Design Aspects of an Optical Correlator Based CNN Implementation

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Abstract **– Optical correlators provide efficient optical implementation of the CNN computers with high parallelism. A semi incoherent optical correlator with design considerations is presented. Theoretical and experimental study of an optical feed-forward processor using bacteriorhodopsin (bR) as a dynamic holographic material and a 2D acousto-optical deflector (AOD) for the implementation of the reconstructing template is given. Special attention is paid for the choice of the optical architecture, what can serve our goals the best. General definition of the requirements against dynamic holographic materials applied in optical processors is given in a previous paper of us [14] and a detailed specification and functional model of the bacteriorhodopsin based dynamic memory is worked out. Some preliminary correlation results are shown to corroborate the feasibility of this approach.**

1 Introduction

Purpose of this paper to show that using a special optical correlator we are able to implement optically efficiently a feedforward-only CNN. So far only a few attempts were made for the optical implementation of the CNN paradigm [1-3]. Main advantages of optical implementations are the higher order parallelism – each template operation can be fulfilled on a few million pixel images - and the applicable considerably greater template sizes. Attainable frame rate of the optical correlators is only slightly smaller than its VLSI counterparts. Since fast, stored programmability and local analog memories and nonlinearities are essential components of the CNN-UM's high computational performance, we intend to use our optical CNN implementation within a so-called POAC (programmable opto-electronic analogic CNN) computer framework [4, 5]. In this framework rapidly (re-)programmable large neighborhood operations are accomplished by an optical CNN, while the correlation detection and further necessary (e.g. adaptive nonlinear) processing is done by a VLSI CNN-UM chip [6]. Furthermore, the CNN paradigm [7-9] provides efficient algorithmic frame for optical correlators.

The optical correlator, that we introduce here, is based on fundamentally new ideas. It is superior, from several different points of view, to other known correlator architectures. First we introduce our optical correlator, optical CNN implementation (2). Its basic structure will be given and with its comparison to other existing optical correlators. Next, basic characteristics of the applied tools and materials will be described (2.2; 2.3). Later we shall express some design aspects of the optical CNN, especially from the optical architecture point of view (2.4). Feasibility of our approach will be demonstrated with some of our experimental results (3). We shall discuss the already achieved and in the near future attainable computational performance (4). We analyzed also the ways, how it can be accomplished. Here we outline the bottlenecks of this approach and show some possible ways to overcome these limitations. Finally, (5) we shall conclude our results.

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2 Optical correlator

In the majority of the correlator applications – especially those, which are incorporated in stock products – VanderLugt type of correlators (VLC) are used [10-12]. In these approaches Fourier domain filtering takes place. Although this method favorable from energetic point of view, it needs slow, offline construction of complex, computer designed holographic filters, corresponding to the desired templates (reference objects). Nevertheless, VLC is extremely sensitive for exact positioning of the elements. Joint transform correlator (JTC) [13] – an alternative optical correlator with several advantages comparing to VLC [4] - is also sensitive for the phase errors of the optical system, which seems to be unavoidable if we use liquid crystal spatial light modulators (LCD) as input elements. However from our previous studies we concluded, that within a JTC-like architecture we could use reference objects, i.e. templates in the reconstruction step, while in the recording step we applied only a parallel reference beam. In this way after each hologram recording step a great number of reconstructions, correlation evaluation steps can be completed.

2.1 Semi incoherent optical correlator

To incorporate all advantages of the JTC correlators and to overcome its sensitivity to phase inaccuracies we invented a semi incoherent correlator. It evaluates correlation in two consecutive steps. In the first step a hologram of the input image is recorded in a special transient holographic material (bacteriorhodopsin films (2.2)). In the following step (steps) we reconstruct the recorded hologram with specially adjusted parallel laser beams, which correspond to the different template pixels. These beams are coherent but mutually incoherent. The above mentioned angular coding of the template pixels is accomplished by a 2D acousto-optical deflector (2.3) followed by a beam expander (telescope). This way, each beam reconstructs an appropriately shifted version of the original image. In the correlation plane, on the sensor's surface, these reconstructions overlap and form a correlogram. Schematic view of the correlator can be seen in Fig. 1.

Individual reconstructions are mutually incoherent due to the AO deflector caused different Doppler shifts and time difference. This way, although both the holographic recording and reconstruction are coherent, the shifted images are summed incoherently. Incoherent correlation is especially beneficial, when different kinds of phase errors are present in the system.

2.2 Bacteriorhodopsin

In one of our earlier investigation we summarized the Bacteriorhodopsin (BR) biological, physical and chemical properties and concluded that it is exceptionally suitable for our goals (details can be found there [14]). BR is a transient holographic material with extremely high resolution (5000 lines/mm). This resolution even exceeds the ordinarily applied optical system's capabilities. The BR's ground state, Br (absorption maximum is at 568 nm) can be driven to M state (absorption maximum is at 400 nm) by adequate illumination. This way we can record a holographic pattern into the material. The pace of hologram recording step is determined by the speed of the photocycle: Br→…→M→…→Br. It can be as fast as 50-100 μsec. However, due to the limited laser power and LCD speed, in our first model we intend to use it only at a slightly higher frequency than the video frame rate (30-180Hz). Measured diffraction efficiency of our BR samples almost reaches the 1% value.

2.2 Acousto-optical deflector

To implement the required, appropriately shifted reconstruction we applied a 2D acousto-optical deflector. Physical limits of its speed is under 1 μsec per template pixels in the used TeO_2 AO deflector, but due to the present electronic driver's limitations we were able to reach only ~30 μsec/pixel speed. In the following versions of the correlator we shall use a driver which has much higher speed (1 μsec limit is easily achievable). The available frequency bandwidth of the AO deflector was 20 MHz, which produces a 22 mrad angular deflection bandwidth. Within this deflection range we can set 128 frequencies. This way we are able to implement up to 128 by 128 pixel templates, but due to device's speed and angular bandwidth limitations we used only 32 by 32 size templates. In the applied 2D AO deflector the overall diffraction efficiency reached the 40% value.

2.3 Design aspects

Input images were recorded in two kinds of hologram setups: using a Fourier optic lens or without lens. The former one can be used also for nonlinear processing utilizing saturation effects of BR in the spatial frequency domain. Lensless version is simpler, but the input image size is more limited. Viewing angles of the pixel pitches of the input SLM and that of the template SLM has to agree to get correlation. Using of a 2D AOD only a virtual template was realized, but the gained correlation results were better than

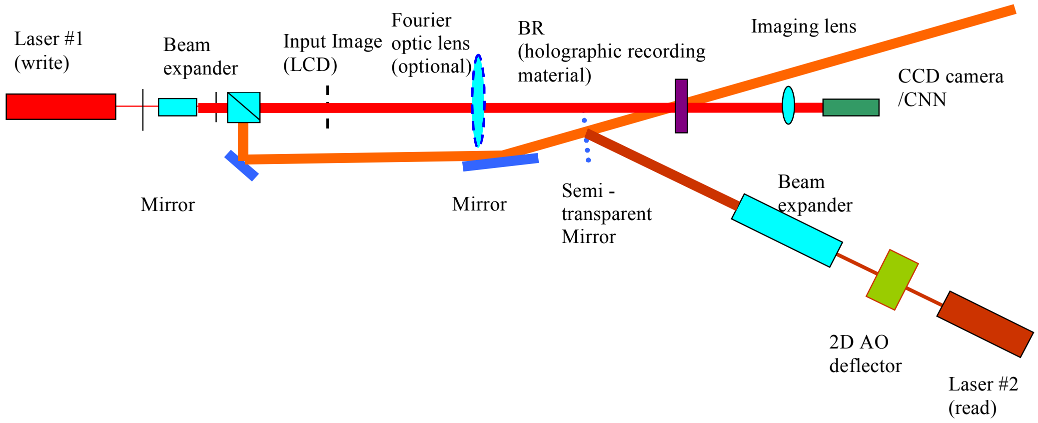

Figure 1: Semi incoherent, acousto-optical deflector based Optical CNN implementation.

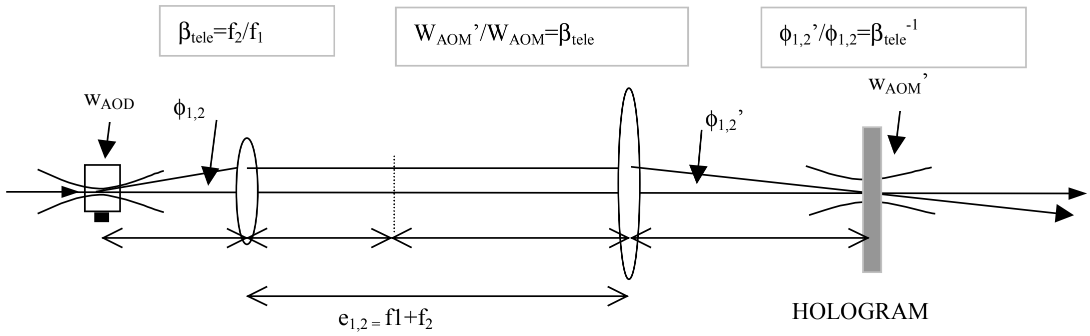

Figure 2: A telescopic (afocal system) enlarges the laser spot to match the hologram aperture while decreases deflection angle by β_{tele}.

with a real SLM. Largeness of the reference beam and reconstructing beams had to be adjusted to cover the whole hologram surface, determined by the input image size (in lensless case) and extent of its first order diffraction pattern. In the case of Fourier setup the input pixel pitch and the focal length of the Fourier lens determine it. As can be seen in Fig 2 there is inverse relationship between spot size and angular magnification. So the speed of the AOD and its angular bandwidth is limited due to the required beam expansion.

Pre-processing of either the input image or more advantageously the template improved correlation discrimination. A Visual CNN-UM chip will do all the necessary post-processing of correlograms. Preliminary simulation results showed its high potentiality.

3 Results

Based on the above assumptions we built a breadboard model. Overall structure and photo of the semi-incoherent correlator can be seen in Fig. 3

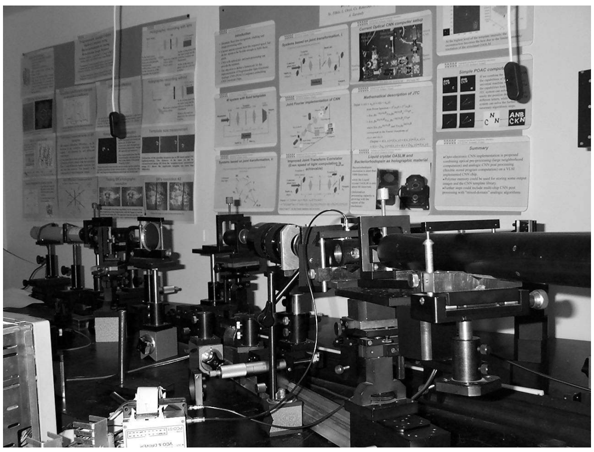

Figure 3: Photograph of our semi-incoherent optical CNN setup.

We were able to implement optical correlations effectively with our semi incoherent optical correlator. A sample of our preliminary results can be seen in Fig. 4.

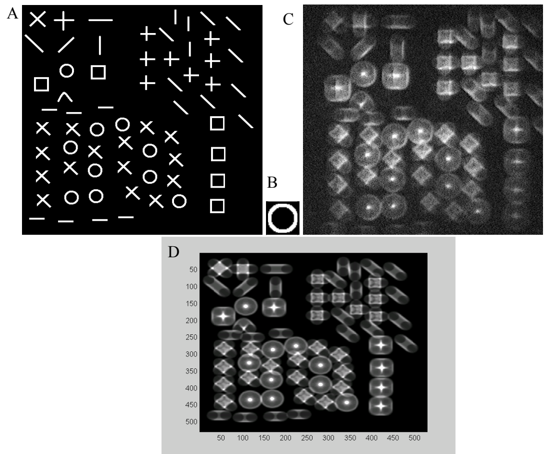

Figure 4: You can see the measured correlation result (C) of our optical correlator, between an input test pattern (A) (500x500 pixels) and a reference template (B) (30x30 pixels). Although, due to the uneven illumination, some parts of the correlogram exhibits moderate brightness, the comparison of the measured and computer generated correlogram shows satisfying agreement. (Computer generated correlogram was displayed in constrained dynamic range to model the CCD camera's gain control mechanism, which is the main reason of the correlation peaks' degradation.)

Speed of the current setup reached the video frame rate. Further speed-up can be obtained applying a more appropriate AO driver. This was not yet done, because the main bottleneck of the current setup (and majority of the other correlators as well) is the limited speed of the sensory (CCD) device.

Quality of the correlation results will be improved considerably in the near future, applying more appropriate beam expanders, better quality BR films and improved optical architecture.

As we intend to use this optical CNN implementation within the POAC framework, serial downloads of all the intermediate correlograms are not necessary. In the POAC framework a VLSI CNN-UM chip will be the sensory device, what it can fulfill all the required further processing tasks. So only the final output, the concluding results will be the output of the system. This way we can overcome the conventional systems' bottleneck caused by the basically serial readout.

To fulfill more complex CNN operations by this implementation, the adaptively thresholded correlograms can be fed back to the optical CNN's input SLM. This way another B-template operation can be accomplished on the result.

If the template size increases, due to the AOD produced fundamentally serial reconstruction, the whole systems performance drops. By alternative scanning mechanisms (e.g. with a vertical cavity laser array or appropriate micro-mirror devices) the speed of the reconstruction can be further enhanced and the size of the correlator can be dramatically decreased.

4 Further prospects

In the near future we intend to apply a much faster AOD driver in our optical CNN implementation, beside utilization a much faster CMOS or CCD camera. Applying a fast and controllable detector seems to be essential due to the camera's undesired gain control effects. We can further decrease size and complexity of the correlator by application of appropriate diode, or miniaturized diode pumped solid state lasers. Applying only one laser by a suitable modification of the current optical architecture seems to be promising. After completing these modifications the speed of our optical CNN implementation will reach 10^{12} operations per second.

5 Conclusions

We have built a breadboard model of an optical CNN implementation and demonstrated that our new semi-incoherent correlator architecture is functional and superior to the totally coherent ones. Its computational power can compete even with the VLSI CNN implementations. However, a hybrid architecture (POAC), including our large neighborhood optical CNN correlator and a visual CNN-UM chip, has the greatest promise.

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