Optical Metrology for Industrialization of Optical Information Processing

David Casasent, Carnegie Mellon University
Pittsburgh, PA 15213
C. L. Wilson, National Institute of Standards and Technology
Gaithersburg, MD 20899

Abstract

One of the major barriers to commercial application of optical technology to information processing is the high cost of system development and manufacture. This problem has been solved in other industries through the use of computer aided design (CAD) and integration of system design with manufacturing. The development of better system level metrology is needed to allow more computer-based methods to be used in this process. As a test case, we are designing an optical pattern recognition system to be performed on an input image (at video rates) versus a large reference set, for example 1000 faces, with images of 640 by 480 pixels or larger. We have constructed both an optical pattern recognition system and a holographic memory system which we have instrumented and used to address the metrological needs of these applications. This has allowed us to evaluate the level of system and component level metrology needed for real-time video processing. This report addressed the metrological issues encountered in building and testing these systems.

1 INTRODUCTION

Optical metrology refers to measurements and quantitative performance of all components of an optical information processing system; the two systems considered as examples are OPR (optical pattern recognition) correlators and optical memories. The motivations for this and optical CAD (computer aided design) concern industrialization which require: (1) mass production without individual system modification; (2) design each portion of a system and the system and determine manufacturing tolerances prior to manufacture; and (3) CAD etc. to determine manufacturing yields.

OPR and optical memories were chosen as test systems because the combination of these two processing systems would allow large scale OPR to be performed on an input image (at video rates) versus a large reference set, for example 1000 faces, with images of 640 by 480 pixels or larger. OPR, if properly designed, will locate the highly correlated faces in the image plane and should not require additional segmentation. One correlation on 300,000-pixel images requires about one second on a high speed engineering work station, or

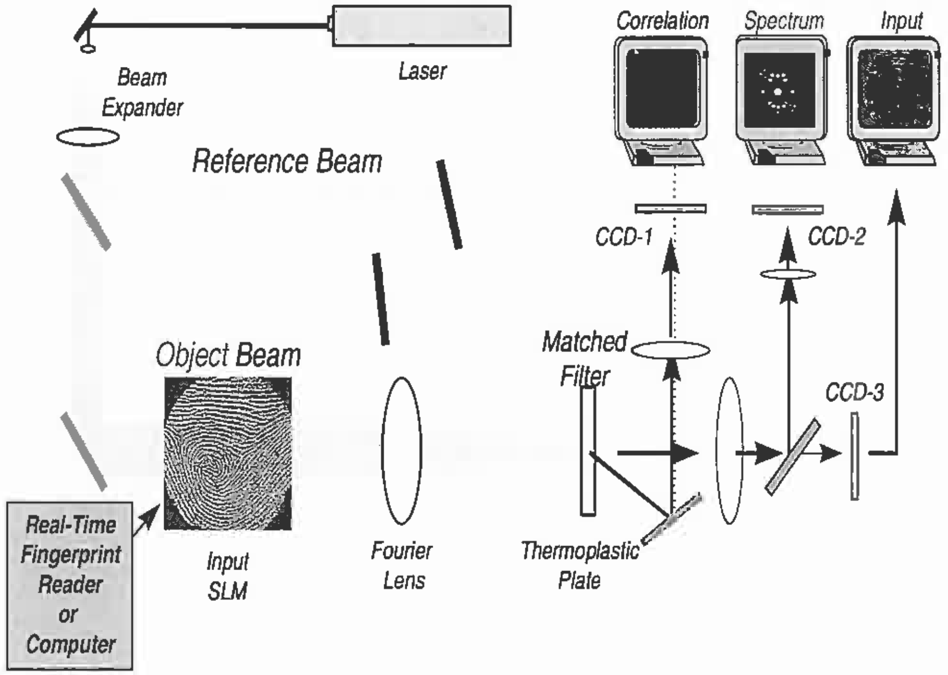

Figure 1: Diagram of the optical pattern recognition system

eight hours to perform the 30,000 correlations necessary (30 frames/second on 1000 images) to process one second of data. This suggests that optics has the potential for performing pattern recognition tasks that are well beyond the capabilities of existing general purpose computer systems.

As a first step in evaluation of optical metrology needs for the proposed real-time video system, we have constructed test-bed versions of the two subsystems that would be needed in a high speed OPR application. In the process of building the optical systems needed for real-time video, we have made various type of measurements at both the system and component levels that were necessary for evaluation of the subsystems and components for future design work. The discussion of these metrological issues forms the main body of this report. The test-bed systems are briefly discussed below as is a proposed design for the combined real-time video system.

1.1 Optical Correlator

Figure 1 shows a schematic diagram of the optical pattern recognition system. It is based on the conventional VanderLugt correlator [1]. The target fingerprint image is loaded on a spatial light modulator, SLM, and is Fourier transformed by a lens. The resulting Fourier spectrum interferes with a reference beam to record a Fourier transform, FT, hologram, or a matched spatial filter (MSF). After recording is finished, if an arbitrary input fingerprint is presented on the SLM, the correlation of the input and the target appears in the correlation output plane.

In the global correlation experiment, fingerprint images are generated from the NIST fingerprint database [2]. In the real-time correlation experiment images are generated by a live-scan fingerprint scanner. An electrically addressable liquid crystal spatial light modulator (14 mm diagonal) is used as an input device. The SLM is mounted on a rotational stage to facilitate precise rotational tolerance settings.

Holographic filters are recorded on a thermoplastic plate that allows fast non-chemical processing, high diffraction efficiency and high reproducability. Although the recording process cannot be achieved in real-time (close to 1 minute per hologram), the time-consuming comparison of an input with many other images in a large database can be done very fast, once a hologram is made (see Sect. 1.3).

A 10 mW HeNe laser with a ND 2 filter was used as a light source, and so only 0.1 mW is needed to view the correlation output due to the high light efficiency of the system.

The system is also equipped with the real-time in-situ monitoring of the input image, its Fourier transform, and the correlation output. These monitoring parts, combined with a frame grabber and other analytic tools, permit real-time quantitative analyses and accurate characterization of every stage of the system's operation.

The correlator system is capable of shift-invariant pattern recognition over a broad range of input positions and has high signal to noise ratio (SNR) due to accurate alignment using an interferometer and a microscope.

1.2 3-D volume holographic storage system

Volume holographic storage is promising due to its large storage capacity (1 Tb/cm^3) and fast access (several microseconds per page). Figure 2 shows a schematic diagram of our volume holographic system. The light from a laser (0.2 watt frequency-doubled Nd:YAG laser, green color, 532 nm) is expanded by a beam expander which consists of two lenses, and is divided by a polarizing beam splitter into object and reference beams. The object beam is modulated by an input page loaded on an SLM through a frame grabber. The input image is then Fourier transformed at the focal plane of a lens. At the focal plane, a spatial filter is placed to remove the grid structure of the SLM. The reference beam is steered to the desired direction by a mirror mounted on a mechanical rotation stage. The mechanical stage can be replaced by an electro-optic or acousto-optic beam deflector for faster beam steering (one microsecond). To keep the same position of the reference beam at the recording material for different beam angles, a telescopic imaging system is employed.

A volume holographic recording material is placed at the intersection of the reference and object beams to record the interference fringes. Each page of information is recorded with a reference beam along a different angle using the angular multiplexing technique. For readout, the reference beam is steered to the original angle to retrieve the corresponding image on a 2-D charge coupled device (CCD) detector array.

The SLM used in this experiment is an electrically addressable AMLCD (active matrix liquid crystal device) with 640 by 480 pixels in a half-inch diagonal active area. The initial qualitative test shows that the evaluation device may be used for holographic memory application in terms of resolution, contrast ratio, uniformity and transmission quality. A more accurate test and evaluation of the device will be performed later in this project. To reduce the serious image degradation due to Moire-fringes that occur when a SLM is imaged onto a CCD, the spatial filtering technique is used, as explained previously.

Holograms are recorded in a LiNbO3 crystal (0.02 cut). It showed reasonably good

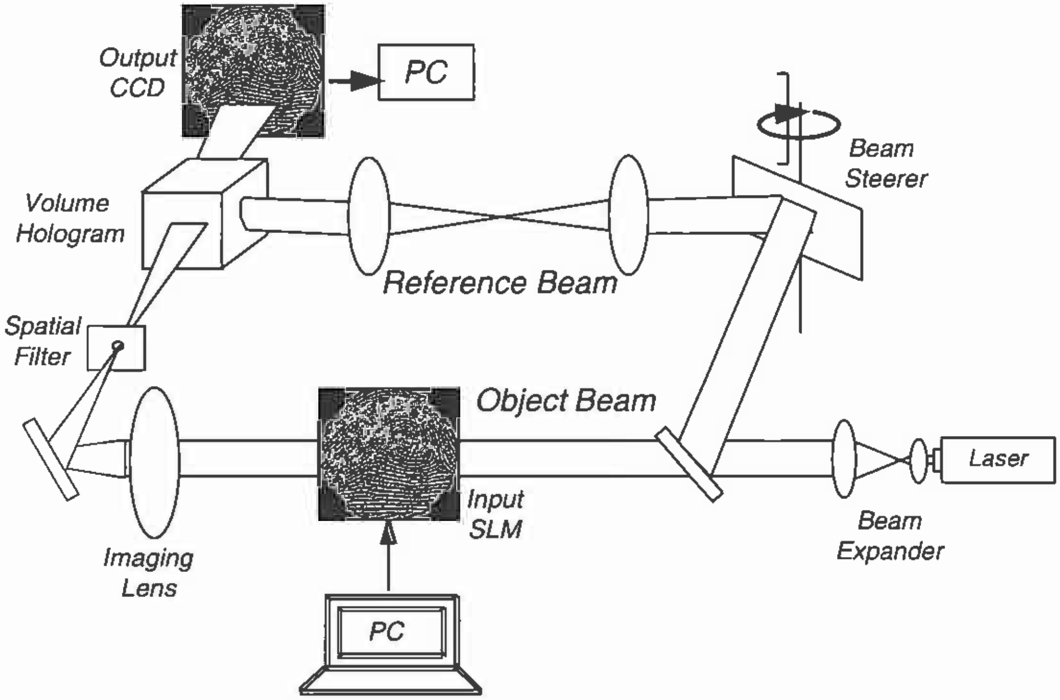

Figure 2: Diagram of the optical memory system

uniformity and low scattering noise. We normally recorded 100 images at 0.2 degree increments in the reference beam angle. Image quality is good enough to recognize persons without any difficulty. However, the speckle noise is serious and is due to dust, interference fringes caused by multiple reflections from various surfaces. To alleviate this problem, we have developed a simple model that can significantly reduce the speckle noise.

1.3 Optical memory correlator system

To carry out the video-based pattern recognition task, the memory and correlator systems must be combined. A proposed design for combining these two subsystems is shown in figure 3.

In figure 3, a matched spatial filter (MSF) of the input data (to be compared to a large reference MSF set) is recorded at P2. The MSF of the input can be calculated digitally and recorded on an electrically addressed SLM at P2; alternatively, the MSF can be optically formed by interference on an optically addressed SLM at P2; both options are shown in figure 3. The digitally calculated MSF will be more accurate, but only several bits of accuracy are typically required, thus an optical MSF should sufice. A reference pattern at one spatial location in memory is read out, its FT is incident on P2, the FT of the light leaving P2 is formed at P3 where the correlation of the input and one reference occurs. If

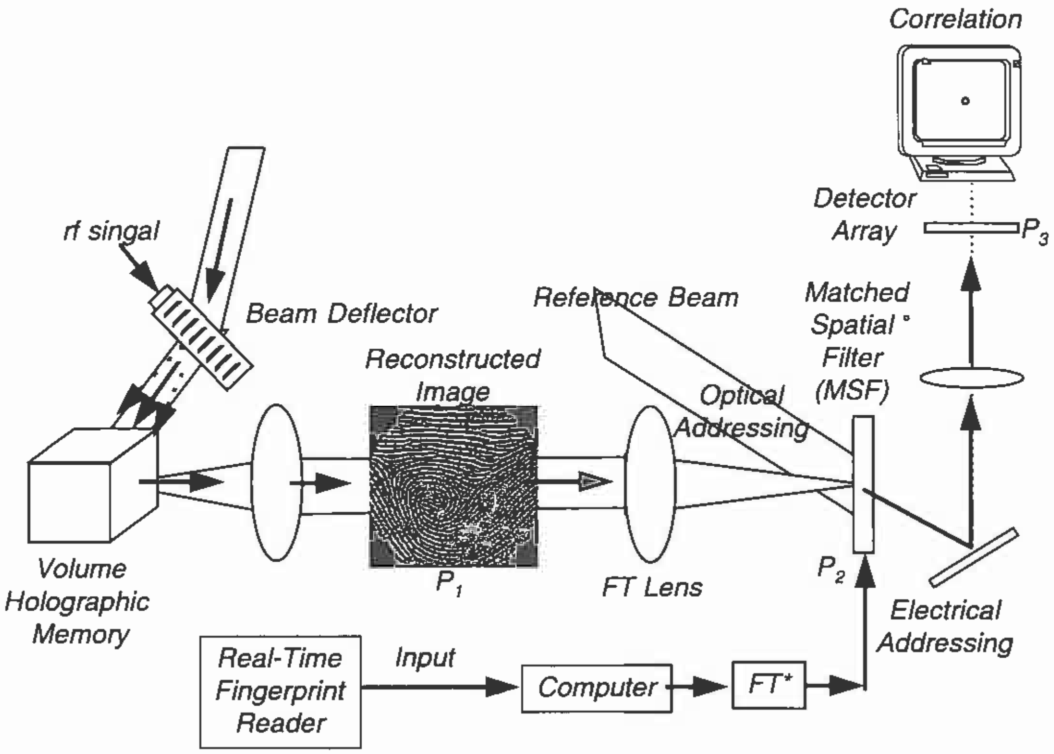

Figure 3: Diagram of the optical memory correlator system

several references are stored (angle multiplexed) at each spatial location in memory, then multiple correlations can be produced in parallel at P3. The P3 detector array need not be large, only the central region of the correlation plane need be searched, and several correlation plane pixels can be integrated onto one P3 detector element. Thus, the P3 detector array can be fast and so can the laser memory access, hence 30,000 correlations per second are possible and the real time video application is possible.

Although the spatial heterodyning technique, often called joint transform correlator (JTC) [3], has many advantages for real-time applications [4, 5] and was used in most recent fingerprint recognition experiments [6, 7, 8, 9, 10, 11], the VanderLugt correlator was adopted in this experiment. For this application the VanderLugt correlator architecture was chosen, since it is faster than the JTC architecture. This occurrs since high speed input data is available from optical memory and the P2 filter need not be changed until 1000 etc. references from momory are processed. Thus, no high speed SLM is needed as is needed with the JTC. This FPC is also preferable for multiple parallel correlations; a similar JTC system requires a very high-speed bandwidth product joint transform plane SLM or CCD. Note that the optical memory cannot be used in the MSF plane of the standard VanderLugt correlator since volume memory filters do not exhibit 2-D shift invariance.

1.4 Metrological Issues

The major issues addressed in this optical metrology task are: (1) what parameters of each optical device and optical subsystem must be measured; (2) how these measurements should be made; (3) their impact on system performance (i.e. what parameter specification are needed); and (4) methods to reduce various device specification requirements (i.e. marry algorithms, the architecture and filter, etc., so that ideal components are not required).

The application of the system will determine what parameter requirements are needed. The two major applications considered for such systems are fingerprint and face recognition.

Lenses were addressed elsewhere and are presently considered ideal. Spatial light modulators (SLMs) are the major optical device. Their test and evaluation procedure is discussed in Section 2. Related optical memory issues are noted in Section 3. Optical engineering, manufacturing, and CAD are briefly discussed in section 4. Recommendations for future work are included in Section 5.

2 SLMs

2.1 Modulation Mode

SLMs can have amplitude only, phase only, or coupled mode (amplitude and phase) modulation. Laboratory tests (no fringe movement with input modulation level) indicate our LCD operates in amplitude mode. Thus, we consider only amplitude mode devices since these are the ones being measured.

2.2 Addressing Mode

SLMs can be optically or electrically addressed. The optical memory applications considered can require both types of SLMs. An electronically addressed SLM is necessary to input new data to the optical memory and can be used to input the test data to a correlator; an optically addressed SLM is generally used to record the output data from the optical memory as input to an optical correlator (this SLM does not appear to be needed).

2.3 SLM Concerns

A general SLM test procedure has been previously detailed [12, 13, 14] and remains valid even now. It is most important to note a vital problem in SLM specifications: no standard test procedure exists. This lack of uniform standards for SLM performance specifications is one valid reason why users have not widely adopted optical processors into systems. Our testing procedure should have a major role here. The four major problems concern static (and not dynamic) specifications, erasure, resolution (at different modulation levels) and linearity.

Remarks on SLM speed issues follow:

(1) You cannot process an image by an FT etc. until the entire image is present. If the SLM writes one line at a time (electrically addressed), no processing can occur until the full 2D data has been written.

(2) During processing (and writing), you do not want the data on the SLM to vary. All SLMs have some rise time; you write the top row of an image first and write the bottom row

last (electrically addressed). The top row may have decayed by the time the bottom row is reached; and the bottom row is not fully charged immediately after it is written. TFTs (thin film transistors) are needed/useful to store recorded data. This is quite different from displays where flicker must be avoided.

(3) Before processing a new frame of data, all of the prior frame must be gone (full erasure, not exponential decay, negligible residual of the prior frame). Thus, an active erase mechanism is vital (i.e. no dependence of present data on prior frame data).

(4) Different patterns should be written in each frame time (do not just repeat the same pattern) to properly measure speed, etc.

Remarks on SLM resolution follow. In this regard, the concerns are resolution, contrast, and speed. All three must be measured simultaneously (in general they are not) at video rates or faster. As resolution increases, contrast or modulation decreases. As speed (frame rate) increases, contrast also degrades. Linearity is another concern; as modulation increases, linearity degrades. Light efficiency is yet another concern; as modulation increases, so does efficiency, but so does nonlinearity. For optically addressed SLMs, MTF (modulation transfer function) is best obtained by recording 2 plane waves of equal strength (this produces a sinusoidal SLM transmittance) with the angle between the two beams varied (this varies the spatial frequency of the recorded sinewave). The Fourier transform (FT) optically formed of these recorded patterns gives the efficiency of the device, and modulation level vs. spatial frequency. Linearity data is also possible (reduce the modulation level by making the intensity of the two interfering beams different; vary modulation until the energy in orders above the first is 20 dB down for 1% linearity). Electrically addressed SLMs have fixed pixels and for them you measure linearity with input voltage signal and contrast (Imax and Imin) for input sine or bar patterns of different spatial frequency (these measurements can be made in an image plane, not an FT plane, although one could aperture off higher orders and analyze the FT plane). An average Imin can be used when some pixel outputs are zero (due to interference etc.). Optical efficiency is measured for sinewave inputs by FT plane analysis. A limit on the useful light level must be selected (we expect to resolve this issue, but it is application and system dependent); the standard NIST resolution at an MTF of 0.02 of the maximum generally does not yield enough useful light (50% might be better).

The writing mode used in the integrated electronics for SLM's are often not available. One can monitor several LC (liquid crystal) pixels in time on one output detector and monitor LC pixels in the first and last row of their LC SLM to determine how writing is done when circuit information is not available. Uniformity of response and optical flatness are also of concern and are easily measured with uniform inputs (voltages etc.) at different levels. The output image for a uniform input will contain a fringe pattern (due to the non flat SLM). The fringe pattern provides optical flatness information; if this fringe pattern varies with input signal, this indicates some device phase and amplitude mode coupling. (our tests show our LC is an amplitude mode device.) Relating uniformity to performance (e.g. gray scale) is application dependent and can be addressed as noted elsewhere.

Optical flatness required is conceptually $\lambda/2$ or interference alone can cause pixels to be 0 or 1. The effect causes an additional fixed pattern (SLM thickness variations) to be present on each input; this will degrade cross-correlations and autocorrelations when shifts are present, but will probably not appreciably affect autocorrelations. It adds common data to all patterns and can thus make cross-correlations worse. Our optical flatness tests show elliptical fringe shapes, thus nonflatness is not just nonparallel surfaces, rather curved ones exist. These fixed flatness variations can be corrected for after fabrication (this is cheaper than doing so during fabrication). The fill factor for electronically-addressed SLMs (amount of each input pixel active and fraction of a pixel that is active, due to electrodes etc.) is also of concern. It is spatially constant. Its main effect is a degradation in the FT from the ideal, but this is present in input and reference and should not be of major concern in correlations, and in the presence of higher-order diffraction patterns, with associated light efficiency loss. Optical scatter from all sources can be measured as the background FT plane level (noise floor). It is another limit on dynamic range.

We note for completeness that many SLM nonideal properties can be corrected. An MSF of the SLM can be used to remove fixed optical flatness deviations (SLMs and lenses). Gamma correction (or lookup tables) can be used to correct for nonuniformity and nonlinear response effects.

The test procedure used for our electrically-addressed LC SLM is now noted, along with other test details. This device writes frames not fields (VGA). A set of increasingly narrow horizontal lines, vertical lines, uniform, and checkerboard patterns are written. As spatial frequency increases, the contrast of the output image attenuates greatly. Care should be taken: that all inputs are biased correctly (use the exposure curve with uniform inputs), that input data are written on an integer number of SLM pixels (and not split between two pixels on the edges of lines), that the SLM is imaged 1:1 to the CCD image plane readout device (one SLM pixels corresponds to one CCD pixel). Some output image rows can have very different intensities otherwise. With a cosine input pattern, when a clipped output square wave image results, this indicates that the CCD (and SLM) must be biased better. We have measured that the CCD is linear, thus if the light is within its allowed range, the issue is SLM bias level. When readout is over 10 msec, this can also affect results and must be analyzed with respect to where this 10 msec readout time concurs within the data write cycle. We have measured output levels at every point in 2D as the uniform input level is varied (2D bias and slope at each point in 2D is measured; repeating the test 50 times gave little variance); however writing was continuous, readout was over 10 msec, and sampling and CCD bias issues can be present. Resolution should be measured at 50% of maximum light efficiency, linearity seems to be needed, and will be measured. Binary and gray scale input gratings seem useful. Fringe patterns make measurements difficult and must thus be corrected first (or a limited SLM region with no fringes should be used and global FT not image plane analysis should be considered).

3 OPTICAL MEMORY

Many large efforts and some test beds exist in this area that should be providing answers. This project should have a major role in determining the issues to be addressed.

A major issue is volatility; this is not acceptable for products. What is used to overcome this readout effect? DARPA, as part of its holographic memory effort, intends to address this. Psaltis [15] measured these readout effects. This should be done with readout light intensity doubled and readout time halved to verify reciprocity.

The time for writing data, TW, must be considered. Because of light source levels available and device sensitivity, 10 sec may be used to write a new pattern, thus writing is continuous over 300 frames (at TV rates). With rise and erase times of the input SLM , the recorded pattern is the average of many frames of time-varying data; hence it can differ from the input.

Cross-talk effects between different pages of data and between data on one page are of concern. Most DARPA attention concerns intersymbol interference (ISI) (one page and between pages) and only binary data is of concern. Low BERs (bit error rates) are required for these applications but not for image storage. Binary encoding methods [16] are not relevant to our application, but test methods used and data on this should be helpful. Requirements for optical image memories are quite different (and much more relaxed, in general). Recording memory data in a plane offset from the exact FT plane is typically done. This must be quantified.

Lens analyses including tolerance and aberration effects have been conducted [17, 18]. Attention is given to storage density and other (probably more dominant) optical memory effects are ignored. Thus, conclusions (most are architectural) of use of large pages of data, depth of field issues, etc. do not seem useful in our application. Prior analyses of reciprocal space designs [19], inter-page crosstalk [20], intra-page crosstalk [21], instrument noise [22], and different multiplexing methods [23] should be analyzed to determine their use in our applications, the validity of crystal etc. models used, and the appropriateness of any lab data. Only λ multiplexing is addressed in [18] (this is not an attractive method); the relation between SLM pixel size, crystal storage volume, fL and λ obtained in [18] seem straightforward; astigmatism is noted to be the major lens aberration effect (thus small SLM pixels are preferable).

In angle-multiplexing, crosstalk effects must be quantified (they have seemingly not been). What angular separation is needed between co-located pages (crosstalk should drop as sinc^2)? The energy in the sinc^2 sidelobes should be calculated and related to crosstalk in the lab. Apodization can reduce crosstalk; this seemingly has never been considered in the optical literature.

Space multiplexing used with angle multiplexing affects results. With angle multiplexing, spatial-multiplexed data must be spaced by more than the size of the FT (else data stored in adjacent spatial regions will be readout and overlap). The effect varies with the number of angle multiplexed pages and the crystal thickness. Recording data in the image, not FT, plane may be better. The issue must be documented and analyzed. Other associated details such as focusing the beams at the center of the crystal during recording and offsetting the FT plane and its dc location outside of the crystal should be detailed.

The exposure schedule also merits attention. The standard schedule published assumes the same average level for each image page. This is not the case for images. In such cases, a different schedule is needed. We have shown this for face data by interleaving all black and all white images. The procedure used is to use a schedule assuming all images have the same average level, measure the readout images, adjust the exposure levels, and repeat the recordings. This should be documented and shown.

Recording energy, E, and recording time, t, effects are expected if short vs. long exposures (with the same E) are used, since charge is moving. This can be assessed by varying intensity and time.

4 OE MANUFACTURING AND CAD

A NIST Workshop on optical engineering (OE) [24] noted the need for CAD in integrated optics circuits and vertical emitting lasers, but such work is not relevant to the free-space optical systems we consider and to optical memory and SLM components. Rather attention is being given to fiber communications, and integrated circuit and integrated optics fabrication issues. This is despite the recognized and listed importance of optical storage [25, 26] (blue lasers were the topics noted) and machine vision with SLMs and optical correlators [25]. Other optical components [27] rather than SLMs are generally being addressed.

Numerous lens design software programs exist [28]. However, they should include wave (geometrical) and physical (diffraction) optics effects to be of use to us. Filter, correlator, Fourier optics, SLM parameter issues, CCD issues are not noted [28]. Thus, most software products are not of use in our application.

The community (to some degree) has recognized these problems, but has generally not pursued them. CAD tools are essential to allow rapid evaluation of new system designs and designs using new devices. It is important for optics to have this with a turnaround time of several weeks; this can aid general use of various proposed optical designs and lead to more prototype systems. The concept and premise is certainly nice. Work exists on free-space optical CAD [29, 30]. However only optical interconnections are addressed. Propagation modules exist [30] and a Gaussian vs. planewave effect analysis (for optical interconnections) exists [30]. Various optical devices are included (Table 2 in [29]) including: lenses, polarizing beam splitters, spot array generators, optical isolators, beam collimators, and lasers. Optical beam propagation can be modeled, including dispersion, noise, and crosstalk (these issues are of concern in optical interconnections primarily). Fourier optics and diffraction models are not presented in [29]. From our own experience [31], full optical diffraction simulations are very computationally expensive. Several Fourier optics software packages will be evaluated for their use and completeness. SLMs are mentioned [30], but only parameters such as bandwidth and light source power are considered (these affect interconnection uses); thus there is a very long way to go (none of the SLM etc. issues noted in Sections 2 and 3 are considered).

An interesting optical correlator software package has been developed by Litton [32]. It considers an optical correlator and 9 optical processing modules (processing functions) in scene analysis (these include: detection, segmentation, preprocessing, filter selection, correlator, post processor, identifier). Many of the functional modules are of concern only with their correlator which performs only binary, BPOF (binary phase only filter), or TPOF (ternary phase only filter) correlations. Standard image processing functions (edge detection, clustering, median filtering, morphology, and adaptive thresholding) are included. These are generally only digital operations, however. Major emphasis is on designing small and compact optical correlators, with emphasis given to the architectural arrangement of the SLMs etc. to yield the most compact system (not necessarily the best performance). The use of the software seems to be to perform optical simulations on different databases (and applications) using the image processing routines (i.e. to determine which digital preprocessing to use before using the optical correlator, what type of BPOF or TPOF filters to use, etc.). We and others simulate optical correlators using SLMs and data with different numbers of gray levels. Various SLM models are included with BPOF and TPOF issues (vs. those in Section 2) generally addressed (the models used are not explicitly noted).

5 RECOMMENDATIONS FOR FUTURE WORK

(1) We can have a major test and evaluation role in SLMs, optical memory, etc., for image processing uses. This is vital if optical processing and optical memory for image processing are to be accepted.

(2) The state of the art of these issues is in its infancy (Sections 2 and 3) and very extensive efforts are needed. Initial results are expected that can better quantify the magnitude of the effort and the scope of test equipment needed.

(3) DARPA holographic memory reports pertinent to test and evaluation should be obtained and analyzed.

(4) SLM modulation mode test methods should be noted and documented.

(5) Can the optically addressed SLM used to record the optical memory data be omitted?

(6) SLM simultaneous speed, resolution, erasure, linearity, and contrast concerns in test and evaluation need to be noted and addressed (Section 2).

(7) Optical efficiency and minimum useful light level is a useful SLM measurement and will be pursued as part of this effort.

(8) Our liquid crystal data (write, rise time, erasure, etc.) will be used to develop a SLM characterization method.

(9) Optical flatness effects wil be corrected as part of the SLM test results (Section 2).

(10) Optical memory issues that merit major attention (Section 3) are: volatility; writing time effects with an input SLM; crosstalk effects and multiplexing dependency; use of image rather than FT plane recording; revised exposure schedule. All merit documentation, and initial simulation and lab results to demonstrate the importance of each.

(11) Much optical engineering CAD and manufacturing work is proceeding. Even though optical memory and optical correlators are recognized as very attractive, CAD and manufacturing of such systems is not being addressed.

References

[1] A. VanderLugt. Signal detection by complex spatial filtering. *IEEE Trans. Inform. Theory*, IT-10:139–145, 1964.

[2] C. I. Watson. Mated Fingerprint Card Pairs. Technical Report Special Database 9, **MFCP**, National Institute of Standards and Technology, February 1993.

[3] C.S. Weaver and J.W. Goodman. Technique for optically convolving two functions. *Appl. Opt.*, 5:1248–1249, 1966.

[4] F.T.S. Yu and X.J. Lu. A real-time programmable joint transform correlator. *Opt. Commun.*, 52:10–16, 1984.

[5] J.L. Horner. Optical processing for security and anticounterfieting. *IEEE LEOS Proceedings, Boston, 18-21 November*, 1:228–229, 1996.

[6] Y. Petillot, L. Guibert, and J.-L. de Bougrenet de la Tocnaye. Fingerprint recognition using a partially rotation invariant composite filter in a FLC joint transform correlator. *Opt. Comm.*, 126:213–219, 1996.

[7] J. Podolfo, H. Rajenbach, and J-P Huignard. Performance of a photorefractive joint transform correlator for fingerprint identification. *Opt. Eng.*, 34:1166–1171, 1995.

[8] B. Javidi and J. Wang. Position-invariant two-dimensional image correlation using a one-dimensional space integrating optical processor: application to security verification. *Opt. Eng.*, 35:2479–2486, 1966.

[9] T.J. Grycewicz and B. Javidi. Experimental comparison of bianry joint transform correlators used for fingerprint identification. *Opt. Eng.*, 35:2519–2525, 1996.

[10] F.T. Gamble, L.M. Frye, and D.R. Grieser. Real-time fingerprint verification system. *Appl. Opt.*, 31:652–655, 1992.

[11] K.H. Fielding, J.L. Horner, and C.K. Makekau. Optical fingerprint identification by binary joint transform correlation. *Ope. Eng.*, 30:1958–1961, 1991.

[12] D. Casasent. Real-Time Spatial Light Modulators and their Applications. *Proc. SPIE*, 128:56–67, 1977.

[13] D. Casasent. Spatial Light Modulators. *Proc. IEEE*, 65:143–157, 1977.

[14] F. Caimi D. Casasent and Khomenko. Test and Evaluation of the Soviet Prom and Priz Spatial Light Modulators. *Applied Optics*, 20:4215–4220, 1981.

[15] D. Psaltis et al. *Opt. Eng.*, CR65:181–213.

[16] J. Heanue et al. *Applied Optics*, 2431, 1996.

[17] M. Neifeld and M. McDonald. *Applied Optics*, 2418, 1996.

[18] M. Neifeld an M. McDonald. Lens design issues impacting page access to volume optical media. *Optical Communications*, 120:8–14, 1995.

[19] G. Rakujic et al. *Optics Letters*, 17:1471, 1992.

[20] K. Curti, C. Gu, and D. Psaltis. *Optics Letters*, 18:1001, 1993.

[21] X. Yi, P. Yeh, and C. Gu. *Optics Letters*, 19:1580, 1994.

[22] M. Neifeld and M. McDonald. *Optics Letters*, 19:1483, 1994.

[23] K. Curtis, A. Pu, and D. Psaltis. *Optics Letters*, 19:993, 1994.

[24] *Optoelectronics and Optomechanic Manufacturing*. NIST, 1995. NISTIR 5715.

[25] A. Bergh. Optoelectronics Technology Program Ideas. In *Optoelectronics and Optomechanic Manufacturing*. NIST, 1995. NISTIR 5715.

[26] M. Dagenais et al. Challenges in Optoelectronic Packaging. In *Optoelectronics and Optomechanic Manufacturing*. NIST, 1995. NISTIR 5715.

[27] H. Kung. Advanced Optoelectronic Manufacturing Technologies. In *Optoelectronics and Optomechanic Manufacturing*. NIST, 1995. NISTIR 5715.

[28] D. Zankowsky. Programs ease optical-systems design. *Laser Focus World*, pages 175–181, 1996.

[29] S. Levitan et al. Computer-Aided Design of Free-Space Optoelectronic Interconnection (FSOI) Systems. *IEEE Workshop on Massively Parallel Processing using Optical Interconnections*, pages 239–245, 1995.

[30] S. Levitan et al. CAD of Free-space OE Systems. working draft.

[31] P. Woodford and D. Casasent. High accuracy and fast new format optical Hough transform. *Proc. SPIE*, 2751:172–185, 1996.

[32] S. Mills et al. Recognition System Rapid Application Prototyping Tool. *Proc. SPIE*, 3073:202–213, 1997.