Translation-invariant object recognition system using an optical correlator and a super-parallel holographic random access memory

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Abstract. We demonstrate a translation-invariant VanderLugt correlator (VLC) for a set of images stored via holographic angle multiplexing of volume gratings in a polymeric substrate. The images read out from the volume gratings are optically correlated in a translation-invariant manner with a dc-suppressed holographic filter. The quality and efficiency of this correlator are observed to be nearly as good as that of another VLC with images directly from a spatial light modulator used as inputs. This experiment is the first step toward realizing a novel optical image recognition system capable of identifying a query image through an exhaustive search in a large database of filter images stored in an ultrahigh capacity superparallel holographic random access memory (SPHRAM). In this system, the identification of the query image is to be performed with a translation invariant, real-time VLC or a joint transform correlator (JTC). © 2006 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2172354]

1 Introduction

In many military and civilian applications, rapid target identification and tracking is essential. Real-time target identification and recognition is usually performed by correlating an acquired image with images stored in a database. Therefore, a huge database of images is required for reliable identification of the target. Current image identification technology relies on digital signal processing (DSP) architectures and algorithms implemented on digital electronic computers. Image correlation with electronic hardware is often too slow for target interception applications because the data is compared serially. Optical correlation techniques possess a tremendous potential advantage in speed because of inherent parallelism in optics. In addition, optical holographic information storage offers data storage capacity much higher than any other existing technology. A volume holographic optical correlator[1] (HOC), in which images are stored holographically via angle multiplexing, offers parallel database searches much faster than DSP. However, the potential of an HOC is limited by the inability to access simultaneously the angle-multiplexed images stored at more than one spatial location. Previously, we proposed and demonstrated the feasibility of a solution in the form of a superparallel holographic optical correlator[2] (SPHOC) architecture that employs spatial multiplexing achievable with the help of a special purpose lenslet array,[3] redirectors, and holographic multiplexers. Thus, the SPHOC can perform optical correlations at thousands of spatial locations simultaneously, resulting in a system performance that could be millions of times faster than the DSP-based correlators. In addition, we recently demonstrated that by operating the SPHOC in reverse, with the addition of a shutter array to the SPHOC hardware, we can realize a superparallel holographic random access memory (SPHRAM) architecture.[4] The SPHRAM device promises ultrahigh storage density and, therefore, enormous data storage capacity, because it employs spatial and 2-D angle multiplexing. For example, a 5-mm-thick 15- × 15–cm square plate of a holographic material can have 1600 spatial locations, each of which can be angle multiplexed for 8000 images in two dimensions. If each of the stored images has 1024×1024 bits, the resulting SPHRAM's capacity will be about 1.3 terabytes.

2 Principle

Since a huge database of images is necessary for reliable identification, performing the correlations in a translation-invariant manner greatly reduces the size of the required database and speeds up the search process. A major disadvantage of the SPHOC in the present form is that it is difficult to achieve translation-invariant correlation when using a thick holographic grating material. In this paper, we propose an alternative object recognition system that consists of the SPHRAM coupled with a translation-invariant real-time joint-transform correlator[5–7] (JTC) or a VanderLugt correlator[8,9] (VLC) based on a thin dynamic material. Images retrieved from the SPHRAM to be used as the correlation filters can be updated at a high rate, and the query images can be correlated with each filter in a translation-invariant manner. With this new approach, we trade the superparallelism of the SPHOC for the shift invariance of a thin correlator. However, we retain the aspects of parallelism in the individual image correlation as well as the ability to access rapidly large amount of data stored holographically.
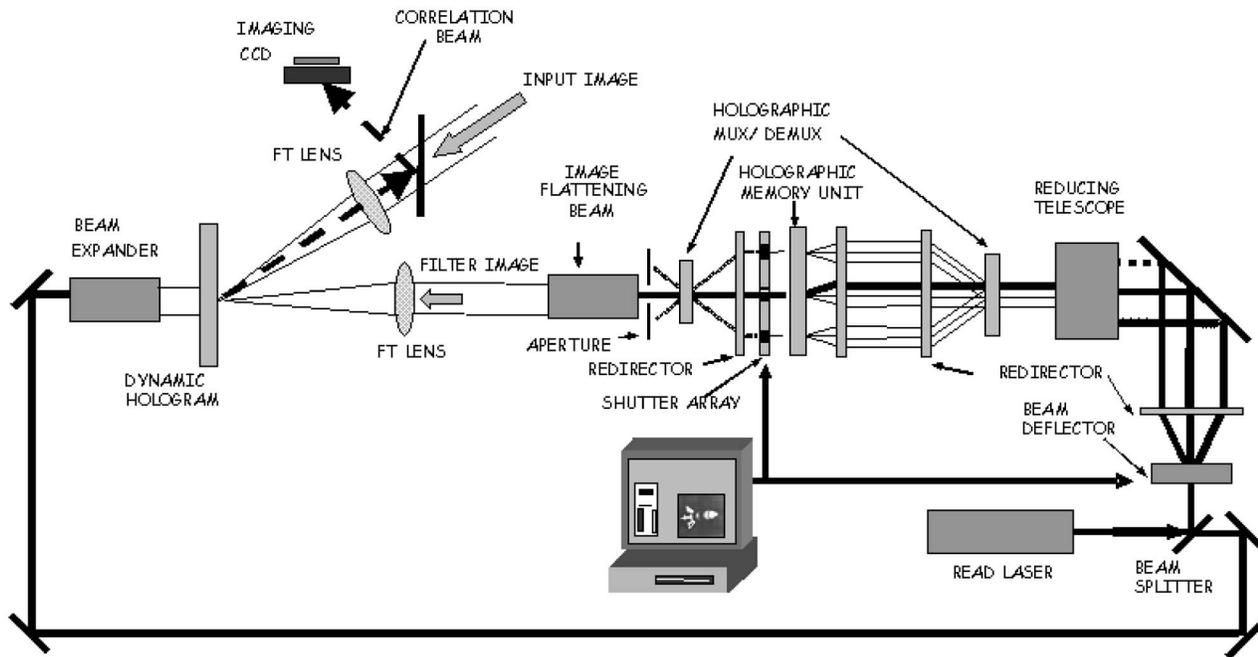

Fig. 1 End goal architecture of SPHRAM combined with JTC.

2.1 SPHRAM with JTC Operation

Schematics of the SPHRAM architecture combined with a translation-invariant realtime JTC are presented in Fig. 1 (for a detailed description of the SPHRAM operation see Ref. 4). The input image is encoded on the laser beam using a spatial light modulator (SLM) (not shown in the diagram). At the same time, a filter image is retrieved from the SPHRAM. The Fourier transforms (FTs) of the input and the filter images are recorded in the dynamic holographic medium. The plane wave read beam diffracts from the grating, and produces a correlation beam. The correlation spot is captured with a CCD camera, and the dynamic holographic gratings containing the joint FT is erased. The process is then repeated with a new filter image retrieved from the SPHRAM. The speed of the SPHRAM operation can be as high as about a megahertz, limited primarily by the operating rates of the shutter array, beam deflectors, and CCD cameras. On the other hand, to the best of our knowledge, the fastest real-time JTC reported in literature can operate at a 10-kHz rate. Thus, unless a faster material is found, the speed of the JTC will be the limiting factor in determining the speed of the SPHRAM+JTC system. However, it is possible to overcome this speed limit if a VLC is used in place of the JTC. As noted in Ref. 6, the rate of a real-time VLC operation is independent of the photorefractive material response time.

2.2 Material Selection

To implement the SPHRAM+correlator system, we must identify the holographic material for the high-density and high-quality permanent data storage required to construct the SPHRAM. In addition, we must select the fast-response dynamic holographic material necessary for a translation-invariant correlator. We have already identified the photopolymer-based Memplex® thick holographic material developed by Laser Photonics Technology Inc.[10] as the medium for a high-capacity and high-efficiency holographic memory. This material can have a large $M/\#(>20)$, and holograms written in this material can survive at room temperature for many years without noticeable degradation.[11,12] There are several possible options for the real-time translation-invariant correlator material sensitive in the visible wavelength spectrum. A translation-invariant JTC utilizing a 48-μm thin Fe:LiNbO$_3$ photorefractive crystal, operating at a 2.5-Hz rate with a 3% diffraction efficiency, was demonstrated in the past.[13] Recently, a high-speed but not quite translation-invariant JTC with an effective thickness of the crystal of 560 μm was demonstrated to operate at a 10-kHz rate with 0.01% diffraction efficiency using a photorefractive Sn$_2$P$_2$S$_6$ crystal.[5] In principle, a translation-invariant correlator in a thick medium can be realized by making use of the high angular bandwidth in the plane that contains the object beam, but is perpendicular to the plane formed by the object and the reference beam.[14,15] Another candidate material is a photorefractive polymer,[16] such as the substrate developed by Nitto Denko Technical Corporation (NDT). NDT makes photorefractive polymer films that are 30 μm thin, and have a 30-ms response time and a 60% diffraction efficiency in the visible spectrum. Before we proceed to construct the SPHRAM with a translation-invariant real-time JTC or a VLC, it is necessary to verify the ability of storing high-quality angle-multiplexed holograms in a sample of the Memplex® material that we will subsequently refer to as the holographic memory unit (HMU). In addition, we must demonstrate the ability to perform a reliable translation-invariant correlation of the images reconstructed from the HMU.

3 Experimental Demonstration

In this paper, we present the results of an elementary demonstration of the key components of the future SPHRAM
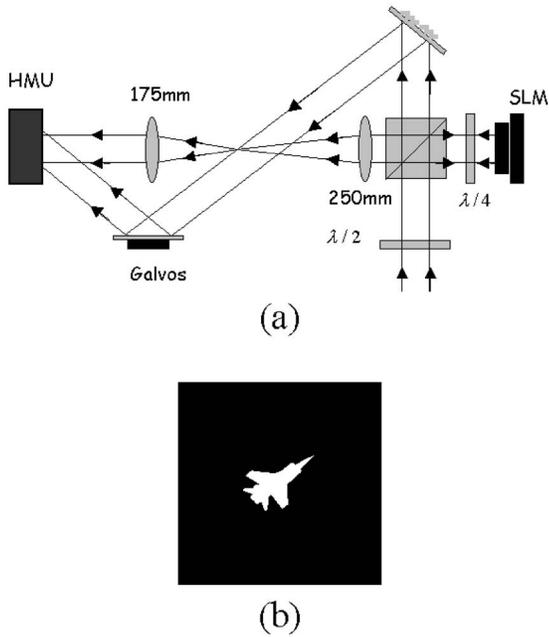
(a)

(b)

Fig. 2 (a) Optical setup for writing images in the HMU and (b) original binary MiG-25 image.

+correlator system. In this experiment, the images were stored in the Memplex® HMU via 1-D angle multiplexing, and later retrieved from the HMU to perform translation-invariant correlation with a static, thin holographic filter in the VLC architecture. Similar experiments involving a correlator readout of images stored via angle multiplexing in photorefractive crystals have been performed in the past.[5,17] However, to the best of our knowledge, this is the first reported result of a correlator readout from holographic memory based on a polymeric substrate.

3.1 Recording Images in Holographic Memory

We used a frequency-doubled ND:YAG laser operating at a 532-nm wavelength in all stages of the experiment. Images were transferred to the laser beam using a 512-× 512-pixel (pixel size $15 \times 15 \mu$m) SLM made by Boulder Nonlinear Systems. Our HMU was a Memplex® plate, 4×4 cm in area and 2 mm thick. Images were recorded in the HMU in the 4-f plane of the optical system shown in Fig. 2(a). The HMU was treated as a 3×3 matrix of spatial locations, with a mask exposing one spatial location at a time. Different sets of approximately 20 images each are stored via angle multiplexing in the horizontal dimension at each of the nine spatial locations of the HMU. Although we recorded images at nine spatial locations on the HMU, we used only one spatial location for the translation-invariant correlation experiment. That particular location of the HMU contained a set of 23 binary images (each about 50×50 pixels) of snapshots of a MiG-25 fighter jet flying in a rotationally invariant loop pattern. One can see the original binary image in Fig. 2(b). The images of the MiG-25 jet were shifted from the center by different distances in different frames, with the largest displacement along the horizontal or vertical axes of about 150 pixels. A set of samples of the images reconstructed from the HMU
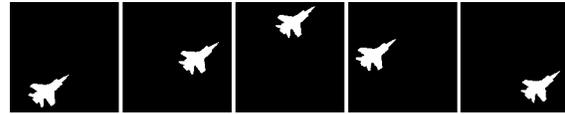

Fig. 3 Samples of thresholded MiG-25 images moving in a loop pattern reconstructed from the HMU.

and recorded with a CCD camera is presented in Fig. 3. We note that there was no noticeable crosstalk between the angle-multiplexed images at the same location or images at different spatial locations. The reconstructed images had a very high quality, which is essential for building a reliable SPHRAM correlator system. We stored only 23 images of the MiG-25 jet, but in principle, in a 2-mm-thick plate, we could store up to 1000 angle-multiplexed images at a single spatial location.[18]

3.2 Edge-Enhanced Filter

The thin holographic filter used in the VLC architecture contains a dc-suppressed FT of the MiG-25 jet image centered in the frame. This filter was prepared with Slavich VRP-M thin holographic plates (with a 6-μ thickness emulsion layer), using the same laser that was used for recording images in the HMU. The optical setup for the holographic filter writing is presented in Fig. 4(a). The dc suppression of the FT was necessary to suppress the chance of correlations with the wrong objects. A common method to eliminate the dc part in the Fourier plane is to install a crosshairs filter.[19] However, this filter is difficult to align and may need to be adjusted every time the image is shifting in the SLM frame plane. We achieved the dc suppression of the recorded FT in a more robust way by employing the dc saturation technique, which is a static holography analog of
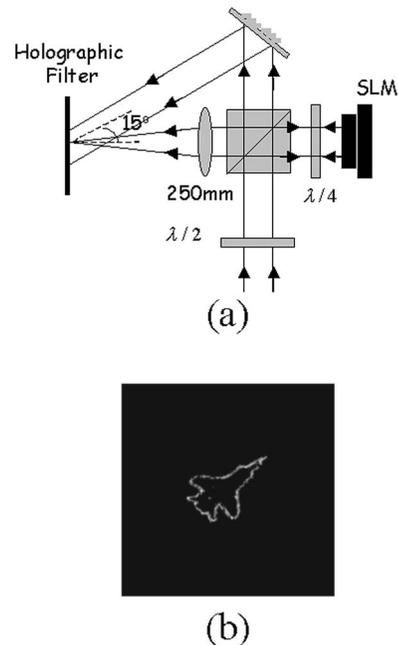

(a)

(b)

Fig. 4 (a) Optical setup for writing the thin holographic filter and (b) thresholded edge-enhanced image reconstructed from the thin holographic filter.
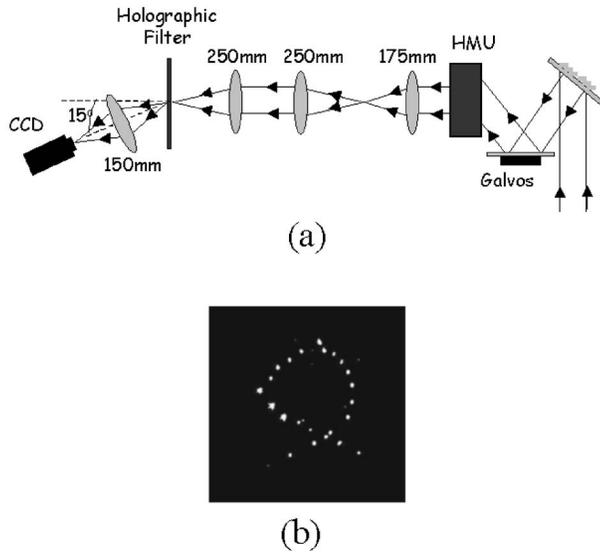
Fig. 5 (a) Optical setup for detection of cross-correlation spots and (b) superimposed thresholded correlation spots showing a loop-pattern trace produced when the image source is the HMU.

the edge enhancement by two-wave mixing in photorefractive materials.[20] This technique is based on the fact that the low frequencies of the spatial FT of an image typically occupy a much smaller area than do the high frequencies. Hence, it is possible to expose the hologram to an amount of radiation such that the intensity in low frequencies of the spatial FT of the image significantly exceeds the material saturation intensity threshold. However, the high frequencies in the spatial FT are not saturated. Therefore, when the hologram is illuminated with a reference wave, the low frequencies are not reconstructed, while the high frequencies that carry the information about the shape of the object produce a diffracted beam. The edge-enhanced image reconstructed from the thin filter is shown in Fig. 4(b). The thin filter was separately tested for its correlation selectivity.

3.3 Recording a Trace

The images of the MiG-25 jet are retrieved from the HMU by scanning the angle of the read beam incident on the same spatial location of the HMU. The optical setup for this experiment is shown in Fig. 5(a). Since the HMU was recorded with a nonsymmetric 4-f system, we required an additional 4-f system consisting of 175- and 250-mm lenses to match the size of the FT of the image reconstructed from the HMU to the size of the FT recorded in the thin filter with a 250-mm lens. The aforementioned 4-f system also served to flip the image retrieved from the HMU, since the images recorded in the HMU in the 4-f plane were rotated about the horizontal axis of the SLM images. The thresholded correlation spot captured on the CCD camera indicated the position of the jet on the frame plane. Superimposing the successive correlation CCD frame grabs produced a trace of the trajectory of the jet, presented in Fig. 5(b). For comparison of the data quality, another VLC was constructed, where instead of the HMU, the same images of the MiG-25 jet came directly from the
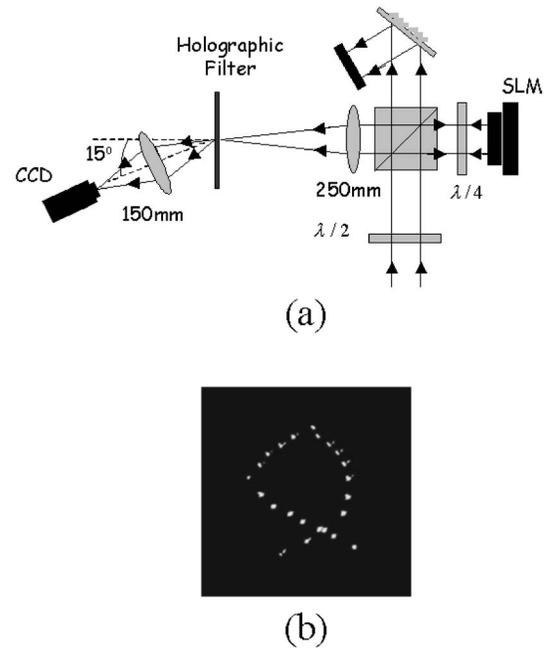

Fig. 6 (a) Optical setup for detection of cross-correlation spots and (b) superimposed thresholded correlation spots showing a loop-pattern trace produced when the image source is the SLM.

SLM [Fig. 6(a)]. The same thin holographic filter was used for correlation. As before, a tracing trajectory of the jet was produced. The loop-pattern trajectory obtained with the images coming from the SLM is presented in Fig. 6(b). We see that the trajectories produced from the two experiments are essentially identical.

4 Conclusion

To summarize, we demonstrated a translation invariant VLC for a set of images stored via holographic angle multiplexing of volume gratings in a polymeric substrate. The next step is to implement the SPHRAM system with a high-density data storage and fast data retrieval, which is based on a high $M/\#$ holographic photopolymer. We will use the SPHRAM in conjunction with a real-time translation-invariant JTC or a VLC based on a fast-response photorefractive material.

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Biographies and photographs of authors not available.