Compact Holographic Data Storage System

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ABSTRACT

JPL, under current sponsorships from NASA Space Science and Earth Science Programs, is developing a high-density, nonvolatile and rad-hard advanced Compact Holographic Data Storage (CHDS) system to enable large-capacity, high-speed, low power consumption, and read/write of data for potential commercial and NASA space applications. This CHDS system consists of laser diodes, photorefractive crystal, spatial light modulator, photodetector array, and I/O electronic interface. In operation, pages of information would be recorded and retrieved with random access and high-speed. The non-volatile, rad-hard characteristics of the holographic memory will provide a revolutionary memory technology to enhance mission capabilities for all NASA's Earth Science Mission.

JPL is investigating an innovative angular multiplexing scheme for the holographic data storage to maximize the storage capacity, data transfer rate, and minimize the system volume. An experimental Liquid Crystal Beam Steering Spatial Light Modulator has been developed, with a industrial collaborator, to enable high-speed, high angular-resolution, random access beam steering for storing tens of thousand of page of holographic data in a cubic photorefractive crystal.

In this paper, recent technology progress in developing this CHDS at JPL will be presented. The recent applications of the CHDS to optical pattern recognition, as a high-density, high transfer rate memory bank will also be discussed.

INTRODUCTION

NASA's future missions would require massive high-speed onboard data storage capability to support both Earth Science and Space Science missions. With regard to Earth science observation, a 1999 joint Jet Propulsion Laboratory and Goddard Space Flight Center (GFSC) study ("The High Data Rate Instrument Study" [1]) has pointed out that the onboard science data (collected by high date rate instruments such as hyperspectral and synthetic aperture radar) stored between downlinks would be up to 40 terabits (Tb) by 2003. However, onboard storage capability in 2003 is estimated at only 4 Tb that is only 10% of the requirement. By 2006, the storage capability would fall further behind to be able to only support 1% of the onboard storage requirements.

For Space Science, the onboard data storage requirements would be focused on maximizing the spacecraft's ability to survive fault conditions (i.e. no loss in stored science data when spacecraft enters the “safe mode”) and autonomously recover from them NASA’s long-life and deep space missions. This would require the development of non-volatile memory. In order to survive in the stringent environment during space exploration missions, onboard memory requirements would also include: survive a high radiation environment (1 Mrad), operate effectively and efficiently for a very long time (10 years), and sustain at least a billion (10^{12}) write cycles.

Therefore, memory technologies requirements of NASA’s Earth Science and Space Science missions are: large capacity, non-volatility, high-transfer rate, high radiation resistance, high storage density, and high power efficiency.

Current technology, as driven by the personal computer and commercial electronics market, is focusing on the development of various incarnations of Static Random Access Memory (SRAM), Dynamic Random Access Memory (DRAM), and Flash memories. Both DRAM and SRAM are volatile. Their densities are approaching 256 Mbits per die. Advanced 3-D multichip module (MCM) packaging technology has been used to develop solid-state recorder (SSR) with storage capacity of up to 100 Gbs [2-4]. The Flash memory, being non-volatile, is rapidly gaining popularity. Densities of flash memory of 256 Mbits per die exist today. High density SSR could also be developed using the 3-D MCM technology. However, Flash memory is presently faced with two insurmountable limitations: Limited endurance (breakdown after repeated read/write cycles) and poor radiation-resistance (due to simplification in power circuitry for ultra-high density package).

It is obvious that state-of-the-art electronic memory could not satisfy all NASA mission needs. It is necessary to develop new memory technology that would simultaneously satisfy non-volatility, rad hard, long endurance as well as high transfer rate, low power, mass and volume requirements.

The comparative specifications of the holographic memory (design goal) and state-of-the-art electronic memory are listed in Table I. As shown in Table I, the holographic memory technology, upon full development, not only is simultaneously non-volatile, high-speed and rad hard, but also superior in power and volume/mass efficiency to its electronic counterpart.

HOLOGRAPHIC DATA STORAGE TECHNOLOGY

The Advanced Holographic Memory (AHM) system will store data in a large number of holograms inside of a photorefractive crystal. Holograms would be formed by recording the light interference pattern caused by a data beam carrying page data (image or binary bits) and a reference laser beam in a cubic photorefractive crystal. Since these images are stored in the Fourier domain and recorded in three dimensions, massive redundancy is built into the holograms such that the stored holograms would not suffer from imperfections in the media or point defects. The $LiNbO_3$ photorefractive crystal has been the most mature recording material for holographic memory due to its uniformity, high E-O coefficient, high photon sensitivity, and commercial availability. One unique advantage for using holographic data storage is its rad hard capability. Holograms stored in photorefractive crystal have been experimentally proven to be radiation-resistant. In a recent NASA LDEF (Long-Duration Exposure on Active Optical Components) experiment, Georgia Institute of Technology (GIT), under NASA Contract NAS1-15370, has flown a Lithium Niobate holographic memory in space. The retrieved crystals only suffered surface damage and still retained their photosensitivity for hologram recordings.

Recently, we developed a bench-top AHM Data Storage breadboard and, for the first time, demonstrated video-rate of memory retrieval for both grayscale image and binary data. A 1000-page long video of Asteroid Toutatis images was recorded and retrieved with very high fidelity. The AHM breadboard used acousto-optic (AO) scanning for multiple holograms recording and readout without any moving parts. This initial development has demonstrated the high fidelity, high-speed data storage capability. A photo of the AO based AHM system and its schematic diagram is shown in Figure 2.

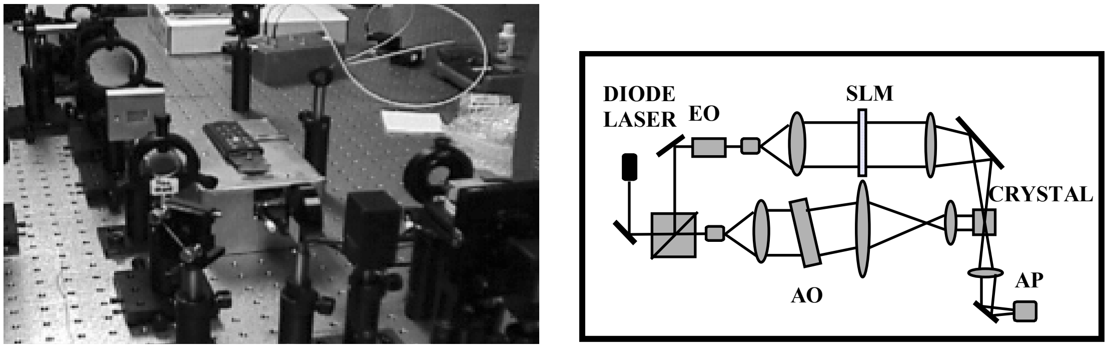

Figure 2. Photograph of the JPL developed AO- based AHM system and its corresponding schematic diagram

An experimental demonstration of the grayscale image recording and retrieving capability has been achieved. A sample of a high fidelity retrieved image set of NASA's image data of asteroid Toutatis is shown in Figure 3.

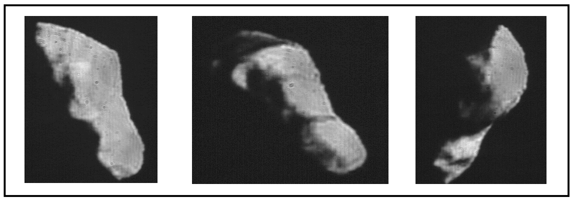

Figure 3. Grayscale Toutatis images retrieved from JPL developed holographic memory

This JPL-developed proof-of-concept acousto-optic-scanner-based holographic memory system has demonstrated the super performance of holographic memory. This breadboard is currently being used for bit error rate analysis of the retrieved holographic data.

In order to further miniaturize the AHM breadboard, a liquid crystal beam steering spatial light modulator (BSSLM) would be used to replace the AO beam steering devices. This device will provide high-resolution beam steering capability to enable the storage /retrieval of more than 10,000 pages of holographic memory. By coupling the BSSLM with a VCSEL array, the storage density will further be increased by more than two orders of magnitude. The introduction of the BSSLM spatial multiplexing scheme would further ensure the system is compact and low power.

ADVANCED HOLOGRAPHIC MEMORY USING LIQUID CRYSTAL BEAM STEERING DEVICES

The proposed holographic memory architecture, as shown in Figure 4, consists of a writing module for multiple holograms recording and a readout module for hologram readout. The writing module includes: a laser diode as the coherent light source; a pair of cascaded beam steering Spatial Light Modulators (BSSLM), one transmissive and one reflective in each pair, for angular multiplexed beam steering; a Data SLM for data input for storage; two cubic beam splitters for beam forming; and a photorefractive crystal for hologram recording. The readout module also shares this photorefractive crystal. The readout module includes: a laser diode with the same wavelength as the writing one; a pair of cascaded BSSLMs to generate phase conjugated readout beam (i.e. the readout beam is directed opposite to the writing beam); the shared photorefractive crystal; a cubic beam splitter; and a photodetector array for recording the readout holograms The system uses an angle multiplexing scheme to store multiple holograms and phase-conjugated beams to read out each hologram.

In hologram writing, the collimated laser beam (top left in Fig.4) splits into two parts at the first cubic beam splitter. 1) The horizontally deflected light will travel across the second cubic beam splitter to read out the input data after impinging upon the Data SLM. The data-carrying beam will then be reflected into the PR crystal as the data-writing beam. 2) The remaining part of the laser beam will go through vertically, passing a BSSLM and then reflected to the second reflective BSSLM. Both BSSLMs are 1-D blazed phase gratings capable of beam steering with an angular deflection determined by the grating periods. By cascading two BSSLMs in orthogonal, 2-D beam steering can be achieved (in the future, only a single 2-D beam steering SLM will be needed). This deflected laser beam will then be directed toward the PR crystal as the reference-writing beam. It will meet the data carrying writing beam inside the PR crystal to form an interfering grating (hologram). Each individual hologram is written with a unique reference angle and can only be read out at this angle (or its conjugated one). By varying the reference beam angle in sequential recording, a very large number of holograms can be recorded in the recording medium.

For hologram readout, we have devised an innovative phase conjugation architecture. This phase conjugation scheme will enable lensless hologram readout with minimal distortion (low bit error rate). As shown in Fig.4, a second pair of transmissive and reflective BSSLMs combination will be used to provide a phase-conjugated readout beam (with respect to the writing reference beam). After the beam impinges upon the PR crystal, the diffracted beam from the recorded hologram will exit the PR crystal backtracking the input data beam path, due to the phase-conjugation property. It then directly impinges upon the photodetector array without the need for focusing optics and reconstructing the corresponding data page, as was recorded and stored in the PR crystal

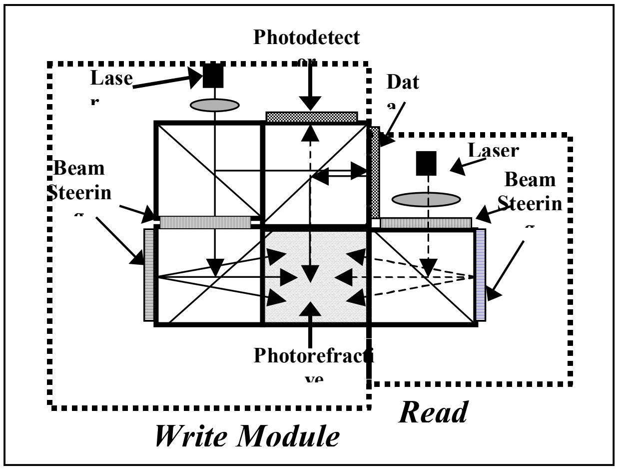

Figure 4. System schematic architecture of an Advanced Holographic Memory

BEAM STEERING SPATIAL LIGHT MODULATOR

JPL has recently collaborated with the Boulder Nonlinear System Co. (BNS) to develop a BSSLMS. This device is built upon a VLSI back plane in ceramic PGA carrier. A 1-dimensional array of 4096 pixels, filled with Nematic Twist Liquid Crystal (NTLC), is developed on the SLM surface. The device aperture is of the size of 7.4 mm x 7.4 mm, each pixel is of 1 mm x 7.4 mm in dimension. Currently, the response time can reach 200 frames/sec. In the future, by replacing the NTLC with Ferroelectric Liquid Crystal (FLC), the speed may be increased by at one order of magnitude (i.e. > 2000 frames/sec). A photo of this BSSLM is shown in Figure 5.

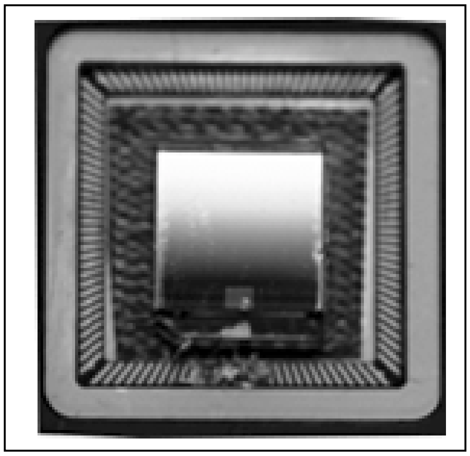

Figure 5 a photographic of a 1 x 4094 Beam Steering Spatial Light Modulator and a magnified view of the grating structure of the SLM.

The principle of operation of this BSSLM is illustrated in Figure 6. Since the SLM is a phase-modulation device, by applying proper addressing signals, the optical phase profile (i.e. a quantized multiple-level phase grating) would repeat over a 0-to-2π) ramp with a period d. The deflection angle q of the reflected beam will be inversely proportional to d:

$$\theta = \sin^{-1}(\lambda/d)$$

Where λ is the wavelength of the laser beam. Thus, beam steering can be achieved by varying the period of the phase grating

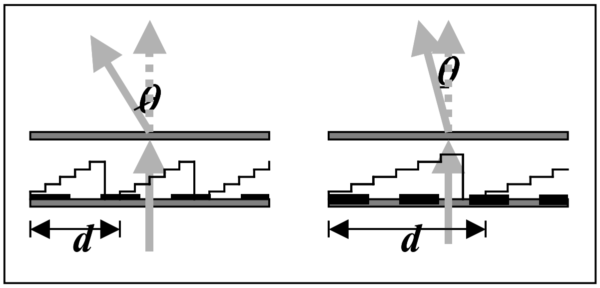

Figure 6. Beam steering using a phase modulation SLM with variable grating period.

The diffraction efficiency, η, of this device is

$$\eta = \left(\frac{\sin(\pi/n)}{\pi/n} \right)^2$$

Where *n*: number of steps in the phase profile. For example□η□~ 81% for *n* =4, and η□~95% for *n* =8.

Number of resolvable angles can be defined by:

$$M = 2m/n + 1$$

Where *m* is the pixel number in a subarray, and *n* is the minimum number of phase steps used. For example, *M* = 129 for *m*=512, *n* =8 with a 1 x 4096 beam steering device.

Primary advantages of using such an electro-optic beam steering device for angular multiplexing for holographic data storage include: No mechanical moving parts; Randomly accessible beam steering; Low voltage / power consumption; Large aperture operation; No need for bulky frequency-compensation optics as in AO based devices. It has been demonstrated at Caltech that up to 160,000 pages (i.e. 160 Gbs of memory) of hologram were stored in a $LiNbO_3$ PR crystal with 1 cm^3 volume using a scanning mirror to create angular multiplexing for each reference beam. However, the scanning mirror scheme that requires mechanically controlled moving parts is not suitable for space flight. In this proposal, we would like to develop an all electro-optic controlled angular multiplexing scheme with high-speed and high resolution. We have solved this problem by utilizing an all-phase beam steering device, the BSSLM.

Both transmissive and reflective BSSLMs are planned to use in the AHM system under development at JPL. The current transimissive BSSLM device is a 1 x 1024 array with resolvable spots at about 64. The reflective BSSLM device is a silicon-based 1-D diffractive beam steering device. The current device is a 1 x 4096 array, which has about 128 resolvable spots. Devices of a higher number of resolvable spots (around 180) will soon be available. Thus total resolvable spots from these cascaded BSSLMs would be around 11,520. By using two cascaded BSSLMs for beam steering, a total of more than 10,000 pages of hologram can be stored and read out in a single cubic centimeter of PR crystal. Since each page can store about 1000 x 1000 pixels of data (1 Mbytes), the total storage capacity will reach 10 Gigabytes.

Recently, we have also applied the AHM technology to support the massive data storage needs of an optical pattern recognition system

APPLYING THE AHM TECHNOLOGY TO SUPPORT MASSIVE STORAGE NEEDS OF OPTICAL PATTERN RECOGNITION

To date, an optical correlator [5] has been extensively developed and applied for pattern recognition. JPL has recently developed, for the first time, a compact grayscale optical correlator (GOC) for real-time automatic target recognition (ATR). As shown in Figure 8, this optical correlator employs a Liquid Crystal Spatial Light Modulator (LC SLM), with 8-bit grayscale resolution for input incoherent-to-coherent image conversion. In the Fourier transform plane, a bipolar-amplitude (i.e. real-valued) SLM is used to encode the correlation filter. The real-valued correlation filter encoding capability has enabled the use of a very powerful optimum filter computation algorithm, Maximum Average Correlation Height (MACH)[6], for distortion invariant correlation computation.

One of the major limitations for more versatile ATR using this GOC is the severe limitation size limitation of electronic memory. This GOC is capable for updating the correlation filter at a rate of 1000 frames/sec. Each filter consists of 512-pixel x 512-pixel with 8-bit grayscale resolution. Thus, to operate the correlator at full speed, the filter data throughput will be at 2 Gigabit/sec. This transfer rate is far beyond that of magnetic hard disk. Only SDRAM could be used with adequate data transfer rate. However, to save a modest number of 1000 filters on-board, it would need two Gigabits of SDRAM memory. The memory board size and power consumption is too excessive for many air and space-borne system to accommodate. Therefore we have looked into holographic memory as an alternative memory solution for real-time pattern recognition using a GOC.

Unique advantages of using holographic memory system for updatable optical correlator applications including high storage density, random access, high data transfer rate, and grayscale image storage capability. All these three characteristics very well meet the memory requirements of a GOC.

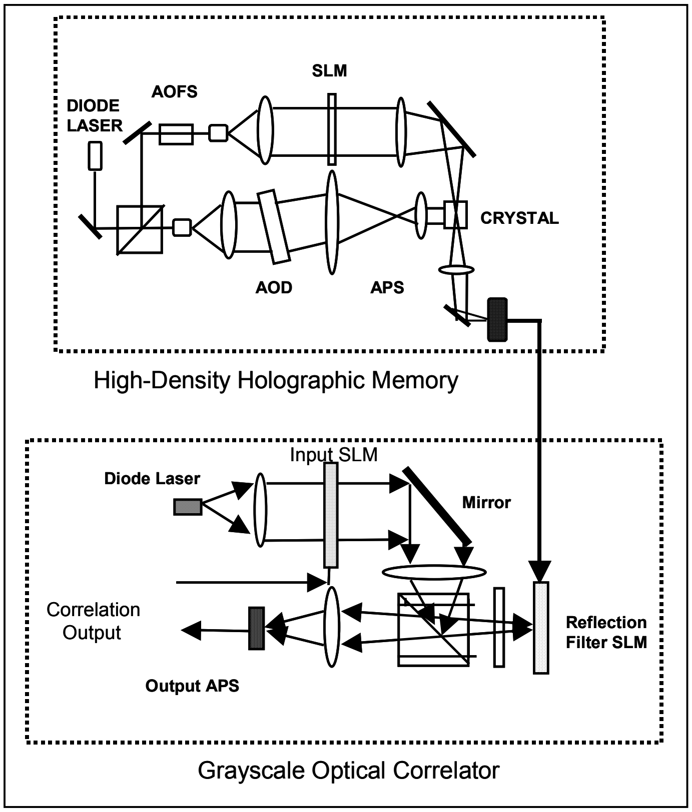

Figure 8. System architecture of an optical correlator using holographically stored and retrieved filter data for real-time optical pattern recognition. The readout data containing grayscale MACH filter data from a high-density holographic memory is directly fed into the filter SLM driver of a GOC to enable real-time ATR.

For real-time optical pattern recognition operation, a large bank of MACH correlation filters data would be first stored in an acousto-based holographic memory as shown in Figure 8. The readout holographic data would then be directly fed into the filter SLM driver of the GOC to support the high-speed filter updating needs.

EXPERIMENTAL DEMONSTRATION OF OPTICAL PATTERN RECOGNITION USING OPTICAL CORRELATOR WITH HOLOGRAPHIC MEMORY

JPL has developed a portable GOC with optically implemented MACH correlation filters [7-8].

A real-time optical pattern recognition experimental demonstration has been performed at JPL. During this experimental test, a JPL developed camcorder-sized GOC was used to perform real-time pattern recognition. A photograph of this camcorder-sized (8” x 4” x 4”) is shown in Figure 9. A CHDS breadboard was used to store and readout MACH correlation filters. The experimental steps are described as follows: First, a set of training images, as shown in Figure 10(a) was selected for developing MACH correlation filters. The image of one of these MACH filters (with 8-bit dynamic range) is shown in Figure 10(b). Second, these MACH filters were recorded into our CHDS breadboard and then subsequently readout and downloaded into the filter driver of the GOC. The dynamic range of the retrieved holographic filter image was carefully preserved to retain the 8-bit resolution.

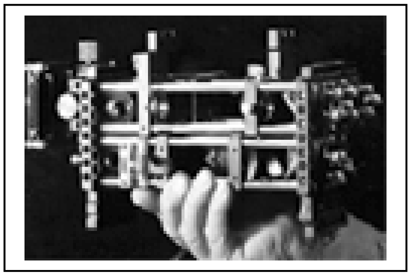

Figure 9. A picture of the JPL developed camcorder-sized Grayscale Optical Correlator designed for pattern recognition.

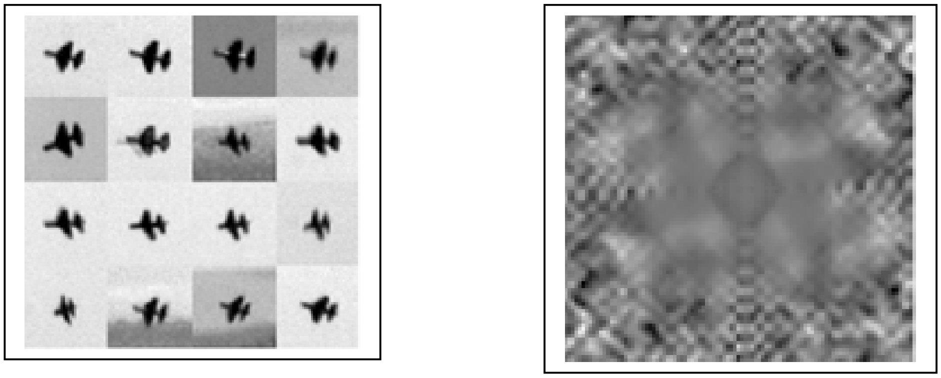

Figure 10. (a) Training image set of a test flight vehicle used for MACH correlation filter computation; (b) A corresponding 8-bit grayscale MACH filter to be stored and retrieved from a holographic memory system.

Third, after the holographically retrieved MACH filter image was downloaded into the filter SLM of the GOC, a video of input scene recorded from a previous flight test, was fed into the input SLM. Sharp correlation peaks associated with the input target in various rotations, scale and perspective were successfully obtained from the correlation output. Some of the correlation output results are displayed in Figure 11.

CONCLUSIONS

We have discussed an advanced holographic memory system for massive, high-transfer rate data storage applications. The development goal of the performance of the memory technology includes: high storage capacity (10 Gigabytes per module), high-speed (1ms per page), and low power (100mW laser power for writing, 10mW for readout).

We have also demonstrated the potential of optical pattern recognition using correlation filters retrieved from a holographic memory system. Experimental results demonstrated that the high fidelity of the holographically stored grayscale filter images was capable of executing distortion invariant optical pattern recognition. The high-density, high transfer rate, random accessibility, and grayscale data storage capability of the holographic memory make it an ideal alternative for replacing conventional semiconductor memory used in the state-of-the-art optical correlator.

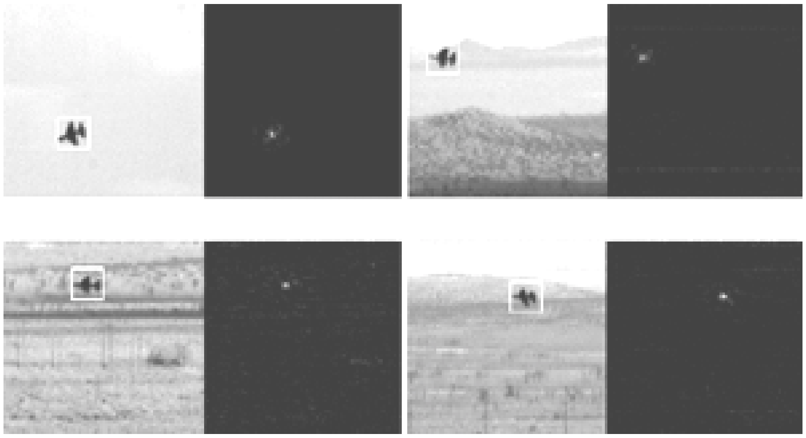

Figure 11. Experimental results of pattern recognition of a test flight vehicle obtained using a GOC using holographically stored MACH filter.

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