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Holography machine HORN-1 for computer-aided retrieve of virtual three-dimensional image

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Abstract

We propose to retrieve the original 3-D objects as a virtual image by computers from a hologram created by real laser system. Then we can input the 3-D surface coordinates of a real object into computer memory. We may use these data as the boundaries to generate a body-fitted grid system for computer simulation, to modify these for computer animation, or to use these for pattern recognition of objects. HORN-1 (HOlographic ReconstructioN) specially prepared machine for this purpose enables us to do this work within quite short time. The machine has achieved a speed of 500 MFLOPS with one circuit. Massively parallel system combined into a LSI chip can work as a real-time recognition system.

Keywords : body-fitted grid, hologram, special-purpose computer

More than fourty years have past since the proposal of holography by Gabor[1]. The realization of this idea was made possible at the advent of laser light. Since then, a great deal of effort has been made on construction of holographic system. Recently, computer holography has been proposed to store 3-D(three-dimensional) image in computers[2-4]. A hologram is created by computers and is used to reconstruct the image of objects on a screen as human eyes see the holographic image. In contrast to this, here we propose to retrieve the original 3-D objects as a virtual image by computers from a hologram created by real laser system. Then we can input the 3-D surface coordinates of a real object into computer memory. We may use these data as the boundaries to generate a body-fitted grid system[5] for computer simulation, to modify these for computer animation, or to use these for pattern recognition of objects. HORN-1 (HOlographic ReconstructioN) specially prepared machine for this purpose enables us to do this work within quite short time. The machine has achieved a speed of 500 MFLOPS with one circuit. Massively parallel system combined into a LSI chip can work as a real-time recognition system.

This can be done by creating a hologram by a laser beam onto CCD (charge coupled device) camera or film , which will be degitized for input to computers. This stored image is only two dimensional and requires less memory size. From this point, our machine starts to function. This machine reconstructs the virtual 3-D image in computers from the hologram. In this article, we introduce the numerical procedure , and give the design of hardware and a preliminary test of the machine.

Let us consider that a hologram is created by a laser beam from a 3-D object, whose shape is given by $A(x, y, z) \equiv A_j$. Reflected beams from A and a reference beam are projected onto a film to construct a fringe pattern $I(\xi,\eta) \equiv I_\alpha$,

$$I_\alpha = [\sum_j \frac{A_j}{R_{\alpha j}} \exp(ikR_{\alpha j}) + 1][\sum_m \frac{A_m}{R_{\alpha m}} \exp(-ikR_{\alpha m}) + 1]$$
$$= 2\sum_j \frac{A_j}{R_{\alpha j}} \cos(kR_{\alpha j}) + 1 + O(1/R^2), \qquad (1)$$

where (ξ,η) is the coordinate on the hologram and we have defined a distance :

$$R_{j\alpha} = R_{\alpha j} \equiv R(x,y,z;\xi,\eta) = [(x-\xi)^2 + (y-\eta)^2 + z^2]^{1/2}. \qquad (2)$$

Hereafter, we use the greek letter α to denote the coordinates on the hologram, while the roman letter i, j or m represents the coordinates of the original object or the virtual image in 3-D space. Beams reflected from the object propagate as $\exp(ikR)$ where k is the wave number of beams and the unity in equation (1) represents the reference beam.

For the reconstruction of holography, another reference beam is employed. This beam is modulated by the fringe pattern in passing through it and is projected onto another screen to make a two-dimensional image of the object. The so-called computer holography and laser holography follow this process to reconstruct an image of 3-D objects onto a two-dimensional screen. Therefore, different two-dimensional image can be obtained with the use of a screen placed in a different place as human eyes see the image. Furthermore, the main purpose of the computer hologram is to make the fringe pattern , that is the hologram, without help of laser light.

In this paper, we try to trace back the process toward the past and to retrieve the virtual image of the original object in 3-D space.

In order to retrieve the 3-D pattern $A(x, y, z)$, we perform the calculation

$$\phi_i = \sum_\alpha I_\alpha \cos(kR_{i\alpha}). \tag{3}$$

It is easy to understand that this process gives $A(x, y, z) \sim \phi_i$. Substituting the expression of equation (1) into equation (3), we have

$$\phi_i = 2\sum_j \sum_\alpha \frac{A_j}{R_{\alpha j}} \cos(kR_{\alpha j})\cos(kR_{i\alpha}) + \sum_\alpha \cos(kR_{i\alpha}), \tag{4}$$

since $O(1/R^2)$ term in equation (1) is negligibly small[4]. The summation over α is performed on the surface of the hologram. It is clear that the summation over α becomes maximum for $j = i$. Then equation (4) reduces to

$$\phi \sim CA_i + D, \tag{5}$$

where $C = 2\sum_\alpha \cos^2(kR_{i\alpha})/R_{i\alpha}$ and $D = \sum_\alpha \cos(kR_{i\alpha})$. Since $\cos^2(kR_{i\alpha})$ is positive, its summation over α depends weakly on i and hence the dependence of C on i becomes quite weak. Furthermore, $\cos(kR_{i\alpha})$ rapidly changes its sign for $kR >> 1$ and the summation in D becomes negligiblly small compared to the first term. Therefore, the spatial variation of ϕ_i reflects that of $A(x, y, z)$.

For a test of the algorithm, we have made a fringe pattern with the method used by Stein et al.[4] on a computer. This fringe pattern I_α is used in equation (3). In order to accelerate this calculation, we have constructed HORN-1, a special-purpose computer for the holographic reconstruction. Since the calculation cost of equation (3) dominates almost the total calculation cost. HORN-1 calculates only this process. All other calculations are performed on a host computer connected to HORN-1.

The system operates as follows. In the first place, the host computer sends a position of reconstruction point (i) in 3-D space to HORN-1. Next, HORN-1 calculates ϕ_i with equation (3). Then, HORN-1 sends the result back to the host computer. This cycle is repeated for all spatial points.

HORN-1 is designed by a pipelined architecture. Figure 1 is the block diagram and a top view of HORN-1. The cost of electronic parts used in HORN-1 is about 60,000 Japanese yen (U.S.$500). We started designing HORN-1 in December 1992 and finished constructing it on March 12, 1993.

When the host computer sends a position of reconstruction point, *i.e.*. x_i, y_i and z_i, the pipeline automatically starts to operate as shown in the following steps:

(1) $|dx| = |x_\alpha - x_i|, |dy| = |y_\alpha - y_i|$

(2) $R_{\mathrm{xy}} = (|dx| + |dy|)^{1/2}$

(3) $\phi_{i\alpha} = \cos[k(R_{\mathrm{xy}}^2 + z_i^2)^{1/2}]$

(4) $\phi_i = \sum_\alpha I_\alpha \phi_{i\alpha}$

Each data is sent to the next step every clock cycle. Therefore, one of ϕ_i is obtained after $(400 \times 400 + 4)t_{\mathrm{pipe}}$. Here, 400×400 is the total number of α points on the hologram, 4 is the number of pipelined steps, and t_{pipe} is the reciprocal of the system clock frequency. Since the pipeline operates with 10 MHz, $t_{\mathrm{pipe}} = 10^{-7}$ sec and hence the time required to calcualte one point ϕ_i is 0.016 sec.

The operations are executed by reading tables written in ROM chips, except for the last accumulation step (4) of products. In steps (1) and (2), we use three 27C1024 1Mbit ($2^{16} \times 16$) ROM chips. In step (2), we output pointers of R_{xy} instead of R_{xy} themselves in order to avoid numerical errors. In step (3), we use a 27C4096 4Mbit ($2^{18} \times 16$) ROM chip for the operation and another 27C4096 ROM chip for I_α data, hologram data on points α. The I_α data have been written in the ROM chip and set on the pipeline before a calculation starts.

Accuracy of the HORN-1 system primarily depends on step (3). Note that any numerical error does not occur in the previous steps. Since output data in step (3), $\phi_{i\alpha}$, have 16bits accuracy, error of $\phi_{i\alpha}$ is $\sim 10^{-4}$. Therefore, total error of ϕ_i is $\sim 4 \times 10^{-2}$, since we accumulate 400^2 data of $\phi_{i\alpha}$. This accuracy is sufficient for this system.

In step (4), we use SM5810. a 16-bit Multiplier made by National Precision Circuits, for the summation of products $I_\alpha \phi_{i\alpha}$. SM5810 chip has 35 bits for output.

We use RS232C serial interface for communications between HORN-1 and the host computer, although the communication speed of RS232C interface is slow. However, it is sufficient for the HORN-1 system because of little communications. With a communication speed of 19200 bps, one of RS232C standard, the communication of 5 bytes needs only 0.002 sec, while it takes 0.016 sec to calculate ϕ_i on HORN-1 as described above.

The calculation of $I_\alpha \cos(kR_{i\alpha})$ is equivalent to about 50 floating point operations on a general-purpose computer. Therefore, the peak speed of HORN-1 with clock frequency of 10 MHz is equivalent to 500 MFLOPS. HORN-1 is, in practice, 100 times faster than a HP(Hewlett Packard) workstation model 705 having the peak speed of 8 MFLOPS.

Figure 2 shows the sliced image of a 3-D object, which is a cone (horn) made of twelve circles whose radius gradually shrinks in the z-direction. In the conventinal holography, an image is projected onto two-dimensional screens and hence the shape of whole structure is projected on the screen. In the present case, however, the virtual image is purely three-dimensional and therefore cross-sections of an object are retrieved on the planes placed at several points Z_0, Z_1, Z_2, Z_3. Calculation of each plane having 100×100 points took about 3 minutes by HORN-1, while it took 4 hours by a HP workstation. The results by HORN-1 seem to have relatively large noise because of low accuracy of hologram data I_α. The results by a HP workstation had much better resolution even with 200×200 hologram because of 32-bit operation throughout the calculation. In HORN-1 we have used only 9 bits for I_α in order to avoid overflow in the final step (4) by 16-bit multiplication. We are planning to replace this part by 32-bit and then we can use 16 bits for I. In real-time machines, the I_α data will be sent from a CCD camera through communication line and the ROM chip presently used for I_α will be replaced by a RAM chip.

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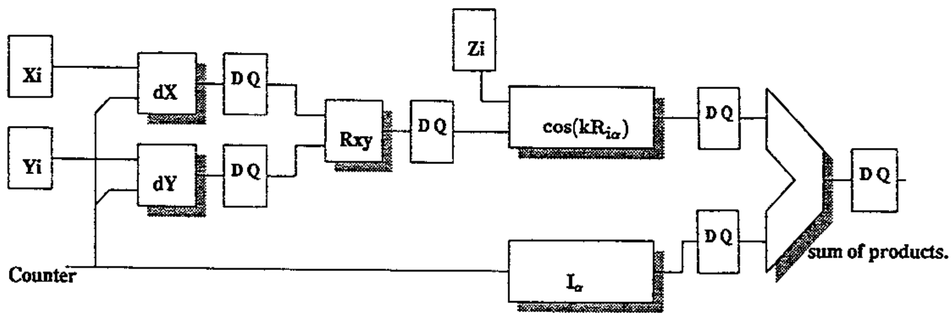
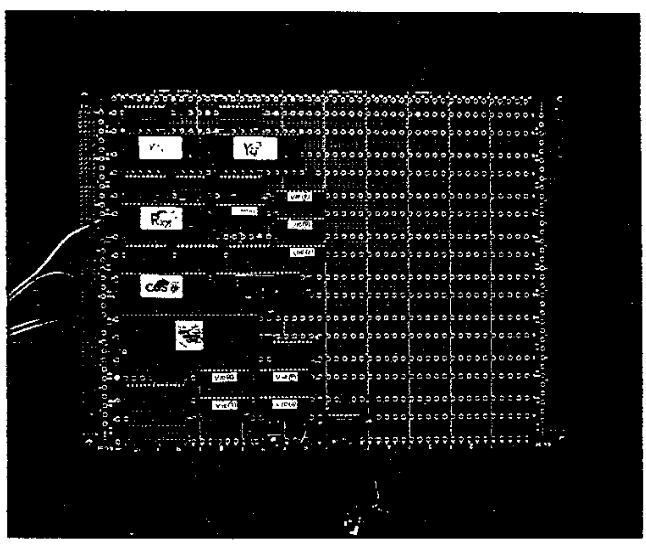
Figure Captions

Fig.1 : (a) The block-diagram and (b) a top view of HORN-1. DQ means the register.

Fig.2 : Top figure shows sample planes where 3-D image was retrieved. The object is a cone. Bottom figure shows the result by HORN-1.


Xi
Yi
dX
dY
D Q
D Q
Rxy
D Q
Zi
cos(kR$_{i\alpha}$)
D Q
D Q
D Q
I$_\alpha$
Counter
sum of products.

(a)



(b)

Fig.1

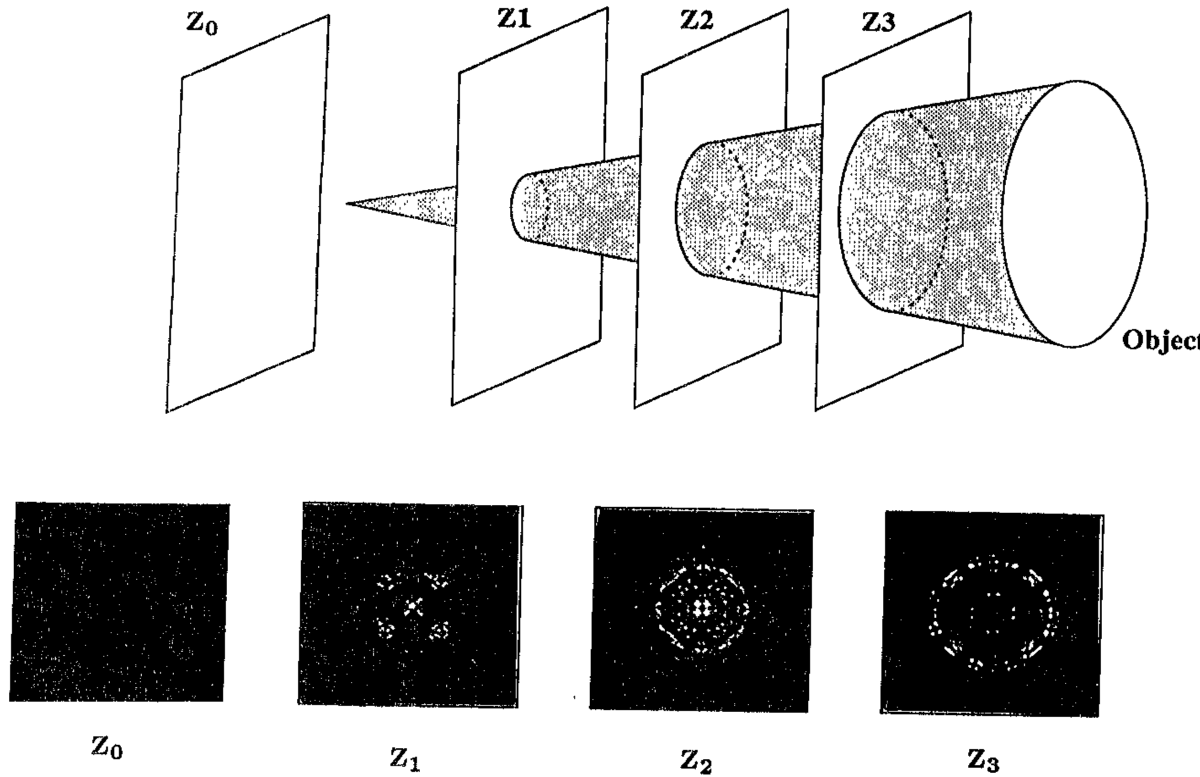


Fig.2

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