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RAM BASED KEY EQUATION SOLVER APPARATUS

Field of the Invention

The invention relates to apparatus for solving the key equation in order to decode Reed-Solomon encoded data containing errors.

Background of the Invention

Reed-Solomon codes are used to provide error correction for blocks of data. For example, they are widely used in communications and data storage applications. Much of the computational effort needed to decode a Reed-Solomon codeword received with errors is spent in solving the so-called key equation. There are several well-known methods for solving the key equation. Among these is a method proposed by Berlekamp. The Berlekamp method is often implemented in hardware in order to meet speed requirements of the application. Previous implementations of the method used individual registers to hold intermediate values required by the method.

Summary of the Invention

The present invention is a circuit for generating a plurality of coefficients of an error locator polynomial and a plurality of coefficients of an error evaluator

polynomial in a system for correcting errors in a Reed-Solomon encoded datastream. The system comprises a syndrome generator outputting syndromes of the datastream. The present invention is coupled to the syndrome generator and receives the syndromes. The present invention comprises an arithmetic unit iteratively generating intermediate and final values of the plurality of coefficients of an error locator polynomial and the plurality of coefficients of an error evaluator polynomial; a random access memory, storing the intermediate and final values of the plurality of coefficients of an error locator polynomial and the plurality of coefficients of an error evaluator polynomial; and a control unit, controlling the arithmetic unit and the memory and detecting when the computation of the plurality of coefficients of an error locator polynomial and the plurality of coefficients of an error evaluator polynomial has been completed.

Brief Description of the Drawings

Fig. 1 is a block diagram of a hard disk drive incorporating the present invention.

Fig. 2a is a block diagram of one embodiment of the present invention.

Fig. 2b is a block diagram of a controller 228 of Fig. 2a.

Fig. 3a is a flow diagram of a state ZZ 301 through a state E 307 of a process 300 which is performed by the present invention.

Fig. 3b is a flow diagram of a state G 308 through a state H 309 of a process 300 which is performed by the present invention.

Fig. 3c is a flow diagram of a state I 310 through a state N 315 of a process 300 which is performed by the present invention.

Fig. 3d is a flow diagram of a state O 316 through a state Q 318 of a process 300 which is performed by the present invention.

Fig. 3e is a flow diagram of a state AA 319 through a state AC 321 of a process 300 which is performed by the present invention.

Fig. 3f is a flow diagram of a state AD 322 through a state AG 325 of a process 300 which is performed by the present invention.

Fig. 3g is a flow diagram of a state AH 326 through a state AK 329 of a process 300 which is performed by the present invention.

Fig. 3h is a flow diagram of a state BA 331 through a state BE 335 of a process 300 which is performed by the present invention.

Fig. 3i is a flow diagram of a state BF 336 through a state BI 339 of a process 300 which is performed by the present invention.

Fig. 3j is a flow diagram of a state BJ 340 through a state BN 344 of a process 300 which is performed by the present invention.

Fig. 3k is a flow diagram of a state BO 345 through a state BV 352 of a process 300 which is performed by the present invention.

Detailed Description of the Invention

In Fig. 1, major subsystems of a hard disk drive incorporating the present invention are shown. The signal recorded on disk 102 is read by read head 104. The analog signal 106 from read head 104 is input to read channel 108, which extracts a digital data stream 110. Digital data stream 110 is input to syndrome generator 112. Syndrome generator 112 computes syndromes for digital data stream 110. If the syndromes are all zero, an error free signal 114 is set and syndrome generator 112 is prepared for the next sector. If some of the syndromes are non-zero, this means that the sector contained errors and the key equation solver is to be activated. When such an error occurs, error signal 116 is set. This activates key equation solver 120, which takes the syndromes 118 as inputs. Key equation solver 120 then generates signals representing an error locator polynomial and an error evaluator polynomial, which are then used by other circuitry (not shown), such as, for example, the well-known Chien search circuit, to correct the errors in data stream 110.

The Berlekamp method, in a form compatible with the present invention, is shown in detail in the pseudocode listing of Table A.

TABLE A

$v \leftarrow [0, 0, \dots, 0, 1]$
 $p \leftarrow [0, 0, \dots, 0, 1]$
 $u \leftarrow [0, 0, \dots, 0, 1]$
 $q \leftarrow [0, 0, \dots, 0, 1]$
 $d = 0$
 for $k = 0$ to $2 \cdot T - 1$

T

$$e \leftarrow \sum_{l=0}^{(k-1) \bmod (2 \cdot T)} v_l$$

if ($e = 0$)
 for $l = T$ downto 1
 $u_l \leftarrow u_{l-1}$
 $p_l \leftarrow p_{l-1}$
 $u_0 \leftarrow 0$
 $p_0 \leftarrow 0$
 else if ($2 \cdot d^3 k + 1$)
 for $l = T$ downto 1
 $u_l \leftarrow u_{l-1}$
 $v_l \leftarrow v_l - (e \cdot u_l)$
 $p_l \leftarrow p_{l-1}$
 $q_l \leftarrow q_l - (e \cdot p_l)$
 $u_0 \leftarrow 0$
 $p_0 \leftarrow 0$
 else
 $d \leftarrow k + 1 - d$
 $g \leftarrow 1/e$
 for $l = T$ downto 1
 $u_l \leftarrow g \cdot v_l$
 $v_l \leftarrow v_l - (e \cdot u_{l-1})$
 $p_l \leftarrow g \cdot q_l$
 $q_l \leftarrow q_l - (e \cdot p_{l-1})$

$$\begin{aligned}u_0 &\leftarrow g \cdot v_0 \\ p_0 &\leftarrow g \cdot q_0\end{aligned}$$

In the method described in Table A, the additions and subtractions are performed modulo two and the multiplications are performed under a Galois field. In a preferred embodiment, the Galois field has 256 elements. The method defines four vectors, u , v , p , and q , each of length $T+1$, where T is the correction power of the code. The u and p vectors are intermediate variables that are discarded at the completion of the process. At the completion of the process, the v vector holds the coefficients of the error locator polynomial and the q vector holds the coefficients of the error evaluator polynomial. The process also uses the variable d , which is used to control branch decisions, the variable k , which counts iterations through the main loop, and the variable e , the error term.

The preferred embodiment of the present invention has been optimized for minimum hardware, at the expense of increased execution time. In the prior art, the elements of the four vectors used by the Berlekamp method are stored in dedicated hardware registers. A considerable savings in hardware and cost is realized in the present invention by eliminating the individual registers and storing all the intermediate variables in a random access memory (RAM) or register file. The saving is achieved through the elimination of both the registers and the multiplexors to route the register contents to the arithmetic units. Placing all

intermediate variables in a RAM creates an execution bottleneck at the RAM. Speed could be recovered by using a multi-port RAM, but a single-port RAM is preferred due to cost considerations.

Fig. 2a is a block diagram of the preferred embodiment, which uses one RAM 204 and other well-known subsystems. Controller 228 controls the operation and timing of all other circuit elements. Control inputs of the various circuit elements are connected to outputs of controller 228. Status outputs of various circuit elements are connected to inputs of controller 228. All input and output connections are shown as control signals 230 in Fig. 2. The control signals used are described in detail below. RAM 204 is a RAM with a single, bi-directional port which can operate in an input mode and an output mode, controlled by control inputs. When in output mode, RAM 204 is coupled to the inputs of multiplexer (MUX) 206 and to Operand Register 1 (OP1) 208. MUX 206 selects between the output of RAM 204 and the output of OP1 208 to determine the input to Operand Register 2 (OP2) 210. OP1 208 and OP2 210 are eight-bit registers with selectable load functions controlled by controller 228. The outputs of OP1 208 and OP2 210 are coupled to forcing circuits 212 and 214, respectively. Forcing circuit 214 either passes the input to the output or drives the output to all zeros(0x00), depending on the state selected by controller 228. Forcing circuit 214 is designated force 0x00 in Fig. 2a to represent its all zeros forcing function. Forcing

circuit 214 includes eight two input AND gates. Forcing circuit 212 either passes the input to the output or drives the output to binary one (0x01), depending on the state selected by controller 228. Forcing circuit 212 includes seven two input AND gates, one two input OR gate, and an inverter.

The output of forcing circuit 212 is coupled to multiplier 224. Multiplier 224 is a Galois field multiplier which generates the product of two operands under the Galois field. Forcing circuit 212 supplies one operand. The other operand is supplied by MUX 220, which selects among the output of forcing circuit 214, the output of accumulator (ACC) 222 and the output of inverse read-only memory (ROM) 226, as controlled by controller 228. The output of multiplier 224 is coupled to adder 202, as is the output of forcing circuit 214. Adder 202 and adder 216 are modulo two adders, that is, each is eight independent XOR gates. Multiplier 224 supplies one operand for adder 202, forcing circuit 214 supplies the other operand. The output of adder 202 is coupled to RAM 204 and data is input into RAM 204 when controller 228 selects the input mode of RAM 204.

Inverse ROM 226 outputs the inverse, under the Galois field, of its input. The size of ROM 226 depends on the number of elements in the Galois field being used. In a preferred embodiment, a 256 element Galois field is used and the size of ROM 226 is 256 bytes. Since the inverse of zero is undefined, location zero of the inverse ROM is not used in normal operation, but is loaded with 0x01 and used

as element zero of the p vector during the first iteration of the main loop. Inverse ROM 226 accepts its input from ACC 222, which stores the data input to it. The input of ACC 222 is selected by MUX 218 from between the output of forcing circuit 214 and adder 216, as controlled by controller 228. Adder 216 accepts as operands the output of inverse ROM 226 and the output of ACC 222.

The size of the RAM depends on the maximum correction power that the key equation solver must support. The size of the RAM is equal to $4 \cdot I \cdot T + 2 \cdot T + 1$ bytes, where T is the maximum correction power of the code and I is the degree of the interleave. In a preferred embodiment, the key equation solver is capable of handling interleaved Reed-Solomon codewords, thus, I indicates the interleave of the codewords. The size of the rest of the hardware excluding the few gates used to generate the address into the RAM is independent of the correction power of the code. Table B gives the RAM size for various correction powers, with a three-way interleave assumed.

TABLE B

Correction Power	RAM Size (in bytes)
1	15
2	29
3	43

4	57
5	71
6	85

Fig. 2b is a block diagram of controller 228 of Fig. 2a. State machine 240 accepts inputs, generates outputs and controls the process. State machine 240 has 52 states, as described in greater detail in Figs 4a-k. Five counters are used to control the execution flow. The size of these five counters depends on the correction power of the code being used. In a preferred embodiment, the counters have the stated sizes. KCount 242 is a four-bit counter used to track iterations through the main loop of the process. DCount 244 is a four-bit counter used to resolve branch conditions in the main loop of the process. LCount 246 is a three-bit counter used as a general loop counter. ShiftIndex 248 is a three-bit counter that tracks how many times the u and p vectors have been shifted. Interleave 250 is a two-bit counter that is used to keep track of which interleave is being processed. Input signal TCount 276 indicates the correction power of the code to state machine 240. Input signal StartKES 278 initiates the process.

Twelve control signals are output from state machine 240. RAMAddr 252 is the address into RAM 204. RAMRead 254, when active, causes a read cycle to be performed from RAM 204. RAMWrite 256, when active, causes a write cycle to be performed to RAM 204. LoadOp1 258, when active, causes OP1 208 to be

loaded. LoadOp2, when active, causes OP2 210 to be loaded. LoadAcc 262, when active, causes ACC 222 to be loaded. ForceOp1 264, when active, causes forcing circuit 212 to drive 0x01 on its output. Otherwise, forcing circuit 212 passes through its input to its output. ForceOp2 266, when active, causes forcing circuit 214 to drive 0x00 on its output. Otherwise, forcing circuit 214 passes through its input to its output. OMuxSelOp1 268, when active, causes MUX 206 to select the input coupled to OP1 208 to be passed to the output. Otherwise, the input coupled to RAM 204 is passed to the output. AMuxSelOp2 270, when active, causes MUX 218 to select the input coupled to forcing circuit 214 to be passed to the output. Otherwise, the input coupled to adder 216 is passed to the output. MMuxSelOp2 272 and MMuxSelInv 274 together control MUX 220. When MMuxSelOp2 272 is active, it causes MUX 220 to select the input coupled to forcing circuit 214 to be passed to the output. When MMuxSelInv 274 is active, it causes the input coupled to inverse ROM 226 to be passed to the output. When both MMuxSelOp2 272 and MMuxSelInv 274 are inactive, the input coupled to ACC 222 is passed to the output. State machine 240 is designed not to allow both MMuxSelOp2 272 and MMuxSelInv 274 to be active simultaneously.

Figs 3a-k are a flow diagram of a process 300 which is performed by the present invention under the control of state machine 240. Each step in process 300 corresponds to a state of state machine 240 and are identified as states. The flow

diagram indicates the states of state machine 240, the output signals from state machine 240 and the input signals to state machine 240. State ZZ 301 is the idle or ambient state. Activation of the StartKES signal 278 causes state machine 240 to transition to state A 302. State A 302 initializes the counters and increments the interleave count. The process returns to this state at the end of processing of the first two interleaves. In state B 303, the computation of the error term e is begun. State B 303 is also the first state of the main loop of the process and so is entered $2*TCount$ times per interleave. The computation of the error term e occurs in one of three paths through the state machine. For the first two iterations of the main loop, e is first syndrome zero, then syndrome one. The path is State B 303 to State E 307. For the third iteration through $TCount$, e has $KCount$ terms and the path includes State B 303, State D 306, State F 305 and State G 308. For the last $TCount-1$ iterations, e has $TCount+1$ terms and the path includes State B 303, State C 304, State F 305 and State G 308. After e is computed, by any of the three paths, State H 309 is entered.

No computation occurs in state H 309 because the process branches on the value of e and e is loaded into ACC 222 concurrently with state H 309 being entered. From state H 309, the process may branch to any one of eleven different states. The first iteration of the main loop is treated as a special case. If $e = 0$, then the execution path is state I 310, state J 311 and state K 312. Otherwise, the

path is state L 313, state M 314 and state N 315. The operation of state K 312 requires further explanation. If $e = 0$, which must be true to be in state K 312, the u and p vectors are shifted. The initial condition of the p vector is element zero is one and all other elements are zero. In the first iteration of the main loop, element zero is set to zero and is never changed thereafter. Therefore, it is not necessary to actually allocate space in RAM 204 for element zero. This non-existent element zero is shifted into element one in state K 312. Since ACC 222 contains zero when in state K 312, the address into inverse ROM 226 is zero. Because the inverse of zero is not defined, this location in the ROM is not used in the normal way. Rather, this location is programmed with 0x01. In state K 312, it is this value which is transferred into the RAM location for element one of the p vector.

After iteration zero has completed, control from state H 309 flows down one of three main branches which correspond to the if, else-if, else structure presented in the pseudocode listing of Table A. Each of these three main branches has three entry points, one for $KCount < TCount$, one for $KCount = TCount$ and one for $KCount > TCount$. The three entry points to each branch are needed because variables stored in RAM 204 are not initialized prior to starting the key equation solver. In iteration k , element $k+1$ of the q vector, element q_{k+1} , must be assigned a new value based on an assumed current value of zero. The same is true for element k of the v vector, v_k . For the second else-if branch, p_{k+1} and u_k are

loaded with zeros. Therefore, if $KCount < TCount$, then q_{k+1} , v_k , p_{k+1} and u_k must be treated as special cases. If $KCount = TCount$, then only v_k and u_k must be treated as special cases. For $KCount > TCount$, all variables have previously been initialized and no special cases need be considered.

The *if* $e=0$ branch is the simplest to implement. For the case $KCount > TCount$, execution passes from state H 309 to state O 316 where $ShiftIndex$ 248 is incremented and control is passed to the next iteration. For $KCount = TCount$, State Q 318 is entered. In state Q 318, v_k is set to zero before going on to the next iteration of the main loop. For $KCount < TCount$, q_{k+1} is set to zero in state P 317, then v_k is set to zero in state Q 318. . .

The *else-if* $2*DCount \leq KCount+1$ branch is handled in state AA 319 through state AL 330. For the case $KCount > TCount$, all variables have previously been initialized. Elements $ShiftIndex$ through $TCount$ of the v vector need to be updated. Elements zero through $ShiftIndex-1$ are not modified because the corresponding elements of the u vector are known to be zero. Similarly, elements $ShiftIndex+1$ through $TCount$ of the q vector must be updated. One less element of the q vector than the v vector is updated because p_0 is always zero after the first iteration of the main loop. The path that handles the normal updating of the v and q vectors is a loop from state AB 320 through state AG 325, with the entry point through state AA 319 and the exit point through state AC 321. For the case

of $KCount=TCount$, v_k is not yet initialized and must be handled as a special case before dropping into the usual execution flow. The special handling is performed in state AL 330 and state AK 329. For the third case, $KCount<TCount$, both v_k and q_{k+1} are uninitialized and must be handled as special cases. Entry for this path is through state AH 326.

The final branch, the else branch, of the main loop is handled by state BA 331 through state BV 352. This branch is considerably more complicated because all for vectors require updating over different ranges of elements. For the case $KCount>TCount$, u_{T-1} through u_0 , v_T through $v_{ShiftIndex+1}$, p_{T-1} through p_1 , and q_T through $q_{ShiftIndex+2}$ must be computed. For the case $KCount=TCount$, the same variables must be updated and in addition v_T must be initialized. For the case $KCount<TCount$, u_k through u_0 , v_k through $v_{ShiftIndex+1}$, p_{k+1} through p_1 , and q_{k+1} through $q_{ShiftIndex+2}$ require updating. In addition, v_k and q_{k+1} must be initialized and u_k and p_{k+1} must be set to zero.

The circuit of Fig. 2a, as controlled by Figs. 3a-k implements the process described in Table A above. For example, Table C describes the interaction of circuitry and control signals which implement the step $q_i \leftarrow q_i - (e_i \cdot p_i)$:

TABLE C

State Machine Action	Result
State AD: RAMAddr = $q[\text{Interleave}][\text{LCount}]$ RAMRead LoadOp2	Fetch q_i : Address of q_i Read q_i from RAM Store q_i in OP2
State AE: RAMAddr = $p[\text{LCount-ShiftIndex}]$ RAMRead LoadOp1	Fetch p_i : Address of p_i Read p_i from RAM Store p_i in OP1
State AF: RAMAddr = $q[\text{Interleave}][\text{LCount}]$ RAMWrite Not active: MMuxSelOp2 and MmuxSelInv OmuxSelOp1	Multiply, subtract and store in q_i : Address of q_i Write $q_i - q_i(e_i p_i)$ MUX 220 selects ACC as one operand to multiplier (e was previously stored in ACC). Multiplier operands are OP1: p_i and ACC: e . Output from multiplier is $e_i p_i$ MUX 206 selects RAM output to be passed to OP2. Operands to adder 202 are multiplier output: $e_i p_i$ and OP2: q_i . Adder outputs $q_i - (e_i p_i)$ which is written to RAM

All the steps of the process described in Table A are implemented similarly, as will be seen by one of skill in the art.



CLAIMS

WHAT IS CLAIMED IS:

1. In a system for correcting errors in a Reed-Solomon encoded datastream, comprising a syndrome generator outputting syndromes of the datastream, a circuit, coupled to the syndrome generator and receiving the syndromes, for performing a computation of a plurality of coefficients of an error locator polynomial and a plurality of coefficients of an error evaluator polynomial, comprising:

an arithmetic unit iteratively generating intermediate and final values of the plurality of coefficients of an error locator polynomial and the plurality of coefficients of an error evaluator polynomial ;

a random access memory, storing data elements representing intermediate and final values of the plurality of coefficients of an error locator polynomial and the plurality of coefficients of an error evaluator polynomial; and

a control unit, controlling the arithmetic unit and the memory and detecting when the computation of the plurality of coefficients of an error locator polynomial and the plurality of coefficients of an error evaluator polynomial has been completed.



2. The circuit of claim 1, wherein the random access memory is a static random access memory.
3. The circuit of claim 1, wherein the random access memory is a single-port random access memory.
4. The circuit of claim 1, wherein the random access memory is a multi-port random access memory.
5. The circuit of claim 1, wherein the arithmetic unit comprises:
 - a first operand means, coupled to the memory, outputting a first operand;
 - a second operand means, coupled to the memory, outputting a second operand; and
 - a multiplier, coupled to the first operand means, the second operand means, and the memory, outputting a Galois field product of the first operand and the second operand for storage in the memory.
6. The circuit of claim 5, wherein the first operand means comprises:
 - a first means for outputting as the first operand a data element read from the memory;



a second means for outputting as the first operand a first predetermined data element; and

means for selecting either the output of the first means or the second means as the output of the first operand means.

7. The circuit of claim 6, wherein the second operand means comprises:

a third means for outputting as the second operand a data element read from the memory;

a fourth means for outputting as the second operand a second predetermined data element;

an accumulator, outputting a data element representing the accumulation of a plurality of data elements input to the accumulator;

a fifth means for outputting as the second operand the data element output from the accumulator;

an inverse ROM, outputting a data element representing the Galois field inverse of the data element output from the accumulator;

a sixth means for outputting as the second operand the data element output from the inverse ROM;



means for selecting the output of one of the third means, the fourth means, the fifth means or the sixth means as the output of the second operand means.

8. The circuit of claim 7, wherein the control unit comprises:
 - a counter, outputting a count of an iteration of the computation;
 - a finite state machine, having a plurality of inputs, including the count of the iteration of the computation and the correction power of the code, and having a plurality of outputs, controlling operation of the arithmetic unit and the memory,
9. The circuit of claim 5, wherein the control unit comprises:
 - a counter, outputting a count of an iteration of the computation;
 - a finite state machine, having a plurality of inputs, including the count of the iteration of the computation and the correction power of the code, and having a plurality of outputs, controlling operation of the arithmetic unit and the memory,
10. In a system for correcting errors in a Reed-Solomon encoded datastream, comprising a syndrome generator outputting syndromes of the datastream, a



circuit, coupled to the syndrome generator and receiving the syndromes, for performing a computation of a plurality of coefficients of an error locator polynomial and a plurality of coefficients of an error evaluator polynomial, comprising:

(a) an arithmetic unit performing arithmetic and logical operations on portions of the received syndromes, comprising:

a random access memory, having a bidirectional port selectably operable as an input or an output, storing a plurality of signals representing a plurality of data elements,

a first operand register, having an input coupled to the port of the memory and an output, storing a data element output from the memory,

a first forcing device, having an input coupled to the output of the first operand register and an output, selectably outputting either the input data element or a predetermined fixed data element,

a first multiplexer, having a first input coupled to the output of the first operand register, a second input coupled to the port of the memory and an output, selectably outputting either the data element output from the first operand register or the data element output from the memory,



a second operand register, having an input coupled to the output of the first multiplexer and an output, storing a second operand,

a second forcing device, having an input coupled to the second operand register and an output, selectably outputting either the input data element or a predetermined fixed data element,

a second multiplexer, having a first input coupled to the second forcing device, a second input, a third input and an output, outputting a data element selected from among the data elements present at its inputs,

a multiplier, having a first input coupled to the output of the first forcing device, a second input coupled to the output of the second multiplexer and an output, generating a data element representing the Galois field product of the data elements present at its inputs,

an accumulator, having an input and an output coupled to the second input of the second multiplexer, outputting a data element representing the accumulation of a plurality of data elements input to the accumulator,

an inverse ROM, having an input coupled to the output of the accumulator and an output coupled to the third input of the second



multiplexer, outputting a data element representing a Galois field inverse of the data element present on its input,

output from the accumulator,

a first adder, having a first input coupled to the output of the accumulator, a second input coupled to the output of the multiplier and an output, generating a data element representing a Galois field sum of the data elements present at its inputs,

a third multiplexer, having a first input coupled to the output of the second forcing device and a second input coupled to the output of the multiplier, outputting a data element selected from between those present at its inputs, and

a second adder, having a first input coupled to the output of the multiplier, a second input coupled to the output of the second forcing device and an output coupled to the port of the memory, outputting to the memory a data element representing a Galois field sum of the data elements present at its inputs; and

(b) a controller, controlling the sequence of operations performed by the arithmetic unit, comprising:

a first counter outputting a count of iterations of the computation,



a second counter outputting signals allowing branch conditions to be resolved,

a third counter outputting a loop count,

a fourth counter outputting the count of shifts of data elements stored in the memory,

a fifth counter outputting an interleave, and

a finite state machine, having as inputs the outputs of the five counters and having a sixth input accepting a signal indicating the correction power of the code and a seventh input accepting a signal indicating the state machine is to begin processing, and having twelve outputs, comprising:

a first output for the address of the data element to be accessed in the memory,

a second output which causes a data element to be output from the memory,

a third output which causes a data element to be input to the memory,

a fourth output which causes the first operand register to store a data element output from the memory,



a fifth output which causes the second operand register to store a data element output from the first multiplexer,

a sixth output which causes the accumulator to store a data element output from the second multiplexer,

a seventh output which causes the first forcing device to output a predetermined fixed data element,

an eighth output which causes the second forcing device to output a predetermined fixed data element,

a ninth output which causes the first multiplexer to select the data element stored in the first operand register to be output to the second operand register,

a tenth output which causes the second multiplexer to select the output from the second forcing device to be output to the accumulator,

an eleventh output which causes the third multiplexer to select the output from the second forcing device to be output to the multiplier, and

a twelfth output which causes the third multiplexer to select the output from the inverse ROM to be output to the multiplier.



11. The circuit of claim 10, wherein the random access memory is a static random access memory.

12. The circuit of claim 11, wherein the random access memory is a single-port random access memory.

13. The circuit of claim 12, wherein the random access memory is a multi-port random access memory.