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Efficient optical implementation method for symbolic substitution logic based on shadow casting

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A new method based on shadow-casting principles is introduced for implementing symbolic substitution logic. The key features of this new method are: energy efficiency, system flexibility, generality, and programmability.

The primary advantages of optical systems are the massive fine-grain parallelism and the high degree of interconnections and communication capabilities. These attributes coupled with the escalating demands for computational power and speed are motivating computer scientists to design parallel optical computers that will provide a quantum leap over electronics in high speed parallel processing.[1] Major research efforts are being made both for analog as well as digital optical computing. Among the wide variety of techniques that have been proposed for digital optical computing, optical symbolic substitution logic (SSL) introduced by Huang,[2] and optical shadow casting (or optical pattern logic) introduced by Tanida and Ichioka,[3] have gained wide popularity. In this Communication I briefly describe these techniques and their limitations and then introduce a hybrid implementation system that takes full advantage of the best features of the two computing schemes.

To compute combinatorial logic functions a lensless shadow-casting system with a light emitting diode (LED) array as an incoherent light source has been proposed.[3] In this system, divergent light beams radiating from the LED array (representing the source plane) illuminate spatially encoded patterns (representing the input plane) and project multiple interlaced shadowgrams of the input plane onto a screen. The projected shadowgrams are then decoded through a decoding mask. The decoded image corresponds to logical operations of the encoded input images. This technique is attractive for computing combinatorial functions because it is parallel, programmable, and cost-effective. However, it has several unavoidable drawbacks such as input image coding and the lack of cascadability (the output plane is no longer compatible with the input plane).[4] Nevertheless, extensive research is being conducted by its inventors to overcome these drawbacks.

Symbolic substitution (SS) is a pattern transformation technique for performing digital logic optically. In this method, data are encoded as spatial patterns and operators are seen as pattern transformation rules or SS rules. In its operation, SSL consists of two pattern processing steps: (1) a recognition phase where all the occurrences of a search pattern (representing the left-hand side of a SS rule) are simultaneously searched in the input plane, followed by (2) a substitution phase where a substitution pattern (representing the right-hand side of a SS rule) is substituted in all the locations where the search pattern is found. Theoretically, this method seems to exploit a high degree of optics parallelism both at the implementation level as well as the processing level.[5] At the implementation level, each of the two steps (pattern recognition and pattern substitution) can be carried out in parallel and in constant time (at least for a given SS rule). At the processing level, each SS rule can be applied to several sets of data and several SS rules can be carried out in parallel.

The most widely used approach for the parallel implementation of SSL applies a thresholding operation to a composite of shifted replicas of the input image (where an input image in this case represents several sets of data).[6] Depending on the coding scheme, the recognition phase can be made to recognize patterns of ones, patterns of zeros, or patterns of zeros and ones. To simplify the design, dual-rail coding was used.[6,7] Assuming dark pixel recognition, the input image is replicated as many times as there are dark pixels in the search pattern and each replica is shifted horizontally and/or vertically by an amount that brings a corresponding dark pixel to a designated reference pixel. These shifted replicas are then superimposed and the resulting image is inverted via a NOR-gate array. The output of the NOR-gate array is passed through a mask and the masked output is known as the recognition plane. For each bright pixel in the substitution pattern, a replica of the recognition image is made. These replicated images are then shifted by an amount corresponding to the position of the bright pixels in the substitution pattern. These shifted replicas are optically ORed (via superimposition). Although this method of implementation is simple and straightforward, it cannot be used in practice for the general case because of the following problems:

The number of replicated image grows linearly with the number of pixels in the search pattern for the recognition phase and with the number of pixels in the substitution pattern in the substitution phase. For a pattern with N pixels, the input image must be replicated N times. For $N = 2$, this can be easily implemented using geometric optics or holographic techniques.[6,8] However, for $N > 2$, the implementation method becomes impractical, since this requires a 1-to-N image splitter and consequently an energy loss of $1/N$ at each iteration.

The amount of shift applied to each replicated image depends on its location with respect to the origin pixel. For a pattern with N pixels, the replicated images have to be shifted up to N locations. This can also become a problem

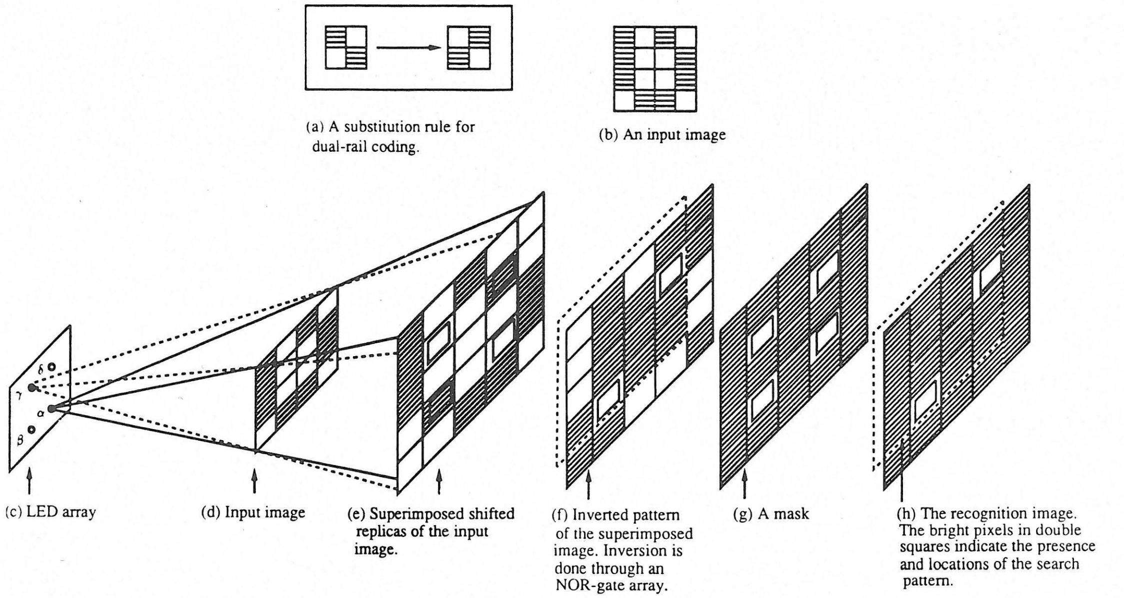

Fig. 1. Implementation of the recognition phase of symbolic substitution logic using shadowgrams: (a) example of a dual-rail logic symbolic substitution rule; (b) input image; (c) LED configuration; (d) input image; (e) superimposed image; (f) output of the NOR-gate array; (g) inverted image masked via mask M; (h) recognition image.

for simple optical shifting methods. Complicated shifting methods can be used at the account of less parallelism and lower processing speeds.

Holographic elements can in theory be used to losslessly combine several images; however, the space–bandwidth product (SBWP) available to each SS rule becomes inversely proportional to the total number of rules. A system with M SS rules has only $1/M$ of the overall SBWP available per rule.

Programmability of an optical symbolic substitution system based on the known implementation methods seems to be difficult. The programming method proposed by Brenner[9] for SSL reduces the computational power of the system and limits its flexibility. In Brenner's methodology, the data plane is partitioned into data and control pixels where each data pixel is controlled by two control pixels. The resulting data plane contains more control pixels than data and therefore less data points are processed at each step.

In this Communication, I propose an implementation method for symbolic substitution logic that circumvents the limitations stated above. In this hybrid method, a shadow-casting technique is used to provide the lossless and faster image replication and spatial shifting. These two operations are fundamental to the parallel optical implementation of SSL and were identified as bottleneck in previous implementations. The geometric configuration of the lensless shadow casting is identical to the one proposed in Ref. 3. By choosing the spacing between the LEDs and distance from the source plane to the input plane and from the input plane to the screen, we can obtain replicated and shifted copies of the input plane superimposed on the screen. The number of replicas and the amount of shift are a function of the ON–OFF switching states of the LEDs, which in turn depend on the structure of the search and substitution patterns. The method is general and can be applied to complex SS rules rather than just to a small set of SS rules of predefined shape.[6]

Using dual-rail logic, the binary values 0 and 1 are represented by two pixels (dark-bright pattern for 0 and bright-

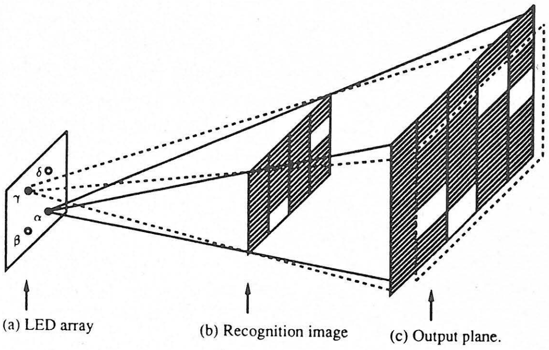

Fig. 2. Implementation of the substitution phase of symbolic substitution logic using shadowgrams: (a) LED configuration; (b) recognition image; (c) output image.

dark patterns for 1). This encoding implies that the input image, the search pattern, the substitution pattern, and the output image contain as many dark pixels as there are bright pixels. The method is best illustrated by an example. Figure 1(a) shows the SS rule that we implement using shadow casting, and Fig. 1(b) shows the input plane to which this rule is applied.

We assume a dark-pixel pattern recognition. The recognition phase is shown in Figs. 1(c)–(h). First, we need two replicas of the input plane corresponding to the two dark pixels present in the search pattern. These two replicas need to be shifted and superimposed on the screen such that the two dark pixels overlap in a reference location. The reference pixel is chosen to be the low-right pixel of the search pattern. The replication, shift, and superimposition are accomplished by the LED configuration shown in Fig. 1(c), where LEDs (α,γ) are in the ON state and LEDs (β,δ) are in the OFF state. The plane of shifted and overlapped repli-

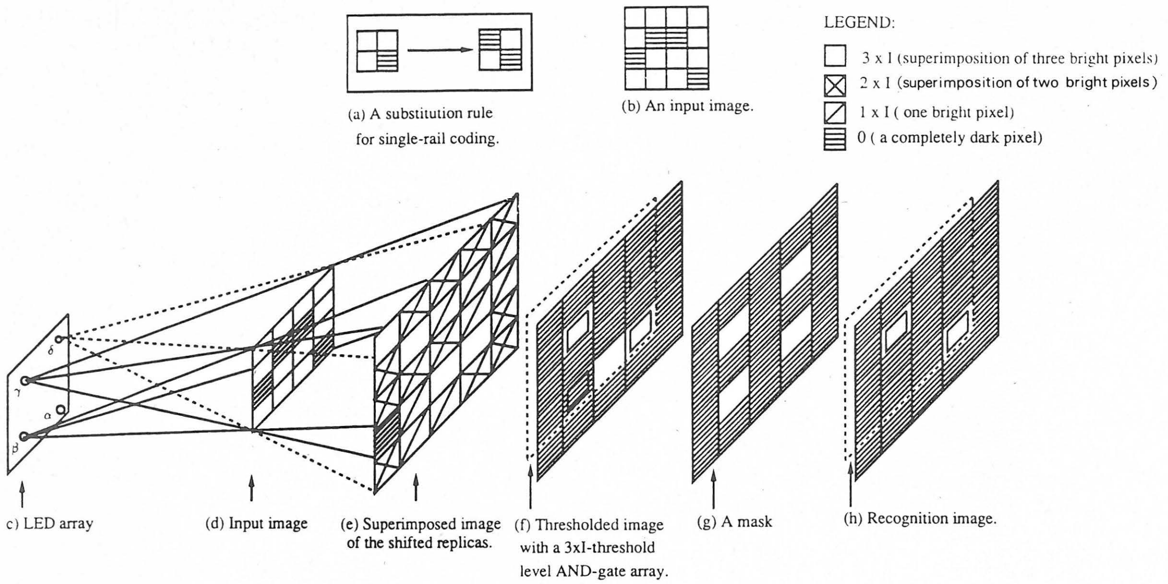

Fig. 3. Implementation of the recognition phase assuming single-rail logic and AND type thresholding: (a) example of a single-rail logic symbolic substitution rule; (b) input image; (c) LED configuration; (d) input image; (e) superimposed image; (f) superimposed image thresholded through an AND type optical nonlinearity; (g) mask; (h) recognition image.

cas is shown in Fig. 1(e), where the double square pixels represent search pattern reference locations. The superimposed image is incident on a NOR-gate array [Fig. 1(f)] whose output leaves the dark pixels of the superimposed image in the bright state. The inverted image is passed through a mask [Fig. 1(g)] that contains a transparent square in every other square and is opaque everywhere else. The location of the transparent squares on the mask coincides with the reference pixels in the inverted image. Therefore, all bright pixels after the mask indicate the presence and location of the search pattern in the input image Fig. 1(h)].

Once the occurrences of the search pattern are located in the input plane, the next step is to scribe the substitution pattern at every bright pixel of the mask output. This step is shown in Fig. 2. The LED array configuation of Fig. 2(a) provides a superimposed image of shifted replicas of the recognition plane. The replicas are shifted and superimposed with the net result that the substitution pattern is scribed in all the occurrences of the search pattern as shown in Fig. 2(c). The LED configuration is dictated by the placement of the bright pixels in the substitution pattern. In this particular example, the same LED configuration is used for recognition and substitution phases.

The method described above implements dual-rail coding logic. However, the same optical setup can implement single-rail coding of arbitrary patterns. In single-rail coding, the logical values 0 and 1 are represented as dark and bright pixels, respectively, without their complements. In this general case, the NOR-gate array required for the recognition phase is replaced by a thresholding AND-gate array with a threshold level depending on the number of bright pixels in the search pattern. Let us assume bright pattern recognition and apply the SS rule shown in Fig. 3(a) to the input image of Fig. 3(b). By making the three LEDs (β,γ,δ) ON [Fig. 3(c)] we get the three replicas of the input plane onto the screen; each replica corresponds to one bright pixel of the search pattern and is shifted accordingly [Fig. 3(e)]. The superimposed image [Fig. 3(e)] is impinged on the threshold AND-gate array whose threshold level is three (corresponding to three bright pixels in the search pattern). Bright pixels in the reference pixel of the search pattern in the output of the gate array indicate the locations of the search pattern in the input plane Fig. 3(f)]. This output is passed through a mask [Fig. 3(g)] that filters out erroneous pixels, and the resulting image is then fed to the substitution phase whose LED configuration is shown in Fig. 4(a).

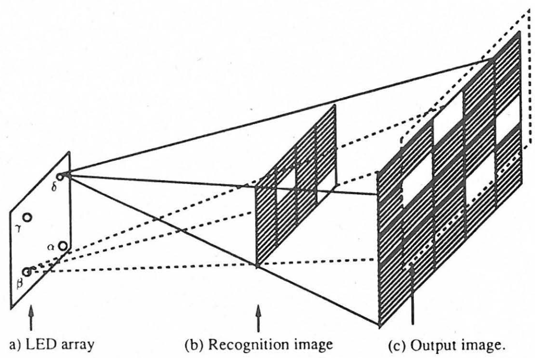

Fig. 4. Implementation of the substitution phase of a single-rail logic symbolic substitution rule: (a) LED configuration; (b) recognition image; (c) output image.

This new shadow-casting implementation method of symbolic substitution has the following advantages over conventional schemes:

(1) Instead of performing energy inefficient image replication and spatial shifts through beam splitters, shadowgrams of the input image are generated and superimposed.

(2) Unlike the implementation method described in Ref. 6, where the optical setup is hardwired to implement only patterns of 2 × 2 pixels, the new method is flexible in that the same optical setup can implement SS rules of any shape by simply adjusting the LED configuration.

(3) The new system is programmable. By programming the ON–OFF states and the configuration of the LED array,

different operations can be carried out. Moreover, the programming methodology does not limit the computational power of the system since the data plane is entirely reserved for data points rather than data and control pixels as in Ref. 9.

(4) The system is cascadable since the input and output are of the same form; no decoding is required. In addition, signal regeneration may not be as severe as in previous methods because of the lossless replications and shifts.

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