Superparallel holographic correlator for ultrafast database searches

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We describe a superparallel holographic optical correlator that performs two-dimensional spatial and angular multiplexing simultaneously. The key step in this architecture is the use of a holographic multiplexer to split a query image into many copies before it applies them to the holographic database. A holographic demultiplexer, in conjunction with an aperture, is used to identify the location and the angle of the brightest correlation peak. This architecture uses only $O(\sqrt{N})$ detector elements to search through N unsorted images in a single query. We demonstrate the basic features of this architecture, using three spatial locations with eight angle-multiplexed images in each location. © 2003 Optical Society of America

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In many situations it is necessary to identify a target rapidly. In a military context, a target is typically detected by synthetic aperture radar.[1] One then compares the image obtained with images stored in a database to ascertain the identity of the object in question. There are many techniques for performing this task. One technique employs digital signal processing,[2] wherein a digital-signal processing chip or a dedicated electronic circuit is used to compare the images serially, bit by bit, and thereby to identify the image with the highest degree of correlation to the target image.

An important alternative to this approach is use of a holographic optical correlator (HOC), which takes advantage of the inherent parallelism of optics. Specifically, the images that compose the database are stored in a hologram by means of angular multiplexing.[3] With a spatial light modulator (SLM) the target image is transferred to an optical beam, which in turn illuminates the hologram while it scans the beam's angle of incidence. If a match is found, a bright correlation beam is produced in a specified direction, thereby identifying the target match.[4,5] HOCs are employed for many optical signal-processing applications, including pattern and character recognition,[6] in computer–robotic vision for object tracking,[7] and in the implementation of artificial neural networks.[8]

HOCs can perform correlations nearly 3 orders of magnitude faster than typical digital signal-processing-based correlators. This increase in speed results from the fact that in the HOC the bits are compared in parallel. However, the HOC is limited in terms of the number of images that can be queried at one time. Specifically, the maximum number of images that can be stored in a single spatial location by angular multiplexing is typically limited to a few thousand.[3,9] This problem can be overcome by spatial multiplexing, whereby different sets of images are stored in different spatial locations. By use of a large holographic substrate it may be possible to employ more than 1000 different spatial locations. A disadvantage of this approach is that the substrate must be translated in two dimensions to provide access to each location, thereby significantly slowing the effective speed of correlation.

We have developed an architecture that overcomes this limitation. Specifically, we propose a design wherein the query image is split into many copies. This is done by a highly efficient holographic multiplexer–demultiplexer (HMDX), which we produce by writing multiple high-efficiency Bragg gratings in a thick substrate, with a common reference beam and multiple object beams at various angles. Thus multiple query images are formed, and each is presented to a different spatial location in the holographic memory unit (HMU). We then use a series of optical elements to decipher the resultant diffraction patterns. The net result is that the images in all the memory locations are queried, and a potential image match is achieved in the same amount of time that it takes for the conventional HOC to query the images at one location. This superparallel holographic optical correlator (SPHOC) exhibits a parallelism beyond that of conventional optics. In our current implementation

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we perform our comparisons with actual images instead of with Fourier transforms. An advantage of using a Fourier transform is that the correlation is spatially invariant. An investigation to identify a spatially invariant version of this architecture is under way.

The SPHOC architecture is shown schematically in Fig. 1. Two-dimensional angular multiplexing is used to store images in each spatial location of the HMU before the correlation task is performed. If there are r discrete angles in one dimension and s in the orthogonal dimension, rXs images are stored. The search starts with the acquisition of the query image by the camera, synthetic aperture radar, or other means. The query image is then sent to the control computer for recording. It is also passed to the SLM via a high-speed data bus. Alternatively, the query could represent an object-to-image data map, which requires a much smaller amount of information for representing the image in a rotation-invariant way. A collimated laser beam is expanded to match the size of the SLM.[10] This beam reflects off the SLM and is passed through the image flattening beam reducer (IFBR), which is a set of two lenses that reduces the image size by the ratio of the focal lengths. We use the term "image flattening" to represent the fact that the angular spread in the image at the input of the HMDX is the same as that at the face of the SLM. This is necessary because the HMDX may have limited angular selectivity owing to its thickness, and therefore beam divergence must be minimized. The HMDX produces a two-dimensional array of copies nXm (where there are n columns and m rows of memory cells on the HMU), which correspond to the total number N of spatial locations on the HMU. For the HMDX to diffract N beams efficiently, each holographic grating must have a diffraction efficiency $1/N$, and the following requirement holds: $M_\# \geq (\pi/2)\sqrt{N}$,[11,12] where $M_\#$ is a material parameter of the substrate that characterizes the degree of index modulation achievable for a given substrate. The output beams from the HMDX are passed through a holographic redirector (HR), which has a single slanted grating at each beam location and directs each beam toward the HMU. An identical copy of the image impinges upon the HMU at each spatial location. The HMU contains of the order of 10^3 images angularly multiplexed at each spatial location. If the target image matches a stored image in one of these locations, a diffracted beam will emanate from that location at a specific angle. In Fig. 1 we show all such diffraction beams (in one dimension, for simplicity of drawing); keep in mind that only one of these beams (shown by the thicker, solid line) will be produced for a given target image. The goal of the rest of the architecture is to identify the spatial location to which the beam belongs and the angle at which the beam emerges from that location. These two pieces of information will uniquely identify which image has been matched.

The beams coming out of the HMU are first collimated by a lenslet array and then split by a beam splitter (BS) into two components. One component gets focused by another lenslet array onto an nXm pixel array of CCD elements (CCDA). Identifying the detector that sees the highest signal yields the information about the spatial location of the matching image. The other part of the beam goes through another holographic reflector. This reflector redirects all the incident beams to a central point without focusing the beams coming from the same spot with respect to one another, as shown.

These beams are now passed through another HMDX, which is identical to the one used at the input but is now operating in reverse. However, the reverse operation has the potential problem that additional beam patterns (weaker than the one generated along the axis) will also be produced. A simple aperture can be used to eliminate these unwanted beams. After the aperture, a beam expander (BE) is used to match the size of the second CCD array, which contains rXs elements, corresponding to the number of angles used in the two-dimensional angular multiplexing during the writing stage. The element of the CCD that sees the brightest signal yields the information about the angle of the matched image. Note that, for a database of K images, the number of detector elements to be monitored is only $O(\sqrt{K})$. Data obtained from both CCD arrays, properly thresholded, can be sent through a digital logic circuit to identify the image that is matched. For typical parameters, the whole process will take less than microsecond.

Our experimental results were obtained with Memplex material produced by Laser Photonics Technologies in Amherst, Mass. This material and a variant thereof were used previously for memory storage and nonspatial filtering applications.[13–16] The substrates were 3.7 cm × 3.7 cm in lateral area and 2 mm thick. Our holograms were written and read with a frequency-doubled Nd:YAG laser operating at 532 nm.

Figure 2 displays experimental images from two HMDXs that we produced. Figure 2a is a schematic of the 3 × 3 HMDX working as a 1 × 9 splitter. Figure 2b is a CCD capture of the SLM image that was used to illuminate the splitter, and Fig. 2c is an image of the resultant output. The irregular bright spots in the background of Fig. 2b are due primarily to dust contamination of the SLM surface and imaging optics. The irregular spacing of the far-right-hand images in Fig. 2c is a result of the imaging optics and was not due to the HMDX. Figure 2d is an image of the output of a 1 × 20 HMDX when it was illuminated with a plane-wave beam.

Figure 3 displays experimental images obtained during testing of the HMDX and HMU components

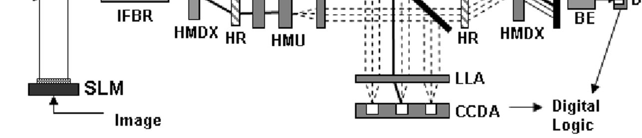

Fig. 1. Schematic of the SPHOC. See text for details.

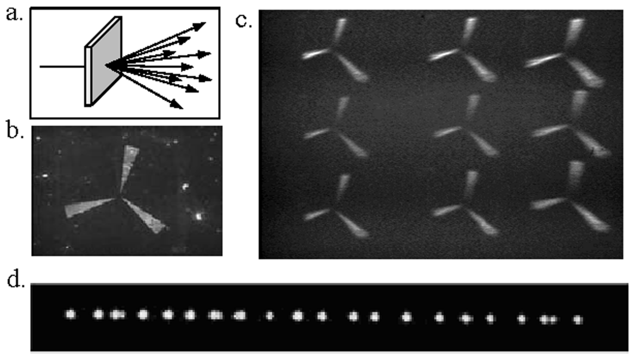

Fig. 2. Demonstration of a HMDX. a, Schematic of the 3×3 HMDX; the query image is input at the left, and nine copies result. b, SLM image that was input to the HMDX; c, CCD capture of the nine resultant images. d, Output of a 1×20 HMDX that was illuminated with a simple plane-wave beam.

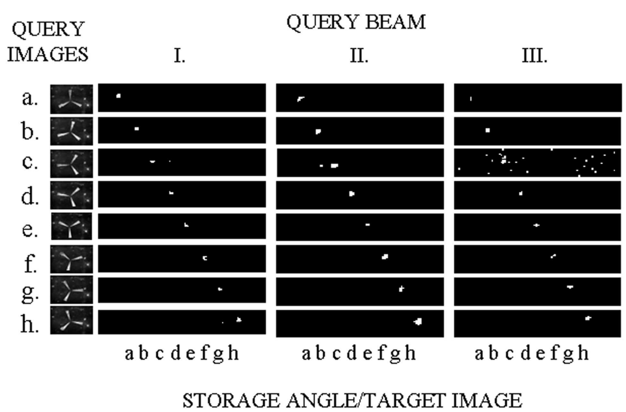

Fig. 3. Correlation data from three multiplexed query images. The images at the far left represent the query images presented to the HMU unit. The same images were stored in the HMU. The images in columns I, II, and III display the CCD images of the diffracted beams that emerged from the HMU when query beams I, II, and III, respectively, were directed onto the HMU. The lateral positions of the bright spots (a, b, c...) indicate which of the stored images has matched the query image.

of the SPHOC architecture. The SLM query image was routed through a 1×3 HMDX. We then used the three resultant images to query three separate HMU locations, all containing identical sets of images. The column at the far left displays the query image used during correlation. Each of the other three columns in Fig. 3 displays data collected by use of one of the three query beams. The eight images in each column are CCD captures of the diffracted beams that emerged from the HMU during correlation. The letters at the bottom of each column indicate the location of the diffraction spot that corresponds to a stored image. Taking the top image in column I as an example, we see that image a has excited a diffraction spot in position a, which is the matching image. The data clearly show that the appropriate diffraction beam or spot is being excited by each query image, which demonstrates the way in which our architecture will identify the target images.

In summary, we have proposed a superparallel holographic optical correlator in which two-dimensional spatial multiplexing and two-dimensional angular multiplexing are performed simultaneously. We have demonstrated two of the key components: a holographic multiplexer to split a query image into multiple copies and a holographic memory unit.

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References

1. W. W. Goj, *Synthetic-Aperture Radar & Electronic Warfare* (Artec House, Norwood, Mass., 1992).
2. D. Stranneby, *Digital Signal Processing: DSP and Applications* (Oxford U. Press, London, 2001).
3. G. Barbastathis and D. Psaltis, in *Holographic Data Storage*, H. J. Coufal, D. Psaltis, and G. T. Sincerbox, eds. (Springer-Verlag, Heidelberg, 2000).
4. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, New York, 1996).
5. A. VanderLugt, IEEE Inf. Theory **1,** 139 (1964).
6. N. Collins, *Optical Pattern Recognition Using Holographic Techniques* (Addison-Wesley, Reading, Mass., 1988).
7. A. Bergeron, Proc. SPIE **4734,** 65 (2002).
8. A. V. Pavlov and E. I. Shubnikow, Opt. Memory Neural Netw. **2,** 4 (1993).
9. G. W. Burr, C. Jefferson, H. Coufal, M. Jurich, J. Hoffnagle, R. Macfarlane, and R. Shelby, Opt. Lett. **26,** 444–446 (2001).
10. J. L. Sanford, IBM J. Res. Dev. **42,** 411 (1998).
11. D. Psaltis, D. Brady, and K. Wagner, Appl. Opt. **27,** 1752 (1988).
12. G. W. Burr, F. H. Mok, and D. Psaltis, Opt. Lett. **21,** 896 (1996).
13. J. E. Ludman, J. Riccobono, N. Reinhand, Yu. Korzinin, I. Semenova, and M. S. Shahriar, Quantum Electron. **26,** 11 (1996).
14. J. E. Ludman, J. Riccobono, N. Reinhand, I. Yu. Korzinin, M. S. Shahriar, H. J. Caulfield, J. Fournier, and P. R. Hemmer, Opt. Eng. **36,** 6 (1997).
15. M. S. Shahriar, L. Wong, M. Bock, B. Ham, J. Ludman, and P. Hemmer, in *Symposium on Electro-Optics: Present and Future*, H. A. Haus, ed., Vol. 23 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1998), pp. 97–104.
16. P. Hemmer, M. S. Shahriar, J. Ludman, and H. J. Caulfield, in *Holography for the New Millenium*, J. Ludman, H. J. Caulfield, and J. Riccobono, eds. (Springer-Verlag, New York, 2002) pp. 179–189.