the initialization routines for the speech and imaging functions of the system when the user is ready to begin. When the initialization routines finish, this window then invokes the main window of the system.

In addition to the startup window, the Stereo Display application has four other windows:

- The main window.  
This window is the primary window of the application. From this window the user selects cases and sees information about the case currently being viewed. It has control buttons for selecting the type of display and for invoking the cursor. It also has the menu bar for accessing all of the functionality and the other windows of the system.
- The Enhancements Palette window.  
This window contains the controls for manipulating the grayscale map as well as inverting depth or color. The Registration window can also be called from this window. . This window is invoked from the Tools->Enhancements Palette menu on the main window.
- The Registration window.  
This window contains the controls for aligning the images, for panning/scrolling, and for magnifying. This window is invoked from the Tools->Registration menu on the main window or from the "Adjust Registration" button on the Enhancements Palette window.
- The Cursor window.  
This window is invoked when the user requests a cursor on the display by clicking the Stereo Cursor icon. It uses the X and Y coordinates of the mouse cursor within its borders to position the crosshair cursor on the display.

### 1. Case Selection

A case is comprised of two x-ray image files: one image file is intended to be seen by the left eye to see and the other by the right eye. A case can be selected for viewing by either explicitly selecting from disk the two image files associated with the case, or by selecting a case from a database.

#### ***Read Case Files from a Disk***

This command allows the user to specify the two image files for viewing. The image on the stereo screen shows the data as they are in the raw image files, without any enhancements.

GUI Controls: Load Stereo Pair button, File->Load Stereo Pair menu

This command brings up a custom file selection dialog that allows the user to specify the two image files at once. The first file selected is seen by the left eye and the second file is seen by the right eye.

VOICE: (not implemented)

### **Select a Case from a Database**

The user can select a case from a database of cases viewed previously by the user and saved. When the user selects a case from the database, the system loads the two image files and initializes the display to the default settings that were saved with the case. On the main window, the system displays the case number, the patient ID, the case description, and the names of the images files that the user is viewing. All of this information was obtained from the database when the case was selected.

GUI Controls: Next Case button, Case->Next Case menu

This command brings up a dialog window with the database of cases shown in a table. The user selects a case by clicking on the row that describes the case. When the user clicks the OK button, the case is displayed.

VOICE command sequence:

User: "Next (case)"  
System: After the tone, please say "Case" followed by the number. <beep>  
User: "Case <a number from 1 to 299 > "  
System: Case <number> is Specimen C.  
User: "OK", or "Cancel", or another case number.

The dialog above between the user and system demonstrates how a user would select a case from the database using voice commands. After the system prompts for a case number, the same dialog window as invoked by the GUI control is displayed so that the user can view the database while making a choice.

### **Save a case to the Database**

The system allows the user to build a database from cases that were loaded initially by reading the files directly from disk (see the method above). After loading a case, the user can optimize the image by changing grayscale settings and registration. When the image is satisfactory, the user can then save the case under a unique case ID number. This command requires the user to confirm the "save" because this action will overwrite data previously stored for this case.

Saving a case writes the following information about that case to the database:

- a unique ID number assigned by the system
- a patient ID field (text from the Patient data entry field on the main window)
- the name of the image file to present to the left eye
- the name of the image file to present to the right eye
- the current brightness setting
- the current contrast setting
- a descriptive text field (text from the Description data entry field on the main window)
- the X and Y offset for the left eye image

- the X and Y offset for the right eye image

After a case has been saved, the user can change the settings or descriptions in the database for that case by first selecting the case, then changing settings or typing in the Patient or Description field on the main window, and finally “saving” the case again. The new data replaces the old data in the database.

GUI Controls: Case->Save Case menu

This command brings up a confirmation dialog that asks the user to confirm the action.

VOICE command sequence:

User: “Save (case)”  
 System: Yes or No. <beep>  
 User: “Yes “ or “No”  
 System: Case saved. or Not saved.

## 2. Grayscale Manipulation

Before they are displayed on the screen, the 8-bit data values in an image file pass through a look-up table that maps each of the input data values into an output display value between 0 (full white) and 255 (full black). By default, the table maps each input data value onto itself. The resulting picture on the display is a true representation of the image data as it exists in the file. The user can change the mapping of input-to-output values to enhance the appearance of the picture on the screen. By changing the mapping the user can change visual aspects of the display such as brightness and contrast, create a “negative” of the image, or highlight a specific data value.

Grayscale manipulation on the GUI is performed from the Enhancements Palette window. All the controls mentioned in this section are on the Enhancements Palette window

### ***Increase/Decrease Brightness***

This command increases or decreases the overall brightness level of the image from its current setting. The value of the brightness level ranges from 0 to 255. The user can change this value in large or small increments as needed. For the default linear map, the higher the value the brighter the display (if the map is inverted, the higher the value the darker the image).

GUI Controls: Scrollbar attached to the “Brightness” rectangle  
 Rectangle labeled “Brightness”

These controls allow the user to make incremental or gross changes to the brightness value.

With the scrollbar, the user can make small changes to the value by clicking the left or right arrows, or make larger changes by dragging the slider or clicking in the. With the Brightness rectangle, the user can increase or decrease the value continuously by placing the cursor in the rectangle then holding down either the right or left mouse button respectively. Releasing the mouse button stops the change.

VOICE commands::

“Increase brightness [slowly]”  
“Decrease brightness [slowly]”  
“Stop”

When the user gives the “Increase or Decrease brightness command, the brightness level of the image begins to change quickly in the designated direction. If the word [slowly] is added, the level changes by one every second. The level continues to change until the user says “Stop” or until an end value (0 or 255) is reached. In addition, this command also updates the GUI controls to reflect the new value.

***Increase/Decrease Contrast***

This command increases or decreases the range-of-contrast value. The contrast range value is a number between 0 and 255 that defines the width of a window about the brightness level. Data values in this window will be mapped from white (0) to black (255). All data values below this range will be mapped to white and all data values above this range will be mapped to black. Increasing the contrast range decreases the amount of contrast in the display: conversely, decreasing the contrast range increases the amount of contrast in the image.

GUI Controls: Scrollbar attached to the “Contrast” rectangle  
Rectangle labeled “Contrast”

VOICE commands::

“Increase contrast [slowly]”  
“Decrease contrast [slowly]”  
“Stop”

These commands are implemented in the same manner as the Brightness level controls and commands. (See Increase/Decrease Brightness section presented earlier more information.)

***Set Brightness to a Specific Value***

This command sets the brightness level to a value between 0 and 255. The higher the value the brighter the display. If the linear map is inverted, the higher the value the darker the image.

GUI Controls: Brightness Scrollbar  
Rectangle labeled “Brightness”

The same controls for increasing/decreasing brightness are used to set the brightness to a specific value. (See the Increase/Decrease Brightness section described earlier for how to use the controls). The user operates the GUI controls until the desired value appears in the text field to the right of the "Brightness" rectangle.

VOICE commands:

"Set brightness to *<a number from 0 to 255>* "

This command sets the brightness level to the number specified. The display is changed to reflect the new brightness value. The GUI controls are also reset to the new value.

***Set Contrast to a Specific Value***

This command sets the range-of-contrast value to a number between 0 and 255: the larger the number the less the amount of contrast in the display and vice versa.

GUI Controls: Scrollbar attaches to the "Contrast" rectangle  
Rectangle labeled "Contrast"

The same controls for increasing/decreasing contrast are used to set the contrast to a specific value. (See the Increase/Decrease Brightness section described earlier for how to use the controls). The user operates the controls until the desired value appears in the text field to the right of the "Contrast" rectangle.

VOICE commands:

"Set contrast to *<a number from 0 to 255>* "

This command sets the range-of-contrast value to the number specified. The display is changed to reflect the new range value. The GUI controls are also reset to the new value.

***Invert Grayscale***

This toggle command inverts the linear grayscale mapping. Normally, input data are mapped linearly into output values ranging from pure white (0) to pure black (255). Inverting the map causes the output values for the same input values to range from black-to-white instead. This has the effect of producing a "negative" of the image. Inverting the grayscale again returns the mapping and display to its former state.

GUI Controls: Invert GRAYSCALE button

VOICE commands:

"Invert [grayscale/ black and white] "

***Reset Grayscale***

This command resets the brightness level and contrast range to their default values of 128 and 256 respectively.

GUI Controls: Reset button

VOICE commands:

“Reset (grayscale) “

Both commands cause the controls on the GUI to be reset to the default values. The display reflects the new settings.

### ***Highlight a Data Value***

This command initially sets the contrast range to one and then displays the input data value that maps to the brightness level as pure white, thus highlighting that one data value. The remainder of the data are mapped linearly into values between 0 and 126. This allows the highlighted value to be observed against a dimmed version of the image.

GUI Controls: Highlight check box

VOICE commands:

“Highlight [On/Off] “

When highlighting is enabled, the image is set to half of its full brightness and only the data whose value equals the current brightness level is mapped into pure white. The user can highlight single data values by leaving the contrast range at one and changing the brightness level, or highlight a range of values about the brightness level by changing the contrast range. Turning highlighting off returns the image to the visual state prior to the “highlight on” command.

### ***Report Grayscale Settings***

This command enables the user to hear the exact values of the current brightness and contrast settings.

GUI Controls: (N/A) Settings are viewable on the Enhancements Palette window.

VOICE command sequence:

User: “Report (settings) “

System: Reporting...Brightness 120, Contrast 46

Following this command, the user hears a spoken report of the current brightness and contrast settings in the headset.

### ***Save Grayscale Settings***

The “Save” command described earlier allows the user to save the current brightness and contrast settings for a case so that when the case is recalled at a later time, it will appear as it did when it was saved. (See the Save command for more information.)

## **Image Display**

### ***Request Stereo or Mono Display***

The user can choose a stereo or a monaural view of a case. In the stereo display, the perception of a three-dimensional image is achieved by presenting one image to the left eye, while presenting a different image, acquired from a slightly different point-of-view, to the right eye. The human visual system is able to fuse these two images into one containing depth.

A mono display simply presents the same image (in this case the image presented to the left eye) to both eyes. The perceived image has no depth.

GUI Controls: Stereo button, Mono button, Display->Stereo menu, Display->Mono menu

### VOICE commands:

“Stereo (display)”

“Mono (display)”

### ***Adjust Alignment***

This capability allows the user to move each of the images up, down, left or right independently to correct for any misalignment of the images that may have occurred when the pictures were taken.

The alignment controls are on the Registration window

GUI Controls: Scrollbar attached to a rectangle identified by eye and direction  
Rectangle identified by eye and direction

Each combination of eye and direction (left/horizontal, left/vertical, right/horizontal, right/vertical) has two controls, similar to the controls used for brightness and contrast. With these controls, the user can move each image independently in the horizontal (left and right) or vertical (up and down) direction.

To operate any of the four scrollbars, the user clicks the left or right arrows to move the image by small increments, or drags the slide or clicks in the track to move in larger increments. To use any of the eye/direction rectangles, the user places the cursor in the rectangle then holds down either the left or right mouse button to move the image continuously in one direction (left or up) or the opposite direction (right or down) respectively. Releasing the mouse button stops the movement.

Once the images are aligned, the user can save these offsets while viewing this case by clicking the OK/Save button when exiting the window. If the user clicks Cancel to exit



the window, the display is reset to the settings in effect prior to invoking the Registration window.

VOICE commands: (not implemented)

### ***Pan or Scroll Image***

This command allows the user to move the image on the display up or down (scrolling), or left or right (panning). In this case the left and right eye images move together.

This control is on the Registration window.

GUI Controls: Scroll check box

To enable panning or scrolling, the user clicks the pan/scroll check box to write an "X" in the box. To disable movement, the user clicks in the check box again to remove the "X". When panning and scrolling are enabled, the images are coupled together and the alignment controls for the left eye serve to move the image on the display up, down, left, or right. The alignment controls for the right eye are disabled. When panning and scrolling are disabled, the images are uncoupled, the alignment controls for the right eye are enabled, and the user can again move each image independently.

VOICE commands: (not implemented)

### ***Zoom Image 1X, 2X, or 4X***

The user can enlarge the image on the display by a factor of 1, 2 or 4. The image is magnified about the center of the current view.

This control is on the Registration window.

GUI Controls: 1X radio button, 2X radio button, 4X radio button

The user can select the magnification factor by clicking one of the radio buttons.

VOICE commands: (not implemented)

### ***Invert Depth***

This toggle command switches the image presentation to each eye (i.e., the image presented to the left eye is shown to the right eye instead and vice versa). The effect is an inversion in depth; whatever appears to have been at the back of the display now appears in front and what was in front appears to have moved to the back.

This control is on the Enhancements Palette window.

GUI Controls: Invert DEPTH button

VOICE commands:  
“Invert depth”

## **Cursor**

### ***Display a Crosshair Cursor***

#### ***Move the Crosshair Cursor within a Depth Plane***

Sometimes the user might want to point to some interesting feature in the image. This command provides a large, crosshair cursor on the display that the user can position horizontally, vertically, or in depth with the aid of the mouse.

GUI Controls: Stereo Cursor Crosshair Icon on the main window

To enable the use of the cursor (cursor mode), the user clicks on the Crosshair icon. The system responds by bringing up the Cursor window. This window covers the entire console screen; its purpose is to use the location of the mouse cursor in its window to position the crosshair cursor on the display. Now when the user moves the mouse, that movement is translated into a corresponding movement of the crosshair cursor on the display. This X/Y movement takes places in whatever depth plane the cursor is in.

To exit cursor mode and return to the main window, the user clicks Close on the menu bar.

VOICE commands:  
“Cursor On”  
“Cursor Off”

The voice command “Cursor On” enables cursor mode and has the same effect as clicking on the GUI control.

The voice command “Cursor Off” disables cursor mode and is comparable to clicking Close on the Cursor window.

### ***Move the Crosshair Cursor to Different Depth Planes***

In addition to moving horizontally and vertically, the crosshair cursor can also move forward and backward in depth, giving the appearance of moving in and out of the image itself. Once the user positions the cursor in depth, then moving the mouse moves the cursor horizontally and vertically in that depth plane.

NOTE: Before voice was added, this function was implemented by holding down the left and right mouse buttons to move backward and forward respectively. However, the speech system uses the right mouse button exclusively as the push-to-talk device when speech input is enabled. Consequently, in order to continue to use the right mouse button

as a control, both the GUI and voice commands below disable voice so that the right mouse button can be used as a controlling device.

GUI Controls: Move in Depth->Enable menu, Move in Depth->Disable menu

VOICE commands:  
"Cursor Move"

These commands disable speech input and enable the ability to move the cursor in depth using the mouse buttons. Once speech input is disabled, the user can hold down the left and right mouse buttons to move the cursor backward and forward respectively. The user cannot issue any voice commands during this time, however. When the user wants to return to voice mode, the user either selects the Move-in-Depth->Disable menu or double clicks either of the mouse buttons. These actions end the ability to move the cursor in depth and re-enable the ability to issue voice commands. The cursor remains at whatever depth plane it resided in when movement in depth was disabled.