Random Access Camera

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Abstract

We describe an optical system that allows for the a bit reversed decimation of an image scene. The optical system consists of a successive sequence of lens arrays. The output of one lens array feeds into the input of the next array. The function of each lens array is to divide the input into its four quandrants. The output of each array is the image formed by summing together the four quandrant images.

Our goal is to design an optical front end for an imaging system that allows for the simultaneous imaging of both a wide angle field of view and a zoomed telephoto field of view. In addition we require image acquisition to be optimized for target tracking.

This described optical design utilizes a multi-lens front end. Each lens images one quadrant of the total field of view onto an image plane. All four images are formed at the same position on the image plane, overlapping one another in space; see Fig. 1. The first set of four lenses are at position L_1. These lenses image each of the object plane quadrants onto plane P_1. All four images also overlap on P_1. Behind P_1 is a second set of lenses denoted as L_2. The four lenses at L_2 image each quadrant in plane P_1 onto plane P_2. These lens stages can be pipelined in sequence as shown in Fig. 1.

The imaging properties of this pipelined system may be understood by relating the shaded areas denoted in each image plane. The shaded area in the object plane represents some small region of the original field of view. The image of the shaded area is shown in each image as it is projected at each stage of the optical system plane P_1, P_2, and P_3. A quadrant detector may be used in plane P_3 to detect the image. Alternately another optical stage may be used to image onto a single detector element located in plane P_4. Note that the operation of a single lens imaging systems flips the image left to right and top to bottom.

If the shaded area represents one pixel in the original object plane image, then an image detector array located in plane P_3, needs only four detector elements (a quadrant detector) to image the entire object plane. However, each image plane contains the overlap of the four quadrants from the previous image plane. This means that the shaded area of plane P_3 actually contains the overlapping images of 64 pixels from the original object plane. It may be undesirable to have overlapping images in this fashion. By placing shutters across each lens aperture it is possible to sequence through each of the sixty four images, one at a time. In this way, by sequencing the shutters, each of sixty four pixels, uniformly dispersed across the object plane, may be viewed by a detector element in plane P_3.

Suppose one additional optical stage followed plane P_3, called P_4, as shown in Fig. 1.

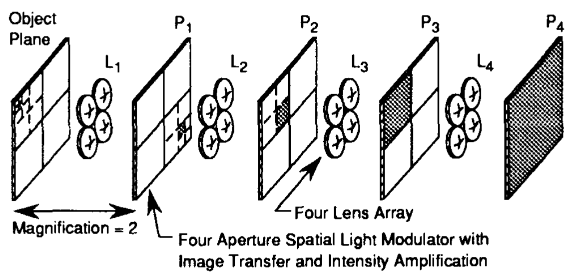

Figure 1. Pipelined parallel optical system for target tracking.

Here an entire 256 (16×16) element image is detected by use of a single time multiplexed point detector. The shutters must be sequenced so that at each optical stage only light from a single lens passes through the system. Each set of open shutter positions represents a single pixel location that is exposed to the detector.

Suppose a (256×256) detector array were used in plane P_4 instead of a single element. Then each "pixel" location in the original image would correspond to a

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(256×256) array. This means that the original scene would be divided into (4096×4096) pixels by the optical system.

The optical system is designed so that each optical stage represents one stage in a two dimensional binary decimation of the image. The most significant digit of the position is controlled by the four lenses L_1 closest to the object plane. Each optical stage represents a progressively less significant digit as we move away from the object plane. For example, suppose we set the shutters so that only one lens is open at each stage, then only one pixel illuminates the detector element in Fig. 1. When each lens in optical stage L_1 is opened, one at a time in turn, we sample the same pixel position in each quadrant of the original image. Then we switch to a different lens in L_2 and sequence through the L_1 lenses again, and so on. The result of this sampling scheme is the so-called bit-reversed sampling scheme [1]. However, it is also possible to utilize the shutter system to perform a random access sample scheme of a field of view to determine target position location.

Random Access Search Methods

In this section, we describe in detail the random access search algorithm. Bit-reversed addressing is a search algorithm that provides optimal mean time to detection of the target. We discuss this scanning algorithm because the random access camera architecture we present in the previous section is a hardware implementation of this algorithm.

In bit-reversed addressing, the object field is segmented into quadrants; an element or group of elements in each quadrant is examined in four successive read sequences. Each of the quadrants are then progressively split into smaller quadrants, with a read from every major quadrant occurring once every four reads. Extending this rule, a quadrant within some square area will be read from every fourth time a pixel is read from that area.

Since the bit-reversed addressing mode uses quadrants, the row and column address indices are determined by reverse mapping of pairs of bits from the binary representation of the pixel read number, ℓ. ℓ is the sequential number associated with a object field element, or pixel. Therefore, if the binary representation of ℓ is given by

$$\ell = \sum_{i=0}^{2k-1} b_i 2^i \qquad (1)$$

where k is an integer. The row index is then given by

$$\alpha_r(\ell) = \sum_{i=0}^{k-1} b_{2k-i-1}\, 2^i \qquad (2)$$

and the column index is given by

$$\alpha_c(\ell) = \sum_{i=0}^{k-1} \mathrm{XOR}(b_{2k-i-1}, b_{2k-i-2}) 2^i\,. \qquad (3)$$

$\mathrm{XOR}(b_i, b_j)$ is the binary exclusive-or function of the bits b_i and b_j. To ensure that the array can be segmented into four equal square areas, the maximum row and column index is given by 2^k. Equations (2) and (3) represent a mapping between reverse ordered pairs of bits from the binary representation of ℓ and the column and row indices. The mapping defined by equations (2) and (3) is listed in Table 1.

Other mappings are possible which result in essentially equivalent scan characteristics. Figure 2 is an example of a bit reverse addressing sequence, showing

b_i	b_{i-1}	$\alpha_r(\ell)^{ith}$	$\alpha_c(\ell)^{ith}$
0	0	0	0
1	0	1	1
0	1	0	1
1	1	1	0

Table 1. Binary mapping of bit pairs in the pixel index, ℓ, to bits in row and column indices.

addressing order over an 8×8 object field. Figure 3 illustrates visually how each major quadrant of the 8×8 field is examined in every four reads. This figure shows the capability of the bit-reversed algorithm to decrease the average distance between read pixels. Each frame in the figure represents read (black) and unread (white) after four reads from the previous frame.

The random access camera is a direct hardware approach to bit-reversed mapping. The system successively divides the object field into quadrants. Even though the system was designed to perform a bit-reversed mapping, other random access algorithms are possible. Therefore, the camera can theoretically solve many of the problems associated with raster scanned cameras. Conceptually, it is well suited for both searching and tracking of targets. The hardware implementations are broken down into two architectures. We call one architecture, an optical train, and the other, the folded-back camera. The advantages and limitations of the various hardware implementations are also discussed.

0	32	8	40	2	35	11	43
48	16	56	24	51	19	59	27
12	44	4	36	14	47	7	39
60	28	52	23	62	55	31	23
3	34	10	42	1	33	9	41
50	18	58	26	49	17	57	25
14	46	6	38	13	45	5	37
62	30	54	22	61	29	53	21

Figure 2. Actual reversed bit addressing element read sequence on an 8×8 field.

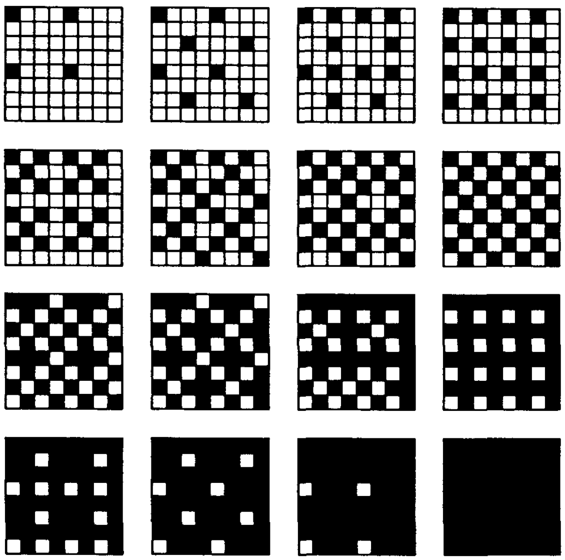

Figure 3. Sequence of elements of an 8×8 object field covered by reverse bit addressing. Shows every 4 reads.

Search Algorithm

A search algorithm attempts to find previously unknown locations for targets with sufficient optical energy above background radiation. Initially, the detector is in a passive search model with all apertures opened. Detection occurs when a signal on the quadrant detector reaches a level indicating a target is within the object field and enables the active search algorithm. The active search mode begins with a scan sequence, which selectively opens individual apertures in the first stage until the threshold radiation energy is again detected. This quadrant is identified with the 2-bit code determining most significant bits of the target address. The appropriate quadrant aperture stays open for the remainder of the search algorithm. At this point, the target quadrant of the first object field is imaged and magnified onto the object field of the second lens stage.

The second stage performs the identical active search sequence described above using the magnified image of the first stage as its object. The quadrants are sequentially opened until the target and the second most significant address bits are determined. The aperture associated with this quadrant will stay open and the sequence is iterated for each successive stage. The final stage provides the second least significant bits of the coordinate address at P_3. Additional resolution generating least significant bit pair is given by the position of the target image of the last lens stage on quadrant detector.

This search mode has the potential to be robust and fast. Initial target detection occurs rapidly since the object field is integrated onto a quadrant detector. After target detection, target location is quickly resolved with only four detector reads required per level.

Random Access Algorithm

Certain cases, such as target tracking or when the signal-to-noise ratio is low, necessitate the use of the camera in the random access mode. In this mode, an individual pixel or pixel groups are tracked in a preselected addressing mode.

If the location of interest is of single pixel size, single quadrants in each stage are selectively gated as determined by the binary coded x-y address pair. With the quadrants selectively gated, the object light propagates through the states, magnified by a factor 2^n, where there are n-1 lens stages. The number stages selectively gated determines how much resolution is used in the addressing. Therefore, groups of $2^p \times 2^p$ pixels can be examined selectively gating the first n-p-1 stages, and gating all quadrants in the last p-1 stages. The quadrant detector provides the final 2×2 area of detection electronically. As an example, if all quadrants in the final stage are gated, with all other stages selectively gated, the resolution is 2^{n-2} and the pixel group is 4×4. Of course, pixel groups can be addressed only on 2^{p-n} boundaries in both the x and y directions.

The most efficient target search sequence examines pixels with a sampling distance equal to the target span. It has been shown that the mean time to detection of a stationary target is

$$\tau = \frac{L}{2}\left[\frac{N}{T} - 1\right] + \frac{N-T+2}{2}$$

where N is the lateral pixel resolution of the camera, and T is the linear target size in pixels.

For targets of unknown size, the bit reverse scanning sequence, as discussed in section 7.1.2, is the most efficient scanning algorithm for a random access camera. A sequential gating of each quadrant of the stage L1 provides an examination of a pixel group in each quadrant. A different gate is activated in stage 2 for the next sweep of the four quadrants. This process is executed for each permutation of gating until all pixels have been examined.

The architecture of this camera lends itself to superpixel scanning. Non-contiguous pixel groups can be scanned by opening more than one aperture in a lens stage. For example, leaving all apertures in stage L1 open, with all other stages selectively gated, a pixel in each quadrant of the object field will be scanned for each combination. By selecting appropriate aperture combinations at each level, any pixel or group of pixels can be addressed making this a true random access architecture.

Limitations and Solutions

The completely free space conception of the random access camera suffers from severe vignetting. Lens array L1 forms an image at P1, but only a small fraction of the light is captured by L2. An actual implementation would require redirection, or amplification of the image to pass it down the train.

A system of relay lenses might be designed to provide the redirection of the image. Whether the relay system can be designed with the proper magnification and still be compatible with the rest of the system is undetermined. The relay lens system still suffers from decreasing signal at each stage and also requires precise alignment for mapping.

Diffusing screens at each plane could be employed for image regeneration. A diffusing screen redirects optical energy towards apertures in the succeeding stage. A diffusing screen approach has the advantage of simple design and construction. However, this implementation is also inherently inefficient, requiring fast lenses.

Addressable image magnifiers at each image field quadrant, such as microchannel spatial light modulators, hold the greatest promise of practical implementation. An image magnifier overcomes decaying signal and is easy to align. Furthermore, image magnifiers can have non-linear transfer functions, thus increasing the signal-to-noise ratio. Image magnifiers are also addressable which eliminates the need for external shutter systems and are generally much faster.

Assuming the optical train is implemented using image magnifiers with linear transfer functions, we can deduce some operating limitations due to background noise. In the passive search mode, a target is captured and amplified by just one quadrant. The amplified background noise in P1 is spread out among the next four quadrants of P2, but so is the noise from the other three quadrants in P1. The result is a wash in the noise after P1. Then the target signal must be greater than the total background energy in the object field quadrant. If the target signal does not satisfy this relation, then stages can be selectively gated; each stage provides a factor of four reduction in signal energy requirements. That is, if the first three stages are selectively gated, the signal must only be $1/4^3$ or 1/64 of the total object field background energy for a S/N=1. The drawback is, of course, that the selectively gated stages must be scanned, increasing the expected time to detection for an existing target. These arguments also ignore image amplifier and electrical noise.

The implementation shown in Figure 1 requires successive repetition of similar arrays of lenses. By feeding back the magnified image through the same lens array, only a single array of lens is required. This implementation of the optical train has the potential of being much smaller and is illustrated in Figure 4. This approach requires an image memory/amplifier to store the

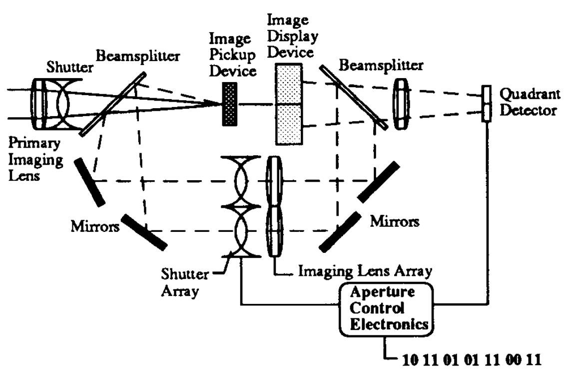

Figure 4. Folded-back implementation of Random Access Camera.

image between each level. Mirrors, beam-splitters and shutters are required to feedback and select the appropriate quadrant for redisplay. The original image is captured in memory and amplified for display. The amplified image is monitored with a quadrant detector through the beamsplitter. Control determines which quadrant the target is in, and selects which shutter to open. This quadrant is magnified by a factor of two and imaged onto the pick-up device. The process is iterated until the target is found to a suitable resolution. The advantage of the feedback implementation is potential compact size. The disadvantage is that this system has image resolution that is limited by the original image acquisition stage.

References

[1] J. P. Allebach, "Effects of Sample Displacement in Time-Sequential Sampling of Spatiotemporal Signals," J. Opt. Soc. Am. Vol. 73, pp. 466-472, April 1983.