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Logical equivalence of optical symbolic substitution and shadow-casting schemes

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The logical equivalence between two powerful optical computing techniques, namely, optical symbolic substitution and optical shadow-casting is investigated. A common basis for both schemes is developed and their roots are traced back to fundamental principles of logic design. Both shadow-casting and symbolic substitution based optical computing operations are shown to be equivalent to logical sum of product operations.

1. Introduction

Optical symbolic substitution (OSS) is a powerful technique for performing digital optical computing/processing on two-dimensional (2D) information [1]. In this scheme, a specific group of spatially oriented 2D patterns present in the input is first recognized. Another set of spatially oriented 2D patterns is then substituted in that location. Such logical operations are performed via a variety of OSS systems by a combination of splitting, shifting, and overlapping operations. The optical shadow-casting (OSC) system [2,3], on the other hand, executes single instruction on multiple data in parallel. In the OSC scheme, computations are done on spatially encoded 2D binary pixel patterns composed of transparent, opaque, and vertically and horizontally polarized subpixels. The set of to-be-processed encoded inputs are placed in contact at the input plane of the OSC system. The resulting overlapped input is illuminated by a set of spatially positioned LEDs thus resulting in an overlap of projected shadows. A decoding mask placed at the output is able then to decode and detect the output. Both OSS and OSC schemes can be used to accelerate the updating of the states in a modified finite state machine by utilizing the parallelism of optics [1].

The purpose of this communication is to point out the logical equivalence between OSS and OSC schemes. First, an algorithmic equivalence of the two optical data processing techniques is identified. Then in the next section, the first proposed implementation of OSS is analyzed step by step and the detailed analogy of OSS and OSC is elucidated. Their methodologies and roots are shown to be based on the fundamental principles of digital logic design. Both OSS and OSC execute optical computing operations based on certain sets of logical function specifications each of which can be expressed as a logical sum of products (SOP) [4]. Thus one can exploit well developed digital design techniques for designing digital optical computing units, such as those used in polarization-encoded optical shadow-casting (POSC) scheme [4]. In addition, systematic approaches may be identified for the design and analysis of any given optical computing module.

2. General equivalence

The OSS scheme implements or resembles a parallel memory search process where the to-be-recognized pattern serves as the address and the to-be-substituted pattern serves as the corresponding content of the memory or truth table [5,6]. However, depending on the algorithm of implementation the physical memory may [7–9] or may not [10,11] be distinctly identifiable. In some algorithms [10,11], the recognition and substitution phases automatically generate the address and substitution pattern, respectively. It has been shown that the OSC scheme is capable of performing logical operation of two or more input variables by changing either the LED pattern or the input encoding. In other words, a particular combination of inputs is first selected (recognized) by means of encoding and/or LED patterns and then a single [2] or multiple [3,12,13] outputs are substituted. Thus OSC system inherently performs a symbolic substitution operation [14].

3. Generic OSS and OSC systems

In OSS systems, the two-dimensional information is encoded according to a specific pattern-rule. In particular, in the case of the dual rail coding, a binary number may be encoded either by a black and a white pixel with the relative position of the two pixels depending on the input value [10], or by the directions of polarization [11,15]. From the point of view of bright true or positive logic [16] (where transparent region or presence of light denotes a binary 1), the OSS system may simultaneously provide the presence of both the input and its complement.

To recognize the occurrence of a specific pattern in an input, depending on the number and location of opaque pixels present in the to-be-recognized pattern, a number of shift and overlap operations are executed. For example, to recognize the pattern shown in fig. 1, each of the two copies (corresponding to the two opaque pixel subcells) of the image is shifted in a way that the corresponding opaque pixel subcell appears at the lower left pixel subcell (designated as the origin) and then these two relatively displaced images are overlapped. By the specific combination of shift and overlap operations, an opaque pixel is generated at each of the locations where the to-be-recognized patterns occur. A subsequent complement operation inverts all the pixel values and hence results in a light output at the corresponding location of the origin, which is decoded by means of a mask. The purpose of the mask is to collect light through the origin of each pattern. These bright outputs denote the presence of the said pixel pattern in the input. During the substitution cycle, the scribe pattern is generated from these recognized bright pixels. For generating the to-be-substituted pattern, the pattern with the bright pixels are copied, shifted and then overlapped so that they may pro-

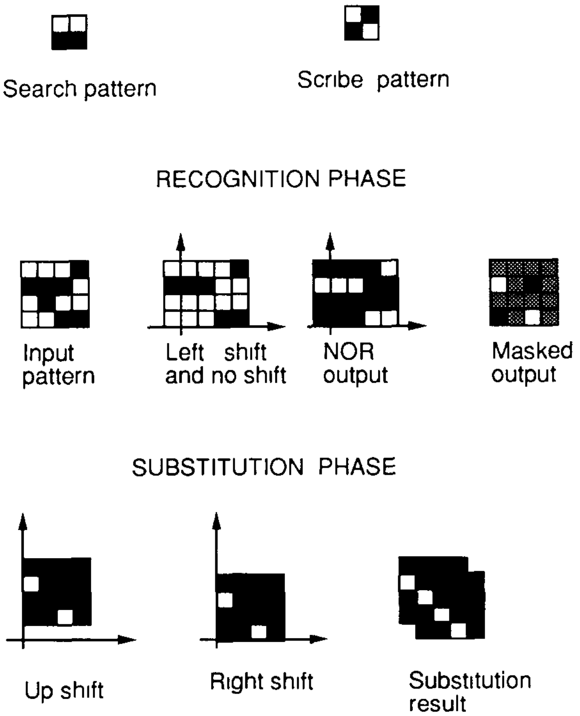

Fig 1 The recognition phase superposition of relatively shifted copies of the input, subsequent inversion, and recognition using masking operation, and the substitution phase: generation of the scribe pattern by overlapping two copies of the recognized output

duce the scribe pattern as shown in the recognition phase of fig. 1. Here one assumes that only the bright pixels need to be generated while the dark pixels are generated by default

Examining the above process in accordance with Boolean logic [4], one notes that the overlap of dark pixels in the OSS is equivalent to an OR operation of the inverted inputs [16]. The inversion at the very end of the recognition cycle completes an INVERT–OR–INVERT operation which by De Morgan's law [4] is equivalent to an AND operation. Then again in the substitution cycle, shifts and overlap of bright pixels regenerate the bright pixels of the scribe pattern. This latter overlap operation is exactly equivalent to an OR operation. Thus the complete sequence of an OSS operation is equivalent to an SOP logical operation.

In the OSC scheme, inputs are encoded into separate planes as shown in fig. 2 and they interact with each other via overlap. As a result, certain locations of the input overlap pattern become transparent with respect to an unpolarized light source [3]. The overlapping of the encoded inputs in this case is nothing but executing multiple AND operations with each input being represented by a separate plane. In particular, by examining the POSC design algorithm [3] for realizing a particular truth table, one observes that the inputs are encoded in such a way that different minterms (corresponding to the nonzero outputs of the truth table) upon overlap produce a transparent pixel. Such transparent overlap pixels correspond to the occurrence of a certain combination of inputs. Thus this overlap phase of POSC scheme is equivalent to the recognition phase of OSS

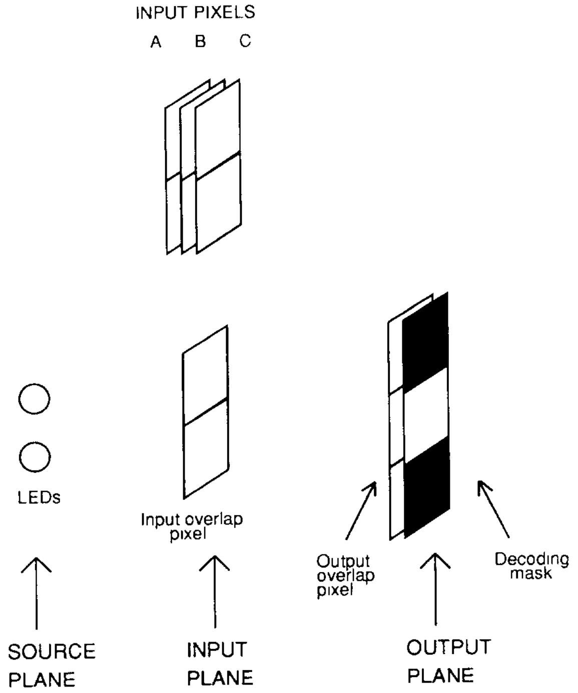

Fig 2 An optical shadow-casting system

Next, in the OSC scheme, substitution operation is accomplished by means of LEDs projecting shadows of the input overlap pattern to the output plane. The position and characteristics of LEDs (i.e., on, off, vertically polarized, and horizontally polarized) are chosen such that the transparent openings (similar to the recognition of bright pixels) can project light at specific locations of the output plane [17,18]. In other words, LEDs are instrumental in causing predetermined shifts and overlap of the shadows of the input overlap pixels. This phase of the POSC scheme is thus analogous to the substitution phase of OSS where one shifts and overlaps the bright pixels to recreate the desired output. The overlap of the shifted shadows in POSC is equivalent to an OR operation since the output is a 1 having received light from one or more transparent openings located at different spatial locations. Therefore the OSC scheme operates exactly same as the OSS scheme by having recognized the occurrence of different input conditions of a truth table and substituted the appropriate output. In fact, POSC scheme is capable of performing multiple recognition and substitution rules of symbolic substitution logic in parallel [3,13]

In OSS, all the inputs remain in the same plane in an interleaved fashion. This particular data arrangement allows the OSS to be different from OSC in the execution of AND operations in the recognition phase. Since the inputs are in the same plane, the only way the data can interact easily in optics is by projecting light through each pixel to a common point thus performing an OR operation. But in order to convert the OR to an AND, one needs to invert the input before and after the OR operation. The final OR (in the substitutional phase) is same in both OSS and OSC schemes. Again, since any arbitrary logical operation can be expressed as a sum of products, both

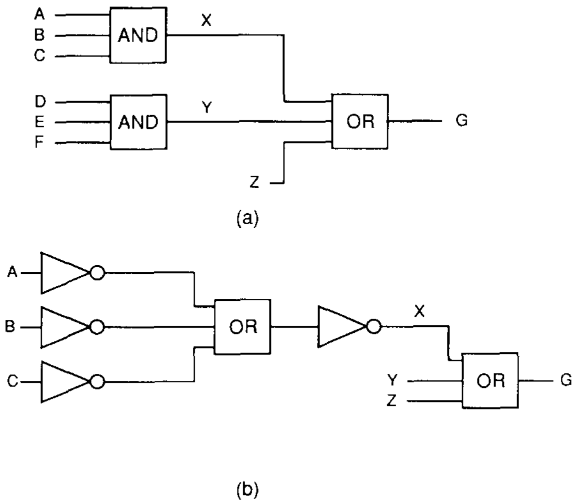

Fig 3 Digital analog of the SOP implementations in (a) OSC, and (b) OSS

OSC and OSS schemes are capable of realizing any logical and/or arithmetic function. This is illustrated in fig 3. The logical expression for the output function is given by

$$G=ABC+DEF+Z=(A'+B'+C')'+Y+Z\,, \qquad (1)$$

where the prime on the literals denote an inversion operation. Note that the AND operation is achieved differently in fig. 3a OSC and fig. 3b OSS.

It must be noted that in some of the OSS systems such as those using optical phase conjugation [19,20] AND operation is done directly without any pre- or post-inversion. Again since the recognition phase of OSS is nothing but a pattern recognition process, a correlation operation can be carried out either by matched filtering [21], or by phase-only holograms [22–24] to recognize the output. A consecutive convolution operation can then perform the necessary substitution operation [21]. The correlation (convolution) operation is analogous to AND (OR) operation in digital logic. Note that a correlation output is produced if and only if both the input and the matched filter for the input pattern matches (are present).

4. Conclusion

Both OSC and OSS operations are based on the familiar SOP form of logic formulation. Differences exist amongst different OSS systems and between OSS and OSC systems in the exact realization of the shift, overlap, inversion, and OR operation implementations [25]. Tilted mirrors, phase only holograms, wedge prisms [22,24], amplitude gratings [26,27], or reconfigurable interconnects [28] may be used to such effects. However, the existence of a common basis for both of these operations suggest that logical functions that are realizable using OSS scheme may also be realized using OSC scheme. Not surprisingly, algorithms suitable and proposed for OSS systems such as carry free addition [29,30] has already been implemented using OSC system [31,32]. Architectural advantages of both OSS and OSC may be combined to get more practical and powerful computing algorithm [33]

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