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PRINT FIG. 1A

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THREE-DIMENSIONAL OBJECT TRACKING SYSTEM
AND METHOD EMPLOYING PLURAL SENSORS
AND PLURAL PROCESSORS FOR PERFORMING PARALLEL PROCESSING

This invention relates to three-dimensional object tracking systems and methods of the type employing cameras provided with charge-coupled device (CCD) sensors.

A multiple sensor/multiple processor 3-D tracking system includes multiple sensor (camera) and DSP combinations and a controller connected so as to create a parallel computer from the multiple DSP's. The camera/DSP combinations and the controller are connected together to form a ring. For 3-D position measurement and tracking applications, each camera/DSP combination is programmed with an identical program to function as a node in a true parallel computer, and the transformation equations are solved in a distributed fashion using the entire parallel machine.

A novel aspect of the invention is that the distributed processor processes the camera x and y point measurements in a distributed and parallel fashion to yield a solution to the coordinate transformation equations much more quickly than is possible with multiple camera/DSP combinations and a single processor.

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THREE-DIMENSIONAL OBJECT TRACKING SYSTEM
AND METHOD EMPLOYING PLURAL SENSORS
AND PLURAL PROCESSORS FOR PERFORMING PARALLEL PROCESSING

5 Origin of the Invention

 This invention was made by an employee of the United States Government and may be manufactured by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

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Field of the Invention

 This invention relates to three-dimensional object tracking systems and methods of the type employing cameras provided with charge-coupled device

15 (CCD) sensors.

Background of the Invention

 The broad concept of tracking objects by cameras is known in the art and is
20 taught by the following references, whose disclosures are hereby incorporated by
 reference in their entireties into the present disclosure: (1) Welch, S.S.;
 Clemmons, J.I.; Shelton, K.J.; and Duncan, W.C.: "Optical Position Measurement
 for a Large Gap Magnetic Suspension System: Design and Performance Analysis",
 NASA TP3438, May 1994. (2) Karara, H.M., ed.: Non-Topographic
25 Photogrammetry, Second Ed., American Society for Photogrammetry and Remote
 Sensing, 1989, pp. 37-57. (3) Golub, G.H.; Van Loan, C.F.: Matrix
 Computations, Second Ed., The Johns Hopkins University Press, 1991, pp. 224-
 225. (4) Golub, G.H.; Van Loan, C.F.: Matrix Computations, Second Ed., The
 Johns Hopkins University Press, 1991, pp. 260-330. (5) Welch, S., "Design and

Performance of an Optical Measurement System for Position Measurement and Control in a Large Gap Magnetic Suspension System," SPIE Vol. 2350 Videometrics III (1994), pp. 115-126. (6) Omachi et al, U.S. Patent No. 4,633,383, December 30, 1986. (7) Sciaky et al, U.S. Patent No. 4,651,283, 5 March 17, 1987. (8) Marinelli et al, U.S. Patent No. 4,884,208, November 28, 1989.

When these references are cited in the present disclosure, the citations will be in parentheses to the reference number, e.g., (ref. 1).

10 In recent years, systems employing multiple cameras to capture images of objects and track the locations of the objects in 3-D have proliferated. This proliferation has resulted in part because of improvements made in charge-coupled devices which have enabled higher resolution images to be recorded with smaller cameras, and in part because of advances made in digital signal processors. In most of the 3-D tracking systems, a single central processor is used to solve the 15 transformation equations which relate the coordinates of the object to be tracked in the camera coordinate systems to an externally referenced coordinate system. Information for the external cameras or sensors is transferred to the central processor via data acquisition hardware across a common bus.

Some recent 3-D tracking systems have incorporated a digital signal 20 processor (DSP) for every camera in order to decrease the processing by controlling camera signals at the camera and solving some of the equations for target (or object) tracking within the camera image. For example, the Optical Measurement System (OMS) (ref.1) is a 3-D point target tracking system in which sixteen linear CCD imagers are used to detect the locations of small light emitting diode targets. In the 25 OMS, a high speed DSP is used for each camera to control image acquisition and camera signals, and an additional mathematical DSP is used for system control and to solve the coordinate transformation equations. Each camera DSP controls the integration time and background level for the corresponding CCD sensor and is used to compute the centroid of the point target image which is acquired. The

estimates of the centroid locations in the sixteen cameras are transferred to the MATH DSP. The MATH DSP is a serial processing machine.

Alternatively, some 3-D tracking systems use a parallel processor to solve the transformation equations. In this case, the parallel processor is a single chip
5 which acts as a central processor in the multi-sensor system. The information from the multiple cameras or sensors must be transferred to the central processor in order to solve the coordinate transformation equations. These parallel processors have a finite number of ports dedicated to external communication. Such an arrangement is shown in Fig. 3; its operation will be described in detail below in comparison
10 with a preferred embodiment of the present invention.

In all prior multiple sensor/multiple processor 3-D tracking systems, the power of the multiple processors has not been fully exploited. That is, the processor which is attached to every camera is used to track the object in the plane of the camera, but is not used to solve the larger transformation equations. Rather,
15 a central processor is used to solve the transformation equations, which central processor is either a serial processor or a parallel processor (resident on a single chip). As a result, as the number of cameras or sensors increases, so too does the amount of information which must be transferred to the central processor as well as the number of equations which must be solved in the coordinate transformation.
20 This results in an increase in the time required to solve the equations as the number of cameras or sensors increases. Additionally, for some systems there is an upper bound on the number of cameras (or sensors) and DSP's which can be connected to and communicate with the central processor.

25 Summary of the Invention

It is an object of the invention to provide a multiple sensor/multiple processor 3-D tracking system and method capable of solving the transformation equations at high speed for any number of sensors.

It is a further object of the invention to provide a multiple sensor/multiple processor 3-D tracking system and method in which the number of ports in a central processor does not limit the number of sensors.

To these and other ends, the invention is directed to a multiple
5 sensor/multiple processor 3-D tracking system comprising multiple camera (or sensor) and DSP combinations connected so as to create a parallel computer from the multiple DSP's. The camera/DSP combinations are connected together to form a ring. For 3-D position measurement and tracking applications, each camera/DSP combination can be programmed with an identical program to function as a node in
10 a true parallel computer, and the transformation equations can be solved in a distributed fashion using the entire parallel machine. The distributed processor processes the camera x and y point measurements in a distributed and parallel fashion to yield a solution to the coordinate transformation equations. The invention is further directed to a method of using this system to solve the
15 transformation equations by parallel processing.

This invention decreases the time required to process data from multiple sensors and solve coordinate transformation equations. In addition, the invention provides for an unlimited number of camera/DSP combinations to be connected together and to be used to solve coordinate transformation equations for point
20 tracking.

Brief Description of the Drawings

The invention will now be set forth in greater detail with reference to the
25 drawings, in which:

Fig. 1A shows a schematic diagram of an optical tracking system according to a preferred embodiment of the invention;

Fig. 1B shows a schematic diagram of one of the sensor/DSP's of the system shown in Fig. 1A;

Fig. 2A-2D show flow charts and a diagram of information flow and processing according to the preferred embodiment; and

Fig. 3 shows a schematic diagram of an optical tracking system according to the prior art.

5

Detailed Description of the Preferred Embodiment

A preferred embodiment of the invention is shown in Figs. 1A and 1B. This embodiment is directed to an optical tracking system 100 where multiple cameras or
10 other sensors are used to image targets and each camera image is processed with a dedicated DSP. The camera/DSP's 102-1, 102-2, ... 102-(n-1), 102-n are connected together to form an external ring parallel processor.

An implementation of this invention on a multicamera system is shown in Figs. 1A and 1B. Each camera/DSP 102-1, 102-2, ... 102-(n-1), 102-n includes
15 camera 110, frame buffer 112, electronics 114 for controlling camera parameters, and high-speed DSP 116 for processing the digital images acquired from the camera. The information extracted from any single camera image by the corresponding DSP is the x and y locations of objects in the image, for example, the x and y centroid locations of different objects or targets, or the x and y locations
20 of the intersection of two lines, or x and y locations which define a boundary of an object, etc. These x and y locations are stored in memory section 118 of the camera/DSP.

Figure 1A shows the camera/DSP combinations connected together in a ring through bus 106. To support this connection, a suitable DSP must have a minimum
25 of two unidirectional external ports 120-L and 120-R, either serial or parallel. Each DSP communicates with its nearest neighbor, or neighbors. Each camera has a unique identification number corresponding to its position in the ring. Camera/DSP's 102-1 and 102-n are connected to an additional DSP or processor 104 which is not connected to a sensor. The additional processor communicates via

ports 122-L and 122-R and the bus to the ring of camera/DSP's, initiates processing by the ring, and is connected to user interface 108 which acts as an interface between the user and the distributed processor and camera tracking system.

This system operates by performing the following operations. The x, y, and z coordinates of an object relative to an external reference frame are related to the x_i and y_i locations of the object in the image of camera i by $B_i d = B_i d'_i$, where

$$B_i = \begin{vmatrix} (m_{11} + x_i m_{31})(m_{12} + x_i m_{32})(m_{13} + x_i m_{33}) \\ (m_{21} + y_i m_{31})(m_{22} + y_i m_{32})(m_{23} + y_i m_{33}) \end{vmatrix}, \quad (1)$$

$$d'_i = \begin{vmatrix} X_i^c \\ Y_i^c \\ Z_i^c \end{vmatrix}, \quad (2)$$

$$d = \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}, \quad (3)$$

and where X_i^c , Y_i^c , and Z_i^c are the coordinates of camera i relative to the external reference frame, X, Y, and Z are the coordinates of the object relative to the external reference frame, and the m's are functions of the camera pointing angles (ref. 2). If the x and y locations of the object are measured by two or more cameras, and the locations and pointing angles of the cameras are known relative to an external reference frame, then the X, Y, and Z coordinates of the object relative to the external reference frame can be determined using weighted least squares. For n cameras, the form of the transformation equations is

5

$$\begin{vmatrix} B_1 \\ B_2 \\ \cdot \\ \cdot \\ \cdot \\ B_n \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} B_1 \\ B_2 \\ \cdot \\ \cdot \\ \cdot \\ B_n \end{vmatrix} \begin{vmatrix} d'_1 \\ d'_2 \\ \cdot \\ \cdot \\ \cdot \\ d'_n \end{vmatrix} \quad (4)$$

One method to find the weighted least squares solution to the transformation
 10 equation $Bd=Bd'$ is the method of normal equations (ref. 3). The normal equations
 are formed by multiplying both sides of the matrix transformation equation by the
 transpose of WB, as

$$\begin{vmatrix} B_1 \\ B_2 \\ \cdot \\ \cdot \\ \cdot \\ B_n \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} B_1 \\ B_2 \\ \cdot \\ \cdot \\ \cdot \\ B_n \end{vmatrix} \begin{vmatrix} d'_1 \\ d'_2 \\ \cdot \\ \cdot \\ \cdot \\ d'_n \end{vmatrix}, \quad (5)$$

15 where W is the weighing matrix given by

$$W = \begin{vmatrix} W_1 & 0 & \dots & 0 \\ 0 & W_2 & \dots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \dots & W_n \end{vmatrix} \quad (6)$$

25

Carrying out the matrix multiplication in equation 5 yields

$$\left| \sum_{i=1}^n B_i^T W_i^T W_i B_i \begin{matrix} X \\ Y \\ Z \end{matrix} \right| = \left| \sum_{i=1}^n B_i^T W_i^T W_i B_i d'_1 \right|. \quad (7)$$

If the normal equations are represented by $Nd=z$, then for B and d' real, N is a 3 X 3, symmetric positive definite matrix. From equation 7 it follows that for

$$N = \left| \sum_{i=1}^n B_i^T W_i^T W_i B_i \right| \quad (8)$$

each i th component,

$$B_i^T W_i^T W_i B_i,$$

is also a 3 X 3 symmetric matrix, Similarly, since

$$z = \left| \sum_{i=1}^n B_i^T B_i d_i \right| \quad (9)$$

is a 3 X 1 vector, each i th component is also a 3 X 1 vector.

The following example demonstrates how multiple individual camera/DSP's can be connected together to form a distributed parallel computer which can be used to solve the coordinate transformation equations presented above. Assume that there are n camera/DSP combinations connected together in a ring, as shown in Fig. 1A, where $n \geq 9$. Each camera is capable of recording a two-dimensional image of a scene, and the corresponding DSP calculates the x and y camera coordinates of an object in the recorded image. The location and pointing angles of each of the n cameras are known relative to an external reference frame and are stored in the

corresponding camera/DSP memory. The operations involved in the setup and solution of the normal equations formed from the coordinate transformation equations using the distributed ring parallel processor would proceed as follows, with reference to Figs. 2A-2D.

5 Images of the object or objects to be tracked are acquired in parallel by the cameras, and the x and y locations of the objects in the camera reference frames are subsequently determined by the corresponding DSP's (step 202). The x_i and y_i coordinates of an object in camera i are used to solve for the components of each B_i matrix and d'_i vector (step 204). The components of B_i and d'_i depend only upon
10 the measured x_i and y_i coordinates and the location and pointing angles of camera i which are known and stored in the corresponding camera/DSP memory. Thus, the calculation of the B_i and d'_i components can be performed in each camera DSP in parallel independently of the other cameras in the ring.

The B_i matrix has the following components

15

$$B_i = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \end{bmatrix}. \quad (10)$$

20

For x_i, y_i independent measurements, the weighing matrix is given by
25

$$W_i = \begin{bmatrix} W_{x_i} & 0 \\ 0 & W_{y_i} \end{bmatrix}. \quad (11)$$

30

From equations 8 through 11 it follows that the ith components of N and z
35 of the normal equations are completely specified by the following nine inner products which can be calculated in each DSP, again in parallel and independent of

every other DSP (step 206):

$$\begin{aligned}
 p(1) &= b_{11} * w_{x_i}^2 * b_{11} + b_{21} * w_{y_i}^2 * b_{21} \\
 p(2) &= b_{12} * w_{x_i}^2 * b_{12} + b_{22} * w_{y_i}^2 * b_{22} \\
 p(3) &= b_{13} * w_{x_i}^2 * b_{13} + b_{23} * w_{y_i}^2 * b_{23} \\
 p(4) &= b_{11} * w_{x_i}^2 * b_{12} + b_{21} * w_{y_i}^2 * b_{22} \\
 p(5) &= b_{11} * w_{x_i}^2 * b_{13} + b_{21} * w_{y_i}^2 * b_{23} \\
 p(6) &= b_{12} * w_{x_i}^2 * b_{13} + b_{22} * w_{y_i}^2 * b_{23} \\
 p(7) &= p(1) * d'_1 + p(4) * d'_2 + p(5) * d'_3 \\
 p(8) &= p(4) * d'_1 + p(2) * d'_2 + p(6) * d'_3 \\
 p(9) &= p(5) * d'_1 + p(6) * d'_2 + p(3) * d'_3
 \end{aligned}$$

Once the p vector is calculated in each camera/DSP, the setup of the normal equations is accomplished by passing each component of the p vector around the ring and summing. This could be accomplished, for example, by executing the following program subroutine in each camera/DSP:

```

j=1 (step 210)
while j<10 (step 212)
  receive(a(j), right) (step 214)
  a(j) = a(j) + p(j) (step 216)
  send(a(j), left) (step 218)
  j=j+1 (step 220)
end (step 222)

```

where the command receive(a(j), right) means that the DSP receives the variable a(j) from the DSP on its right and send(a(j), left) means the DSP sends the variable a(j) to the processor on its left.

Nine components, a(1) through a(9), are calculated which completely specify N and z. The controller processor initiates execution on the ring (steps 230, 232) and passes an initial value of zero for each of the nine components of a to processor number 1 (steps 234, 236, 238). The passing of information and interaction of each

of the n DSPs in the ring in solving for the nine components of the normal equations is illustrated in Fig. 2D. From Fig 2D it is evident that the processing is both pipeline and parallel.

At the conclusion of program execution on the ring, the nine components of the vector have been passed through the processor controller to processor number 1 to determine N and x (step 240) and thus, to begin the solution of $Nd=z$. The solution of the normal equations on the ring can be accomplished by executing a Cholesky decomposition of N and back substituting (steps 242, 244). Subroutines to execute this on a ring parallel architecture are described in reference 4. Because N is 3×3 , only three processors in the ring are required to solve the decomposition and back substitution.

The operation of the preferred embodiment will now be compared with the operation of a known camera-DSP system. Fig. 3 shows such a known system in which a single processor solves the normal equations. This known system includes n camera/DSP combinations 302-1, 302-2, ... 302- n connected to a common bus 306 with an additional processor/controller 304 connected to the same bus. The number of machine cycles required to set up the normal equations using the system configuration of Fig. 3, where the transformation equations will be solved using the additional serial processor, will be compared to the number of cycles required to set up the normal equations using the distributed parallel architecture of Fig. 1. A read or write operation is assumed to be executable in one cycle for both architectures.

For the known system, the calculation of the i th components of N and z (the p 's) are assumed to be performed in each camera/DSP in parallel as is the case with the distributed parallel architecture of the preferred embodiment. At the conclusion of the calculation of the i th components of N and z , the components have to be transferred to the central processor to complete the formation of the normal equations. This transfer requires $18n$ cycles. To complete the formation of the normal equations, $9n$ additions have to be performed in the central processor.

Assuming one cycle per addition, the total number of cycles required for the formation of the normal equations for this case is $27n$.

For the preferred embodiment, the operations to determine the i th components of N and z are performed in each camera/DSP in parallel, as described above. At the conclusion of the determination of the i th components of N and z , as illustrated in Fig. 2D, the summation of these components to form N and z spreads like a wave around the ring of DSPs. The cycles indicated in Fig. 2D are program cycles or loops, not machine cycles. For the case $n \geq 9$, the total number of cycles required to complete the summation and data transfer is $3n + 3(8)$. Thus, for $n = 9$, 51 cycles are required to set up the normal equations using the parallel ring architecture versus 243 cycles using the serial architecture shown in Fig. 3.

For cases where fewer than 9 processors are used, the components of the p vector would be grouped together and passed around the ring. For example, for $n = 3$, 45 cycles are required to set up the normal equations when $n = 3$. Thus, there is still an advantage in using the parallel ring architecture for just three camera/DSP combinations. (It would not be very practical to set up the parallel ring for fewer than 3 processors.) However, the larger the value of n , the greater the time savings for the parallel architecture.

The preceding example explains only one method for connecting together multiple camera/DSP combinations in a ring and using the distributed ring parallel processor to solve coordinate transformation equations which relate the camera coordinates of image points to points in an external reference frame. Other types of operations could also be used to control information flow around the ring and solve these equations using the distributed parallel architecture. For example, the coordinate transformation equations could be solved using a factorization of the B matrices into Q and R matrices and back substitution without forming the normal equations (ref.4). The flow of information and the calculations done in each DSP would be different for this case from what was shown in the above example. Those skilled in the art who have reviewed this specification will be able to make such

modifications and others to the invention and still be within the scope of the claims; therefore, the invention should be construed as limited not by this specification, but only by the claims.

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Abstract of the Disclosure

A multiple sensor/multiple processor 3-D tracking system includes multiple sensor (camera) and DSP combinations and a controller connected so as to create a parallel computer from the multiple DSP's. The camera/DSP combinations and the controller are connected together to form a ring. For 3-D position measurement and tracking applications, each camera/DSP combination is programmed with an identical program to function as a node in a true parallel computer, and the transformation equations are solved in a distributed fashion using the entire parallel machine. The distributed processor processes the camera x and y point measurements in a distributed and parallel fashion to yield a solution to the coordinate transformation equations much more quickly than is possible with multiple camera/DSP combinations and a single processor.

Fig. 1A

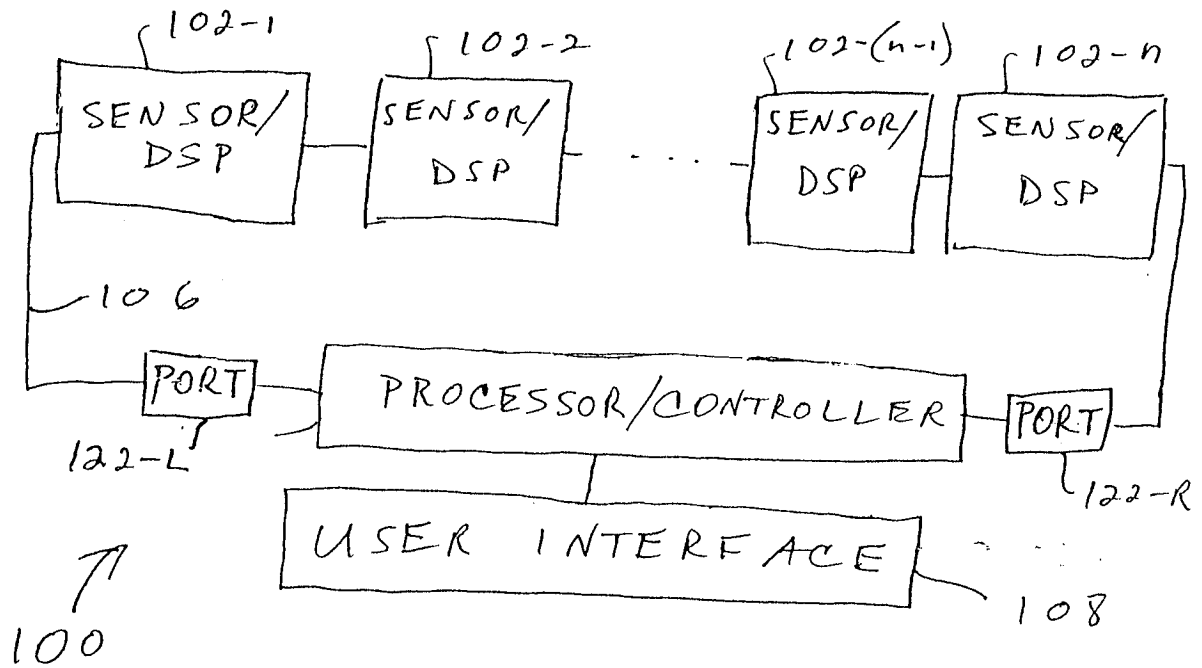
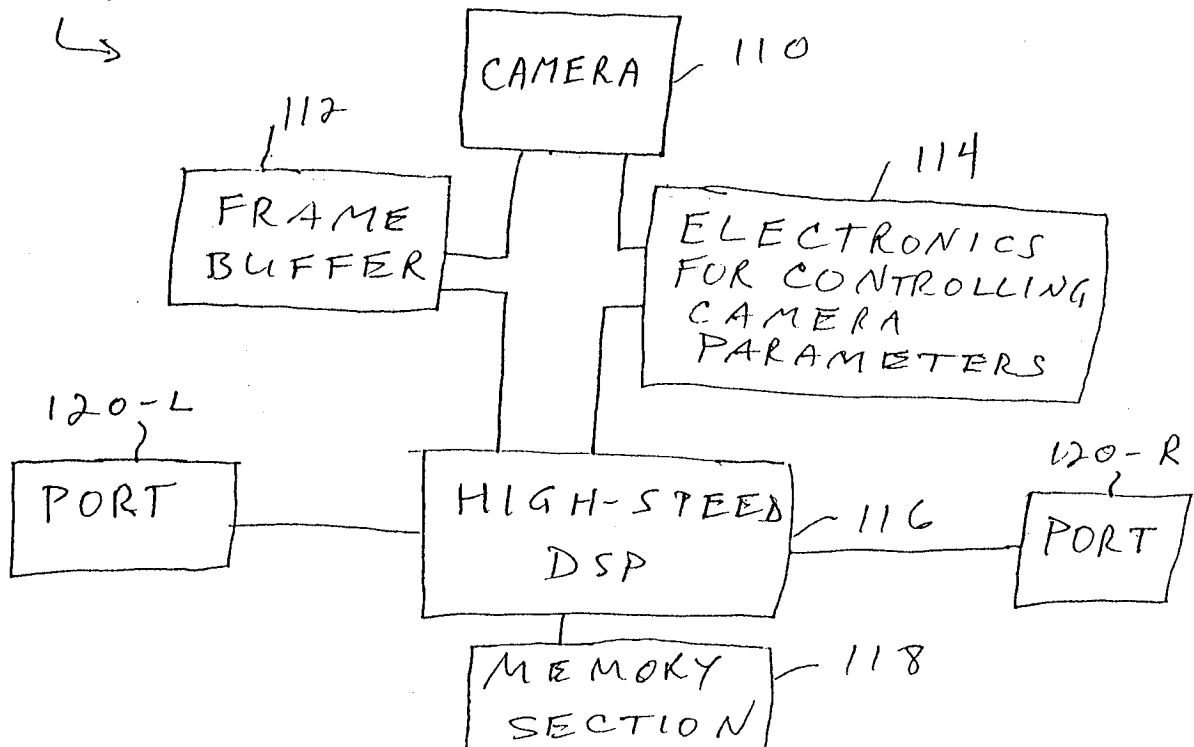


Fig. 1B

102-1
(102-2, ... 102-n)
↳



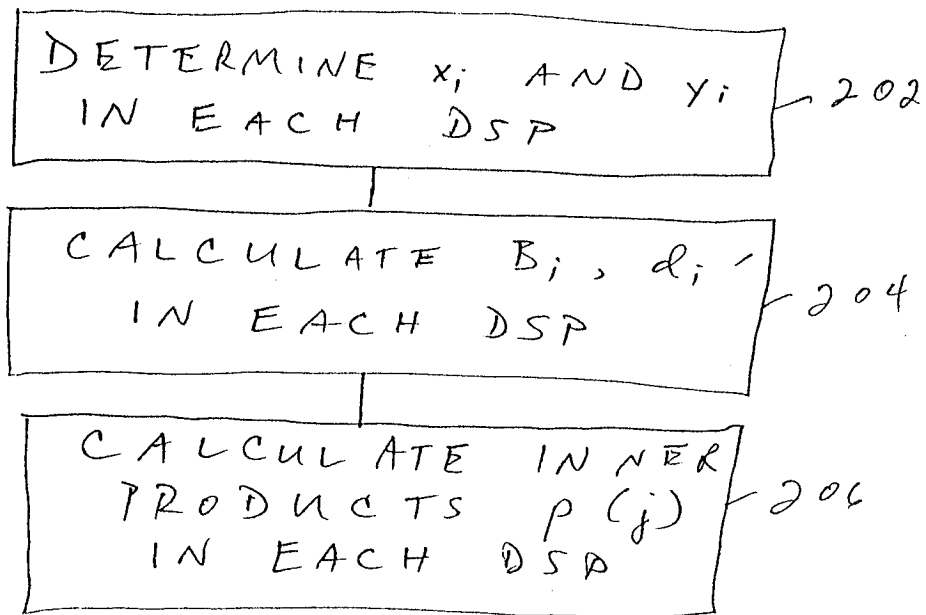


Fig. 2A

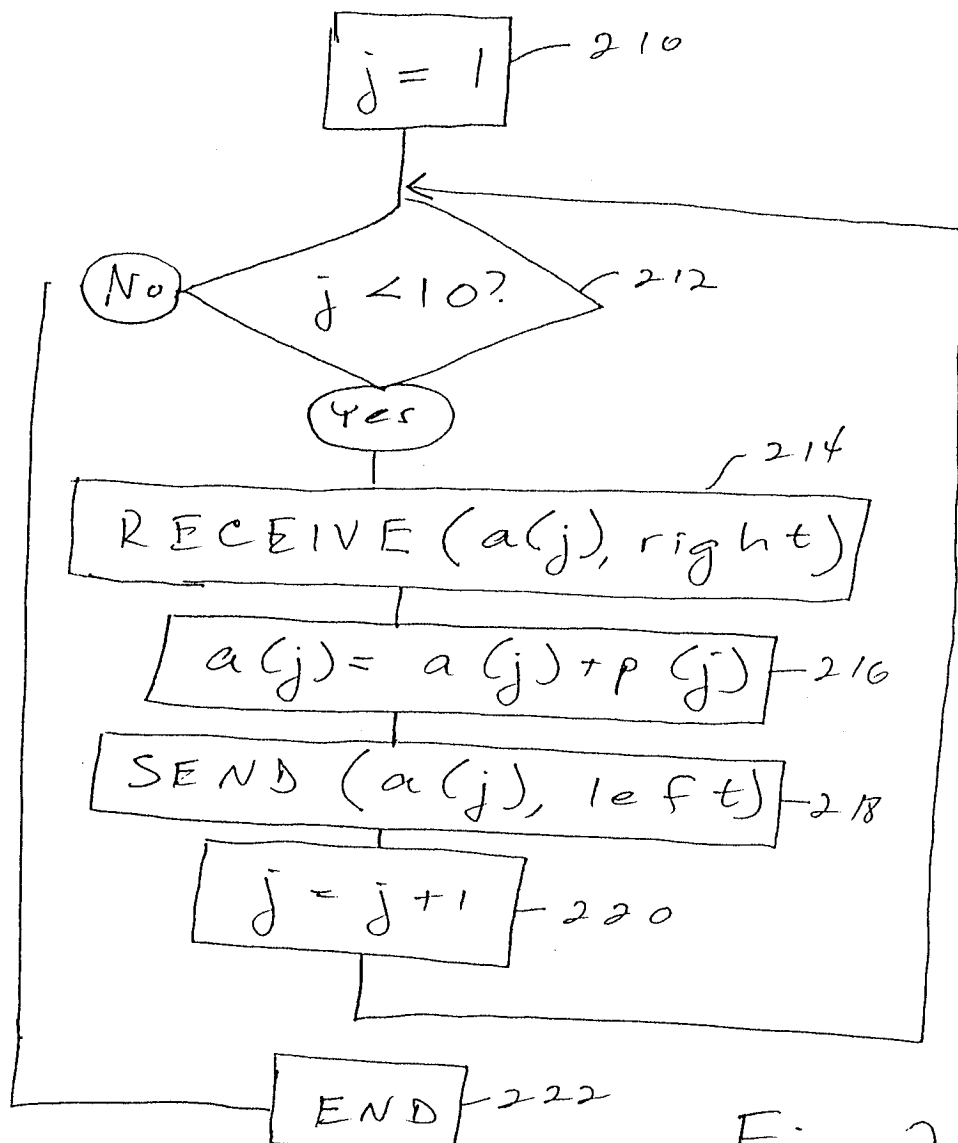


Fig. 2B

Fig. 2C

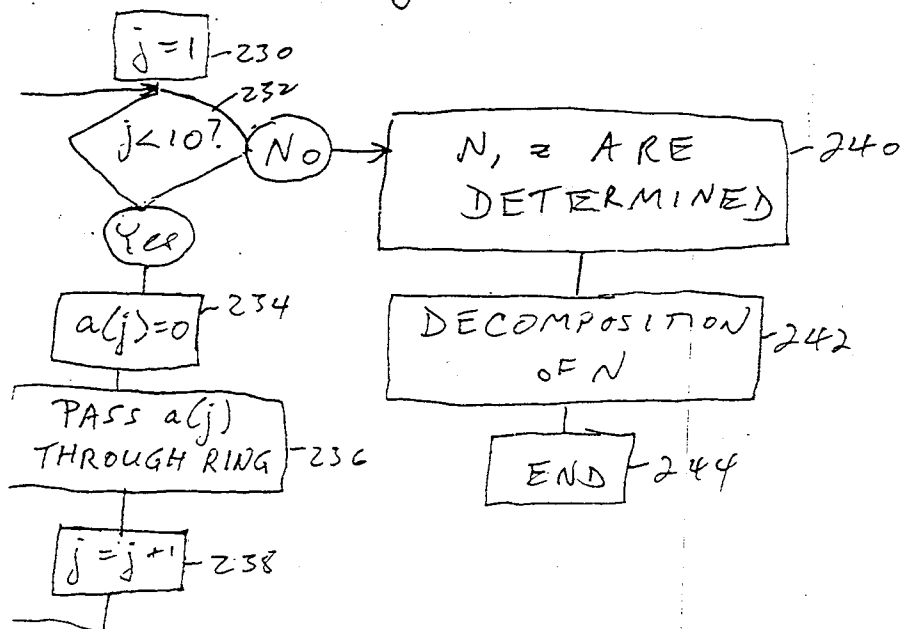
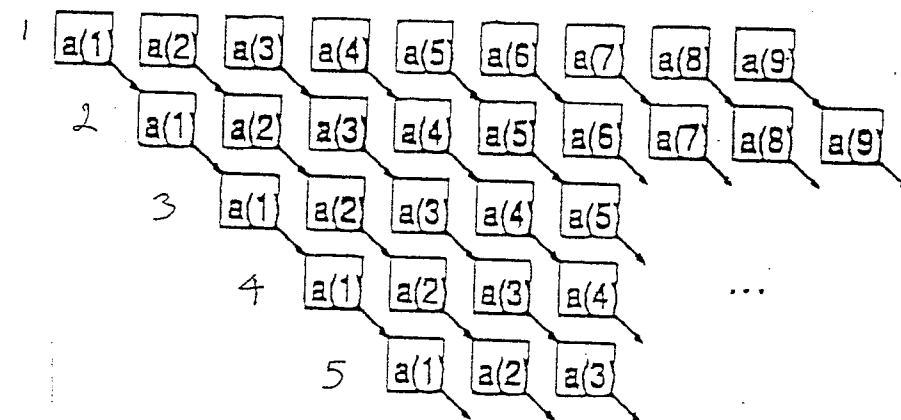


Fig. 2D

Processor Number



Time (cycles)

Fig. 3 PRIOR ART

