An automated recording system for page oriented volume holographic memories

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A system for the automatic acquisition and recording of images from video input scenes to a volume holographic optical memory has been designed and constructed. This memory is intended for use as a template database for reference images for an optical correlator. The system has been tested and commissioned; initial results indicate that system parameters such as hologram reconstruction quality are of a sufficiently high standard for the application. © *1995 American Institute of Physics.*

I. INTRODUCTION

Many optical signal processing/optical computing applications require the encoding or recording of page formatted data to take advantage of the parallel nature of optical systems.[1–4] Commonly, this information is encoded on a uniform optical beam using an amplitude or phase spatial light modulator (SLM). These devices may operate in a binary, digitized, or analogue mode and one such device which is widely used is the Seiko–Epson liquid crystal television (LCTV) display[5–7] which, though not designed as such, gives good performance as a SLM. Our application requires a template database containing the reference inputs for an optical correlator system which can be rapidly addressed for real time image recognition. The reference images are to be stored as two-dimensional input scenes recorded as angle multiplexed volume holograms. These input scenes contain the reference object to be identified in various orientations, although the data to be recorded may as easily be pages of binary data. In this paper we shall describe the design and implementation of two subsystems which automatically acquire the images and, record them holographically.

II. DESIGN DETAILS

A. Automated image acquisition subsystem

Given that the reference object to be identified by the correlator system may have an arbitrary orientation and that the input to the correlator system will be angularly unconstrained, the process by which the reference images are acquired needed to be automated in order that manifold object views may be readily and repeatably captured. To this end, the subsystem shown schematically in Fig. 1 has been built. Overall control originates from a host PC which runs the image acquisition software, developed in-house using Borland C++. The robot is programmed using the VAL™ language with trajectory and initialization programs stored on the mini-floppy disc system of the robot controller. Only a few commands are required for this system and these can be sent to the PUMA-560 robot controller via the full duplex asynchronous RS232 link. Using these commands, one can calibrate the robot position; load a program from the mini floppy; execute the loaded program; move the robot Δx, Δy, Δz; and move any joint through a particular angle $\Delta\theta$ at a particular speed. The robot is initially sent to a calibrated position which corresponds to the center of in-plane (i.e., horizontal) rotation occupying the center of the field of view. The operator can see from the monitor that the robot has positioned itself correctly and use the image on the monitor to set the focus and zoom scale using the motorized lens controller. Note that particular attention has been paid to illumination conditions. In order to minimize any shadows cast by the component, a purposely built light enclosure has been constructed which provides even, omnidirectional illumination. This is important for object recognition purposes as an ideal reference image of the object is needed and shadows act as a "noise" term.

An image is acquired using an ITEX 151 frame grabber which is hosted from a SUN Sparc 20 workstation. An instruction is sent via the network from the PC to grab an image which the SUN saves to a common network drive after converting the 512×512 ITEX format image to Microsoft Windows bitmap (*.bmp) format. The process of incrementing the robot position and grabbing a new image is repeated until the desired image set is obtained. A sample image of a camshaft bearing cap supplied to us by the Rover Group UK is shown in Fig. 2. An ASCII index file of the image file names is also written to the hard disc and this is used to perform sorting and grouping of images for the hologram recording subsystem. This sorting process is achieved using the Borland Paradox relational database. The data from this database may again be exported as an ASCII file for easy integration to the recording assembly.

B. Automated hologram recording subsystem

The image index file, as described above, contains information on the image file name and the position of the robot joints at which the image was captured. This file is read in by the PC host of the recording subsystem. The control software for the hologram recording process has also been developed in house, this time using Microsoft Visual Basic.

A schematic of the recording system is shown in Fig. 3. An argon ion laser (Spectra-Physics model Beamlok 2050) is used to record the volume holograms in the Fe:$LiNbO_3$ crystal. A $\lambda/2$ wave plate is used to rotate the plane of polarization of the laser beam. The output from the laser then passes through the first expander to match the beam size to the

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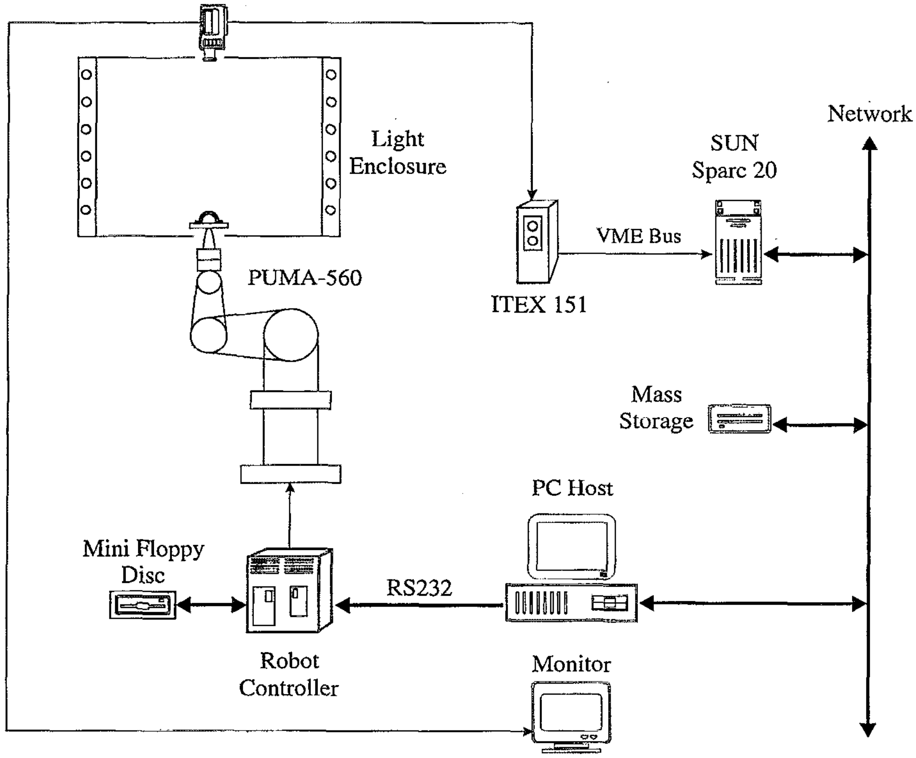

FIG. 1. Schematic diagram of the automatic image acquisition subsystem.

crystal dimensions (10×10×7 mm) and a spatial filter is used to produce a clean, uniform beam profile. A beam splitter produces the reference and object beams with the reference incident on a mirror mounted on an Aerotech ADR150-RE30 rotation table. Angle multiplexing is achieved by angular (but not lateral) translation of the reference beam using a $4f$ optical system with the mirror and crystal located at the back and front focal planes of the first and second lenses, respectively.

The object beam is expanded further to match the beam diameter to the SLM active area. The SLM is a LCTV display device and is used here as an amplitude modulator, thus explaining the presence of the plane polarizer following the SLM. A matching beam compressor restores the beam size to that of the crystal with spatial filtering being used in order to remove higher diffraction orders that arise from the pixellation effect of the SLM. It is estimated that approximately 5% of the incident beam energy is transmitted in the zero-order image of the SLM.[8] The object beam is then combined with the reference in the crystal to produce a volume phase hologram. Reconstruction is achieved by closing shutter 2 as shown in Fig. 3, thereby allowing only the reference beam to be incident on the crystal.

Control of the rotary table is accomplished via an RS232 link to the Aerotech U100 controller. The controller is run using commands which are sent as ASCII strings to achieve direct PC control of the table position. The shutters may be toggled open and closed by a transistor–transistor logic digital signal which is produced using a National Instruments AT-MIO-16F multi input/output card. Software control of this card is via dynamic link library functions provided with the card. The input to the SLM is currently generated using an EGA signal to the video projector electronics as supplied with the LCTV display. However, custom-built drive electronics which will allow true pixel level control of the SLM is in progress.

On executing the control software the rotary table is sent to a calibrated zero position corresponding to the reference beam passing through the center of the $4f$ system. Default

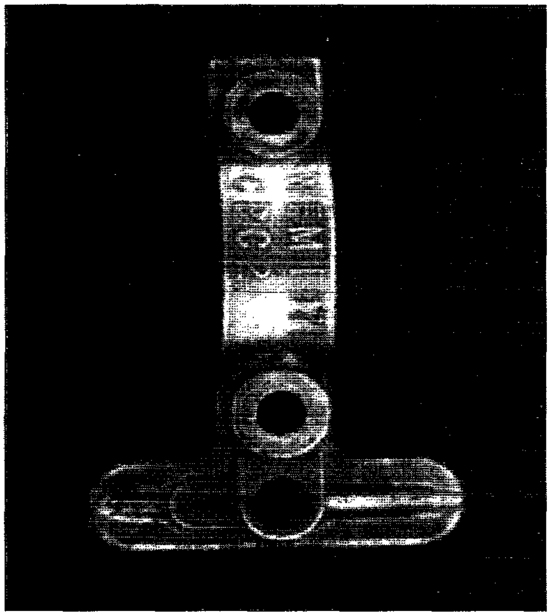

FIG. 2. Sample bitmap image of the Rover camshaft bearing cap.

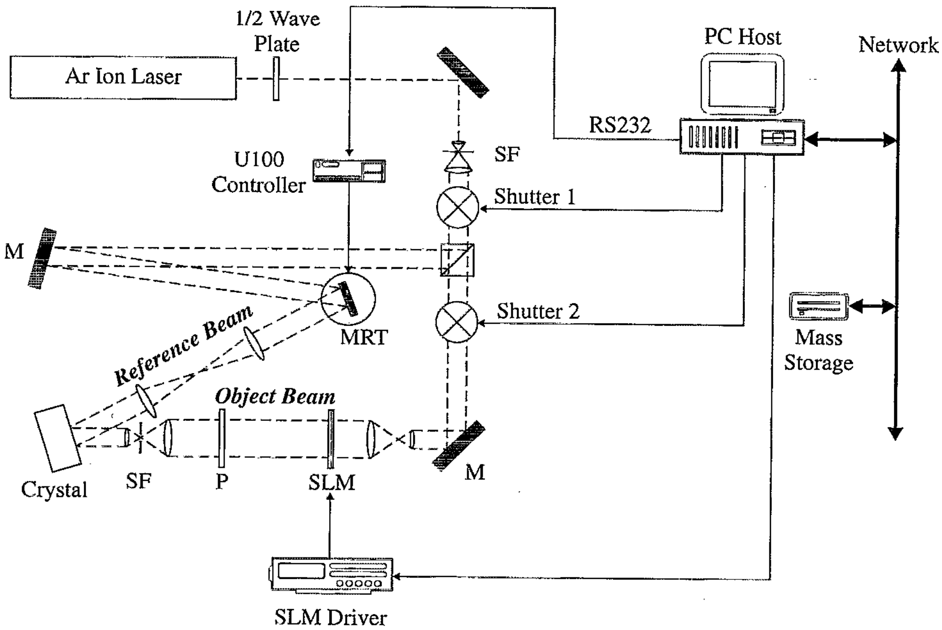

FIG. 3. Schematic diagram of the automatic hologram recording subsystem (SF=spatial filter, MRT=mirror mounted on a rotary table, P=polarizer, M=mirror).

values for the various scan parameters are read from the disc and the shutters are closed. The user must then input the appropriate index file name. This file is loaded and the operator can select, deselect, or view individual image files from a list box. The scan parameters such as start, end position, number of steps, or angular step increment are entered. The operator can now perform the scan with or without recording holograms (and is alerted if the number of angular steps differs from the number of image files selected), position the table relatively or absolutely, and open and close shutters as desired.

Consideration must be given to the exposure sequence for holographic recording in photorefractive media since, in the act of recording a hologram, partial erasure of any previously recorded holograms occurs. To this end, we allow the user to select scheduled recording (using the algorithm of Mok)[9] or incremental recording.[10] The operator inputs the characteristic write and erase times of the particular sample used and, for incremental recording, the number of iterated recording steps. We have characterized the photorefractive response of our samples[11] and found that both techniques provide similar results. The relative sensitivity of the exposure algorithm to errors in the material response times is offset in practice by the stringent repeatability requirements of the sequential method which necessitates an accurate return to the Bragg matching position of each hologram in order to reinforce rather than overwrite that particular hologram. However, it has been reported that the grey scale fidelity using the incremental technique is significantly better[12] which is important in this application.

The recording sequence, once selected, is as follows:

(1) close the shutters if open;
(2) send the table to the start position;
(3) calculate the exposure algorithm if required;
(4) load the image file from disc and display it;
(5) open the shutters;
(6) wait for the required exposure time;
(7) close the shutters;
(8) move the table to the next position
(9) repeat from step (4) above for all images;
(10) if sequential exposure is selected, repeat from step 1 for the number of iterations.

Once the recording sequence is complete the operator is prompted for a file name in which to save the angular position data for each image file. This file is once more an ASCII file and also contains all the information of the original index file. This file may then be used for reference by the optical correlator system.

III. SYSTEM PERFORMANCE

In order that the incremental recording method may be used in the above system and for holograms to be reconstructed successfully using the rotary table, the table repeatability and accuracy must be better than the Bragg width of any given memory page. This has been dealt with by one of our project partners[13] who has calculated the angular tolerance, effects of repeatability, and light utilization issues for the above design. In our system the angular separation of the object and reference beams is approximately 40°. This gives a Bragg width of 18 arcsec, assuming an index modulation depth of 1×10^{-5} and that the light is polarized along the extraordinary axis of the $LiNbO_3$ crystal. The quoted accuracy of the Aerotech ADR150-RE30 rotary table is 5 arcsec with a bidirectional repeatability of one optical encoder count (3.6 arcsec). From this we can see that, with the cur-

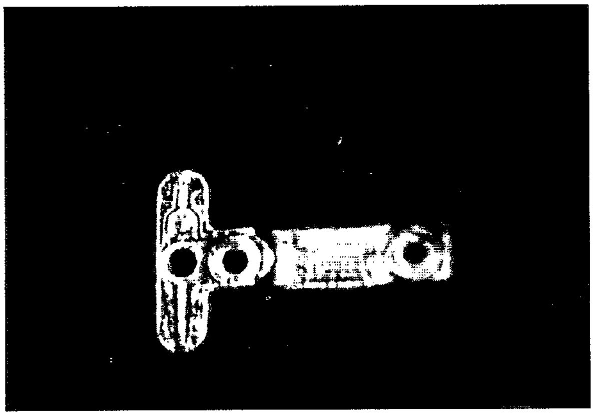

FIG. 4. Typical image quality of a reconstructed hologram.

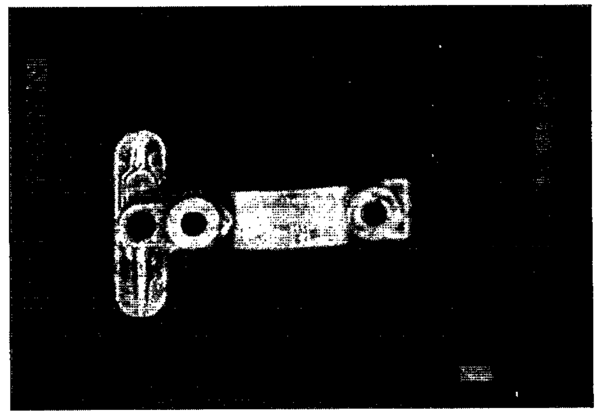

FIG. 5. Image quality from the SLM as recorded in the optical memory.

rent system design, returning to any given hologram and obtaining maximum diffraction efficiency from that hologram should not be problematic.

The key system design feature is automation. This allows us to record a large number of holograms with little demand on operator time. The total recording time is determined by the individual crystal characteristics (write/erase times) and no advantage is to be gained from using one recording scheme (algorithmic or incremental) over another. One further time issue is that of data access time and data transfer rates. This obviously depends on data density per page as well as the speed of response of the reconstruction mechanism. The Epson LCTV used is the European model and as such has a higher pixel density over the more widely reported US model (320×264 pixels). Assuming binary amplitude modulation, this gives a data density of 82.5 kbits per page. Using the table for reconstruction in raster mode (sequential access) with a maximum rotation speed of 80 rpm implies a data transfer rate of 110 kbits/s per page. For random access the settling period for the table to lock in position is of the order of 1 s which gives a transfer rate of 82.5 kbits/s. We have also successfully reconstructed holograms using an acousto-optic deflector[14] which has a random access time of 15 μs. This gives a true random access data transfer rate of 5.5×10^9 bits per s.

Since the correlator system is still currently under development, data storage times have not been an issue since it is possible to simply re-record holograms for testing purposes. In the final demonstrator, it is intended to use thermal fixing[15] to protect the data from destructive readout. To date, we have recorded 72 multiplexed images of an industrial component undergoing an in-plane incremental rotation of 5^0. Reconstruction of these holograms indicates that the image reconstruction quality will be sufficiently high for the purposes of optical correlation. Figure 4 shows a photograph of a typical reconstructed hologram which can be favorably compared to the original image as seen in the photograph of Fig. 5. Future work will include construction of a purposely built interface for the Seiko–Epson LCTV device, moving over to an entirely PC hosted image capture system, and integration of these subsystems with the correlator assembly.

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