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9. M. P. Lesser, Back Illuminated Large Format Loral CCDs, *SPIE Proceedings*, pp. 117-182, Vol **1447**, Feb., 1991.
10. M. F. Piccaro, E. Toker, Development and Evaluation of a CCD-based digital imaging system for mammography, *SPIE Proceedings*, pp 109-119, Vol **1901**, Feb 3-4 1993.
11. A. Karellas, L. J. Harris, H. Liu, M. A. Davis, C. J. D'Orsi, Charge-coupled device detector: Performance considerations and potential for small-field mammographic imaging applications, *Medical Physics* 1992; **19**: 1015-1023.
12. H. Liu, A. Karellas, L. J. Harris, C. J. D'Orsi, Optical properties of fiber tapers and their impact on the performance of a fiberoptically coupled CCD X-ray imaging system, *SPIE Proceedings*, pp. 136-146, Vol **1894**, Jan., 1993.
13. S. R. Kamasz, M. G. Farrier, F. Ma, R. Sabila, S. G. Chamberlain, A High Frame Rate, Motion Compensated 25.4 Megapixel Image Sensor, *SPIE Proceedings*, pp. 155-166, Vol 2172, Feb., 1994.

Electronic Photography at the NASA Langley Research Center

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Abstract

An electronic photography facility has been established in the Imaging & Photographic Technology Section, Visual Imaging Branch, at the NASA Langley Research Center (LaRC). The purpose of this facility is to provide the LaRC community with access to digital imaging technology. In particular, capabilities have been established for image scanning, direct image capture, optimized image processing for storage, image enhancement, and optimized device dependent image processing for output. Unique approaches include: evaluation and extraction of the entire film information content through scanning; standardization of image file tone reproduction characteristics for optimal bit utilization and viewing; education of digital imaging personnel on the effects of sampling and quantization to minimize image processing related information loss; investigation of the use of small kernel optimal filters for image restoration; characterization of a large array of output devices and development of image processing protocols for standardized output. Currently, the laboratory has a large collection of digital image files which contain essentially all the information present on the original films. These files are stored at 8-bits per color, but the initial image processing was done at higher bit depths and/or resolutions so that the full 8-bits are used in the stored files. The tone reproduction of these files has also been optimized so the available levels are distributed according to visual perceptibility. Look up tables are available which modify these files for standardized output on various devices, although color reproduction has been allowed to float to some extent to allow for full utilization of output device gamut.

Introduction

Over the past two years, the Visual Imaging Branch (VIB) of LaRC has been working to establish the capability to provide electronic photography (EP) services to the NASA community. To this end, a significant amount of computer and peripheral imaging equipment has been purchased, and personnel development has begun in digital imaging. Of note in these efforts is an attempt to take a unified view of imaging processes. A major goal is to not only provide capture, processing, and output services, but to also integrate these services with each other to provide optimal image quality and minimize repetition. It is significant that the image quality currently achieved is not only equal to, but frequently superior to that achieved through conventional photographic means.

The idea of achieving improved image quality through digital processing is hardly new. In fact, several NASA centers (such as the Jet Propulsion Laboratory) were pioneers in this field. In general, this processing was done using custom software on sophisticated computers. The efforts discussed in this paper are novel in that the processing is done in a production situation using standard desktop computers, commercial software packages, and off-the-shelf peripheral equipment. This equipment is becoming more available and capable, although the processing routines tend to be unsophisticated from the perspective of an image processing expert. The work described here attempts to elevate production processing by considering photographic, linear systems, and information theory, and sampling and quantization effects. It is recognized that this list does not include some of the newer techniques, such as morphological processing, but the production environment always lags behind research to some extent. The techniques described in this paper are an attempt to narrow the gap between the techniques used in production and the state of the art, while recognizing that it is impossible to eliminate it completely.

A significant amount of the processing required for the production of electronic photographs, however, is subjective. Mathematical analyses and techniques are helpful, but in many cases the final decision about exactly what to do to an image comes from looking at it, trying something, and seeing if there is a visual improvement. Subjective studies have shown that facsimile reproduction is generally not preferred, particularly with tone and color reproduction. It is important that the professional electronic photographer have knowledge of things such as sampling effects and optimal filters, but it is equally important that they be able to subjectively manipulate images to produce the most pleasing visual result, even when this result does not have exactly the same gray levels and colors as the original.

The Imaging & Photographic Technology Section of the VIB has a long history of professional photographic production. Expertise in the subjective side of image evaluation is readily available, but it is important to distinguish between subjective image quality and artistic considerations. Skills which would be defined to some extent as artistic are required in both cases, but there is a big difference in motivation between the artist trying to convey a message or produce an emotional reaction, and the professional photographer trying to produce the most informative or pleasing picture for a client. The latter can take advantage of subjective experiments and studies to develop technical procedures that achieve a desired end.

The Graphics Section of the VIB has several years of current experience in digital imaging, particularly in the design of systems using off-the-shelf materials. Their focus is on the production of graphics through adding text to images, image manipulation, and animation. They contribute experience in the second required element — computer systems. In this case, it is important to distinguish between image processing and enhancement, and image manipulation. The purpose of the former is to produce photographs which accurately convey the subjective impression of the original scene. The purpose of the latter is to change the content of an image for some specific use. In the initial development of EP, a great deal of attention has been paid to the possibilities of digital image manipulation. In many cases, the technical challenges of producing the best quality electronic photograph are greater than those involved in manipulation. The Electronic Photography Lab which has been established in the Imaging and Photographic Technology Section will concentrate on image processing and enhancement, with the Graphics Section continuing to do the manipulation.

The final element required for the production of optimal electronic photographs is image processing expertise. This requirement has been addressed by bringing in outside expertise and conducting training sessions for laboratory personnel. The argument has been made in the past that it is difficult to teach higher mathematics to artists and photographers, but it is less difficult to teach the associated concepts. In fact, the "feel" for imaging systems which many photographers possess makes it easier for them to understand image processing concepts than might otherwise be expected. As long as some of the lab personnel understand the mathematical base for the concepts, it is possible for photographers with limited mathematical backgrounds to apply moderately advanced techniques by using packaged software and following written protocols. They may even be more proficient at choosing exactly what to do to an image, and evaluating the result, than a more traditional image processing expert.

Background

Motivating Factors

A number of factors led to the establishment of the LaRC EP Lab, including:

1. The need to produce electronic image files and documents. It has become increasingly important to be able to disseminate information electronically, and one goal of the Research Publishing and Printing Branch at LaRC has been the production of both electronic and hardcopy versions of technical publications. The actual publishing process has also become more electronic with the advent of computer based page layout and on-demand printing.

2. Demands for greater output flexibility. One of the prime advantages of electronic over conventional photography is that it is not necessary to decide on the final output form until the output stage of the process is reached. Also, multiple, high quality output forms are readily available from a single image file.

3. Improved image quality. The flexibility of EP is much greater than with conventional photography, allowing for potentially higher image quality. Much of this potential has not been realized in the past, but will be in the future.

4. Quantification of image information. In a research environment, the quantification of image information is important. Digital data files produced by scanning film are much easier to perform calculations on than the film originals. Electronic capture also opens up many new possibilities due to the radiometric accuracy typical with solid state detectors.

5. On-line database, catalog, and archive possibilities. It is frequently important to be able to quickly and effectively locate past work. Databases can be constructed for conventional photographs, but electronic image files can be included on-line and linked to the database. Files ranging from small catalog images to large files containing essentially all the image information captured are possible, and with digital image files an unlimited number of "originals" can be replicated.

6. Environmental considerations. EP has the potential to significantly reduce the environmental impact of imaging processes, as compared to conventional photographic processes.

7. Development of management and workflow procedures for the new technology. Organizations who begin to work with a new technology as it evolves remain ahead in terms of developing management strategies and optimizing workflow.

Comparison to Photo CD

The approach taken in this work is similar in some respects to the work done by Eastman Kodak Company in the development of the Photo CD. In both cases a complete system has been designed, with attention paid to all of the relevant aspects of the imaging processes. The Photo CD, however, was designed with the consumer in mind and possesses limitations which are important in some cases. The particular limitations which preclude general adoption of the Photo CD system at LaRC are as follows:

1. *Lack of documentation on scanner characteristics and processing algorithms.* It is difficult to obtain complete information on the exact nature of the scanning and processing done by the Photo CD Imaging Workstation (PIW).
2. *Built-in image processing and user processing features are limited.* It is difficult to perform some image processing because the built-in processing does not appear to be comprehensive, and it is difficult for the user to implement custom processing solutions.
3. *8-bit per color scanner output.* This relatively shallow bit depth (and correspondingly low precision) forces a dynamic range - bit depth utilization tradeoff, limits the post-processing of images, reduces the precision of optimal filters, and effectively limits the final image quality to levels below that of state-of-the-art electronic systems.
4. *Single proprietary file format.* This format does not allow for either lossless compression or high compression ratios, and does not store color information at full resolution.
5. *Image files tend to be different than for other types of capture.* Most other scanners and electronic cameras produce RGB files. Conversions between file types can produce different results depending on the spectral characteristics of the scene captured.
6. *Loss of production advantages with high resolution scans.* The big advantage of the PIW is the throughput. This advantage goes away for scans larger than 2K by 3K.

It is important to note, however, that these limitations are not always of concern, and the Photo CD system does have a number of production advantages. Even in its current form, it is still under study as an alternative for high volume, medium resolution pictorial applications. Future improvements might also make it a viable alternative for other applications. It is the first commercial system to address the entire electronic imaging process, which is one of the reasons it continues to enjoy significant success.

Image Capture

If the Photo CD system is not used for the production of image files, it becomes necessary to re-examine the entire imaging chain in order to design a more appropriate but still comprehensive system.

Film Capture

Film capture remains the primary means for image capture because of the large number of film cameras in use, the current state of development of electronic cameras, the existence of established and sometimes specialized techniques for film capture, and cost considerations. The disadvantages of film capture include the limited radiometric accuracy and repeatability of film processes, and the fact that film must be scanned to produce digital information.

Film Scanning

The scanning of film originals is, at present, the largest single activity of the LaRC EP Lab. Approximately 500,000 film originals have been obtained over the last 75 years, and more are produced every day. A number of films from sources outside LaRC are scanned at the request of LaRC personnel also. Scanning is done on an as-needed basis. Film is not scanned unless there is a request for a digital file of a particular image, but when a film is scanned an attempt is made to extract all the image information contained in the film. This results in the production of image files ranging from approximately 5 to 100 Mb, depending on the film original. These files are then processed in a standard way and stored using lossless compression.

Scanner Bit Depth

A Leafscan 45 is used for film scanning. This device uses a 6000 pixel linear CCD array, the output of which is quantized to 16-bits. (A few of these bits contain noise and are not significant in terms of image information, but still serve to increase the precision of calculations.) The output of more than 8-bits of real image information per color was one of the primary reasons the Leafscan was chosen. The eye can only distinguish approximately 6-bits per color, so one might think that 8-bits per color would be sufficient, and it turns out that 8-bits is sufficient for processed image file storage. However, resampling during processing can severely reduce the effective bit depth of an image. Images which start out as 8-bit may end up below 6-bits after processing, producing visible artifacts. With the Leafscan 45, the initial image processing is done at 16-bits so that the files still contain 8-bits per color after processing. Another advantage of the Leafscan is the automatic color correction software. This software does an excellent job of correcting color negative scans. Color negative scans are very difficult to correct manually, and most of the film shot at LaRC is color negative film.

Scanner Sampling Frequency

The maximum sampling frequency of the Leafscan 45 is approximately 5000 pixels-per-inch (ppi) for 35mm film, 2500 ppi for 120, 220, and 70mm film, and 1200 ppi for 4x5 film. This means that the scanner can capture all the information contained in even very fine grain 35mm film, all the information contained in medium grain medium format film, and all the information contained in coarse grained 4x5 film. Since most of the film shot is medium speed and grain, the maximum sampling frequency is somewhat higher than necessary for 35mm, about right for medium format film, and a bit low for 4x5 film. The limitation for 4x5 film has not been a significant problem, however, because this format is not used much, and even at 1200 ppi scans of 4x5 films produce image files with 28.8 million pixels (82.4 Mb for color images).

Electronic Capture

The need to scan film captured images is an expensive and serious bottleneck in the production of digital image files. Because of this, a long term goal is to use electronic capture whenever appropriate. Until recently, the cameras available for electronic capture have not been capable of sufficient quality for any but the most limited use. The only cameras capable of matching the quality of even a 35mm film camera were designed to be used exclusively in a studio, and did not record moving subjects in color. Studio subjects at LaRC have traditionally be photographed on medium and large format film. The development of portable electronic cameras is proceeding, however, and recently a Kodak DCS 460c has been purchased. This camera appears to be capable of producing direct digital files which are approximately equivalent in quality to medium speed 35mm film. This camera will be used in situations where 35mm capture is appropriate. Investigations will continue into adopting electronic cameras for more applications as more capable cameras become available. The potential of these cameras for improved radiometric accuracy is also of increasing interest.

Processing of Master Image Files

After scanning or electronic capture, the image files are processed to a standard form to allow for efficient storage and easy utilization. These processed image files are called *master image files*, because they are archived and are the source for image files processed for particular output purposes.

Monitor Standard

The master image files are processed to look good on a standard monitor. The standard monitor is calibrated by viewing a digital gray scale with equal digital value steps, and adjusting the monitor gamma using Gamma Control Panel software so that the steps appear to be visually equally spaced on the monitor. The room illumination level is also adjusted so that the optimum gamma setting is 1.8. The result of this calibration is a relatively constant ambient illumination level and monitor gamma. The correlated color temperature (CCT) of the monitor is nominally set to 6500K, although measurements of monitors set at this value indicate that the actual CCT is somewhat higher. The ambient illumination level required for the gamma 1.8 setting to look right is fairly low, so the eye tends to adapt to the monitor in any case. The monitor standard was chosen because most of the visually based image processing is done by viewing the image on a monitor, and because the relationship between the digital level spacing and the visual gray level obtained with monitor standardization allows for efficient use of the digital levels.

Tone Reproduction and Color Correction

The Leafscan software does a good job of automatically producing digital image files which are fairly close to the desired end result. The software also allows for some user input as to the corrections done, so that unusual images can be dealt with. The only real drawback to the software is that it does not tell you what it did to the image file. If absolute quantitative values are important, it is necessary to save either the 16-bit scan data for calibration purposes, or perform all the corrections manually. Unfortunately, the Adobe Photoshop software used for most of the manual corrections does not allow much to be done with 16-bit data.

The procedure currently in use is to do as much of the tone and color correction as possible using the Leafscan software, either automatically or manually. The resulting image files are quite close to the desired end result, and contain a full 8-bits per color of image information. Additional corrections are then done using Photoshop. This may result in some bit depth loss, but since the files start out fairly close to the desired end result the loss is minimal. The photographers making the corrections in Photoshop are aware of the effects of multiple resampling and process the image files in as few steps as possible. In almost all cases the final master files contain more than 7-bits of information. It is also possible to recover some of the bit depth loss through resampling at a lower spatial frequency, if the original sampling was done at a higher frequency than will be required in the master file.

Much of the color correction is also done automatically by the Leafscan software, and some additional correction is achieved when the tone reproduction correction described above is performed. In some cases additional color correction is performed on the monitor, particularly if localized corrections are needed. Again, this results in minimal bit depth loss if Photoshop is used. Software does exit which allows for more extensive processing of the 16-bit scanner data, but using it requires that the Leafscan software automatic adjustments be bypassed. The production advantages of using the automatic adjustments outweigh the advantage of being able to do all the corrections prior to converting to 8-bits, as long as the adjustments made in Photoshop are not too extreme.

Subjective Evaluation

The final evaluation of the tone and color reproduction is done subjectively in most cases. The ultimate goal is to produce master files that look good, and there is no substitute for experienced judgment in determining what looks good. This judgment is made by examining the files visually on a standard monitor, and by checking the digital values in relation to what experience dictates the appropriate values should be at various places in the image. As a final check, the master files are printed on a calibrated, photographic quality printer. Past experience has shown that the eye is not as sensitive to subtle errors on a monitor as it is to the same errors on a hardcopy print. Quantitative devices, such as densitometers and a spectral radiometer, are also available for objective measurements and troubleshooting.

Determination of Master Image File Size

After the tone and color corrections have been completed, the image file is examined under high magnification to determine if it is the appropriate size. In most cases the film will have been scanned at the maximum spatial sampling frequency possible with the scanner, so the only decision to be made is whether to reduce the file size. Both the grain of the film and the image edges are examined. Grain sizes should be on the order of one to three pixels for color film. and a bit smaller than a pixel for black-and-white film. Edges should transition over two to five pixels. If it is found that both the grains and edges are much larger than this in pixel dimensions, the file can be spatially resampled to produce a smaller file without significant information loss. If the grains are the right size but the edges are too large, the part of the image under examination is not in critical focus. Other areas of the image should be examined. If the entire image is out of focus, some reduction in file size may be possible, but the amount of reduction should be aimed at reducing noise rather than the edge transition dimensions. Once the noise has been reduced sharpening filters can be used to reduce the edge transition dimensions.

Noise Reduction

If an image file is determined to be noisy, and is larger than it needs to be, a median filter is applied. This is only done if the file is to be reduced. If the file is to remain the same size, noise filtering is left to the end user.

File Size Reduction

Once the master file size has been determined, and any noise filtering applied, the image file is reduced through resampling. All reductions are by a linear factor of two. This eliminates resampling errors and makes it easier for the photographer to decide if the file should be reduced, since the reduction increments are large.

Dust and Scratch Removal

When the master image file is at its final size, it is examined by the photographer and in most cases dust and scratches are removed. Exceptions are files where it might be difficult for a photographer to differentiate between dust and scratches and actual image information, and where it is necessary to maintain the absolute integrity if the image content. This step is frequently the most time consuming step in the preparation of the master files.

Sharpening

At present, sharpening the image is considered to be an output processing operation and is left to the end user.

Time Required for Master File Preparation

The total amount of time required to produce a master image file varies from about thirty minutes to two hours. The scanner works faster on large format film because of the higher illumination levels, taking as long as 45 minutes for 35mm but only about five minutes for 4x5. Tone and color correction takes from five to fifteen minutes, depending on how much correction is needed. Noise and file size reduction generally takes less than five minutes, but dust and scratch removal can take over an hour. Saving the completed file to disk takes less than ten minutes.

Image Archive and Database

Master File Archive

A considerable investment is required to produce the master image files. Films are not scanned unless requested. but in many cases it would be possible to create the desired output file with less effort than is required to produce the master file. Most of the processing described above is desirable regardless of the final output, but this processing could be speeded up if applied to a smaller file. If the user only requires a 1 Mb file, processing a 100 Mb file requires significant extra time. However the current policy of the EP Lab is to produce master files of all film scans, except in cases where the time available is so limited that it is impossible to work with the large files. The reasons for this policy are as follows:

1. The computers used in the EP lab are equipped to deal with large files. Except for dust and scratch removal, and scanning 35mm, the image processing operations do not take much longer on the larger files.

2. Since much of the processing is done subjectively, it would be difficult to exactly match different scans of the same film original. With the master file approach, the master file becomes the source after its creation, and different output files are consistent. This allows for the development and utilization of standardized output processing.

3. A significant goal at LaRC is to produce an archive of digital images. The master file approach allows the images placed in this archive to be selected by user requests, and the scanning is done when it would have to be done anyway.

4. Even though it may take longer to produce a master file originally, if even one other request is made for a file of the image, the extra time expended is recovered. It is anticipated that the availability of some files on line will increase the chances that they will be used again.

Image Information Database

Full utility of the master file archive requires that there be an accompanying database. This database is used to search for specific images and image types based on information associated with the images. This information is input to the database when the master file is placed in the archive.

On-Line Catalog

A final mechanism to allow users to select master files is an on-line catalog. This catalog is linked to the database so that images selected using the database can be quickly viewed. The images in the catalog come in two sizes: a "snapshot" size for quick access and a video resolution "monitor" view that provides somewhat more detail.

Requesting Images

When users find images they want, they can then request either the master files, or some derivative version processed for output. Transmission is commonly over a network, although the size of the master files can make this cumbersome, particularly if a number of files need to be transmitted. Files can also be exchanged on magneto-optical disks and writeable CD's. Frequently the versions processed for output are smaller than the master files, and in some cases the desired output is a hard copy.

Output Processing

The creation of the master file archive, database, and catalog assumes that at some point the files will be used for some purpose. Film images are not scanned without a specific use having been requested, and even electronically captured images would not have been obtained without some use in mind. The output stage of the EP process is the final, key step. The types of output requested include reduced size versions of master files for inclusion in electronic documents and viewing on monitors, processed versions for output on various output devices (including versions processed for halftoning, inclusion in page layouts, and on-demand printing), and hard copies (prints, transparencies, and negatives).

Output processing is simplified to some extent in the EP Lab at present, because all the image capture and output devices utilize RGB image data. This makes it possible to construct look-up tables for all the output devices. These tables are applied to the master files or a derivative image file prior to output. They are designed to match the tone reproduction of the output device to the monitor, based on photometric readings of a digital gray scale test target. No attempt is made to match color reproduction, other than to calibrate all the output devices to produce a neutral. Consequently, color reproduction is not exact in a colorimetric sense, but it is reasonably close. This is due to the fact that the color hardcopy output devices, a Fujix Pictrography 3000 and a Solitaire Film Recorder, both use photographic dyes. An advantage to this approach to color management, besides simplicity, is that the full output device gamut is used in all cases. This produces output which is frequently subjectively more pleasing than exact colorimetric matching.

Black-and-white output is accomplished by imaging equal amounts of R, G, and B on the Pictrography and the Solitaire, or by using black-and-white film in the Solitaire. Alternately, halftoned output is possible on a VT4200 imagesetter and a LaserWriter Pro 630. Look-up tables are also available for the latter two output devices, and a special table has been constricted which produces halftones suitable for printing on the VT 4200.

Future Developments

Determination of Optimal Filters for Image Restoration

Once the EP Lab is in full production and master image files begin to become available, it should be possible to devote more time to other projects, one of which is the development of optimal filters. These filters would be designed mathematically, based on the noise and spatial frequency response characteristics of both the capture and output devices. They could then be applied to the master files to compensate to some extent for blurring caused by the optics of the electronic camera or scanner and the output device. A different filter would be constructed for each input-output device combination. Optimal filters of this type are typically dependent on the power spectrum of the original subject, but part of this project would be to come up with a "typical" power spectrum. It is anticipated that customizing the filters in this way will effect significant improvement in the image quality even though the actual subject power spectrum might not match the "typical" one exactly.

Reducing File Production Expense

It is already becoming clear that although the master files produced as described above have excellent quality and are ideally suited for many applications, the amount of time involved in producing each file is somewhat prohibitive, and the amount of storage space required for the image information is significant. A number of images just do not need the extremely high quality level. The problem with going to a lower quality level lies in determining which images do not need the high quality. A goal in the construction of the digital image archive is to make files which will never need to be rescanned. It is difficult to say that an image will never need to be better than a certain quality level, unless that quality level is the highest possible given the image capture characteristics. As the EP Lab gains more experience in user requirements, it may begin to be possible to make intelligent judgments of this type. As this ability develops, three approaches may be taken to reduce image scanning and storage expense.

The first approach will be to move toward electronic capture whenever possible, thereby eliminating the very expensive and time consuming scanning step. The savings realized with electronic capture are so large that, other than editing which files are to be saved, no further action should be necessary when this approach is possible.

The second approach will be to start selecting certain film captured images for scanning using a Photo CD Imaging Workstation, either internally or externally. This step would produce somewhat lower quality scans, but at a much higher throughput and at reduced cost. As the PIW quality improves, this approach may become more feasible, particularly if high rate scanning of medium format films becomes possible.

The final approach will be to consider saving some images using JPEG compression. The cost of scanning, however, is much greater than the cost of image file storage space, so there is still some doubt as to whether this approach will ever be implemented. Still, it is better to store a high resolution scan in a small space using JPEG compression than to reduce the image size. It is possible that JPEG compressed image files will be a product for distribution, even while lossless compression is used for the master file archive.