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(54) SYSTEM, METHOD, AND SERVICE FOR PROVIDING A GENERIC RAID ENGINE AND OPTIMIZER

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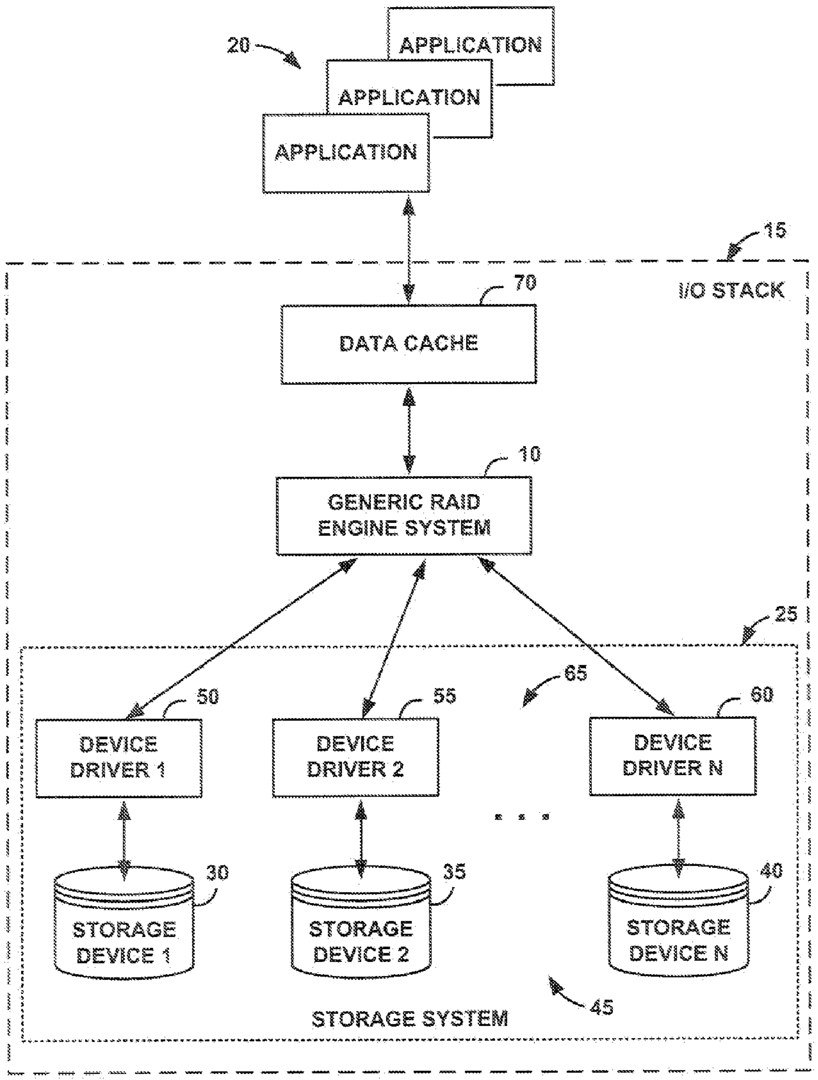
(57) **ABSTRACT**

A generic RAID engine system accepts an access request, accepts a metadata input comprising a layout description and, optionally, a plurality of resource optimization objectives, accepts a dynamic input comprising a dynamic state of an I/O stack comprising the generic RAID engine and a fault configuration of a plurality of storage devices in the I/O stack, and accepts RAID code input comprising information about the RAID code used by the I/O stack. The metadata input, the dynamic input, and the RAID code input are utilized to transform the access request into individual device reads and individual device writes such that RAID code relationships for the storage devices are maintained at all times. An optional optimizer module selects strategies that meet the resource optimization objectives.



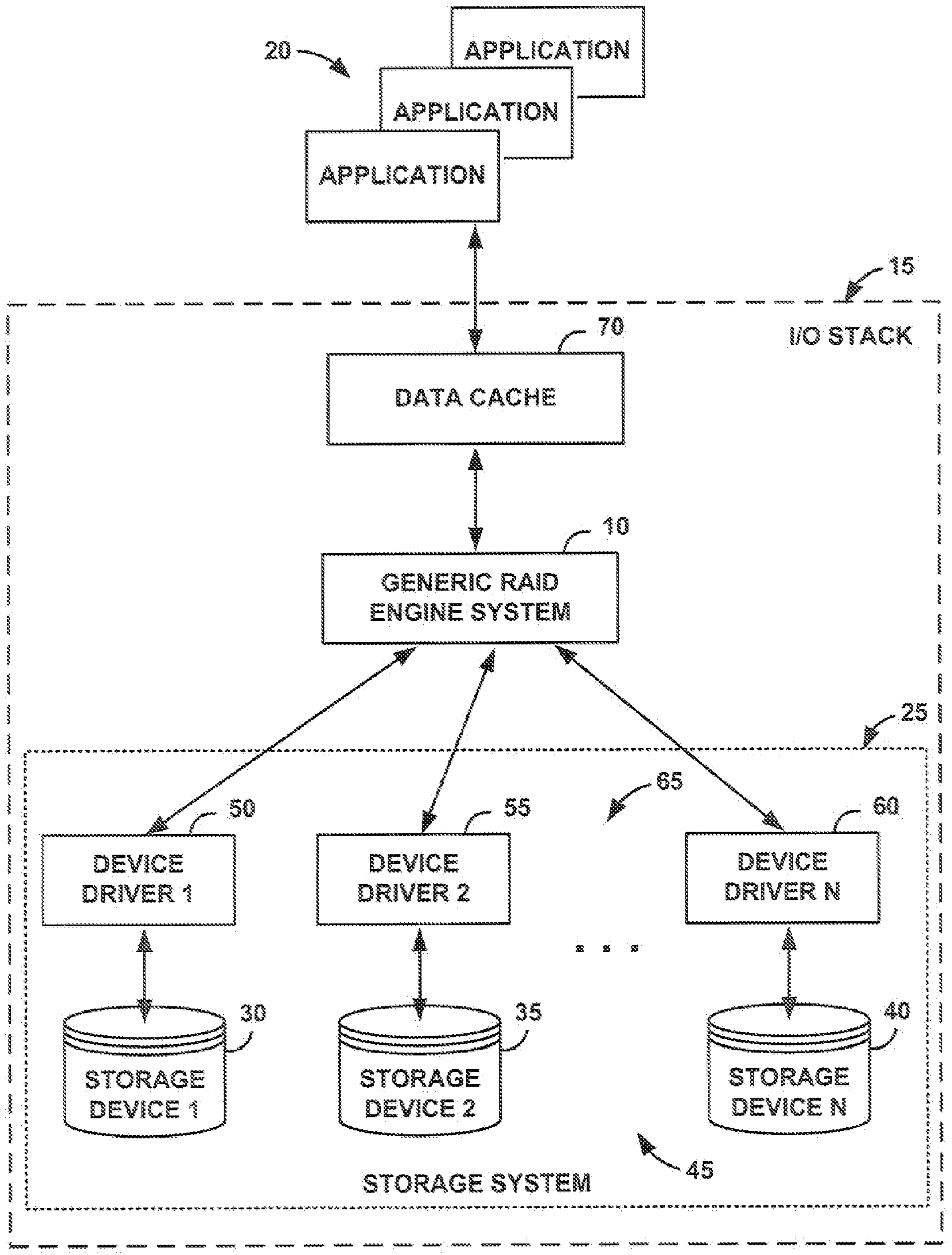

20
APPLICATION
APPLICATION
APPLICATION
15
I/O STACK
70
DATA CACHE
10
GENERIC RAID ENGINE SYSTEM
25
65
50
DEVICE DRIVER 1
55
DEVICE DRIVER 2
60
DEVICE DRIVER N
30
STORAGE DEVICE 1
35
STORAGE DEVICE 2
40
STORAGE DEVICE N
45
STORAGE SYSTEM

FIG. 1

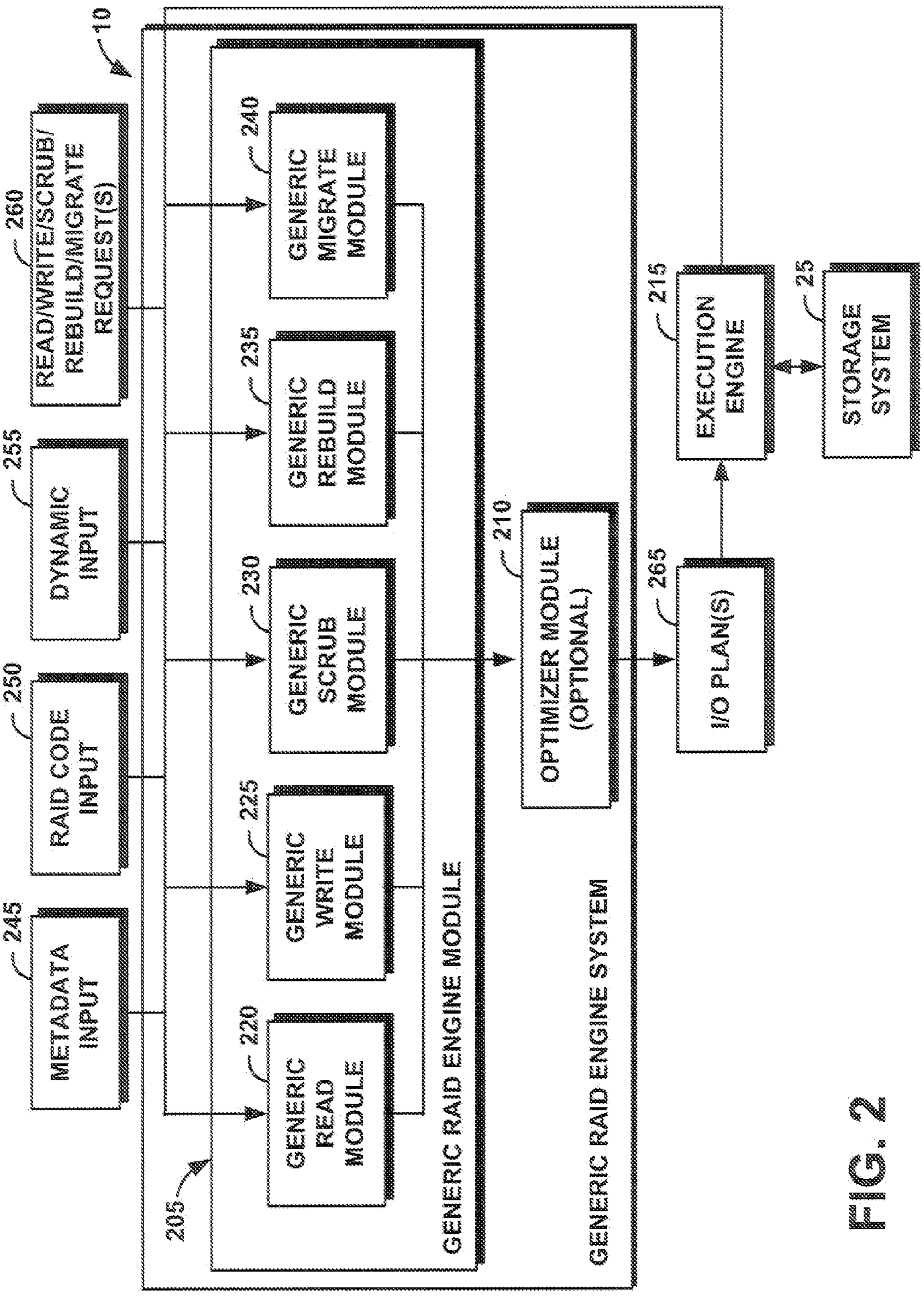

10
METADATA INPUT
245
RAID CODE INPUT
250
DYNAMIC INPUT
255
READ/WRITE/SCRUB/ REBUILD/MIGRATE REQUEST(S)
260
GENERIC READ MODULE
220
GENERIC WRITE MODULE
225
GENERIC SCRUB MODULE
230
GENERIC REBUILD MODULE
235
GENERIC MIGRATE MODULE
240
205
GENERIC RAID ENGINE MODULE
OPTIMIZER MODULE (OPTIONAL)
210
GENERIC RAID ENGINE SYSTEM
I/O PLAN(S)
265
EXECUTION ENGINE
215
STORAGE SYSTEM
25

FIG. 2

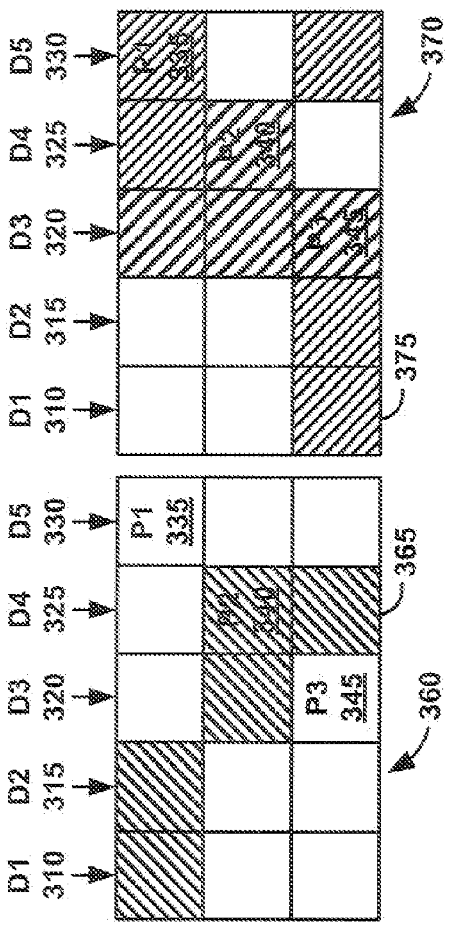


FIG. 3B

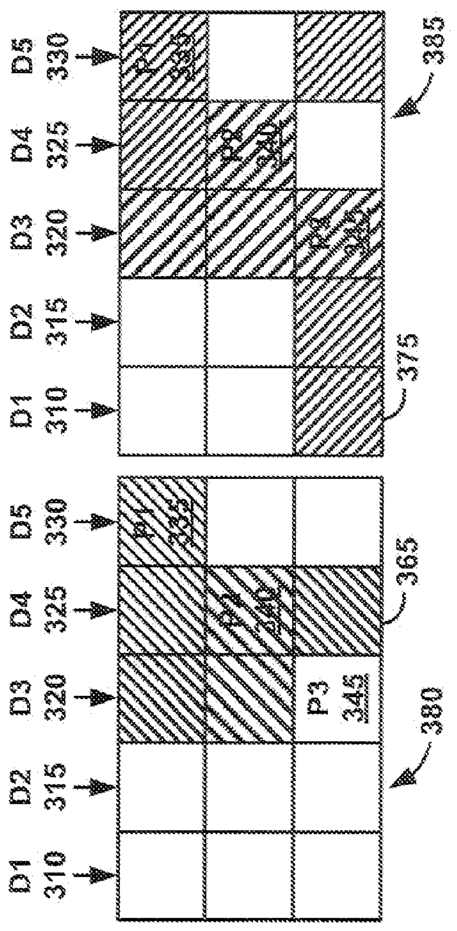


FIG. 3C

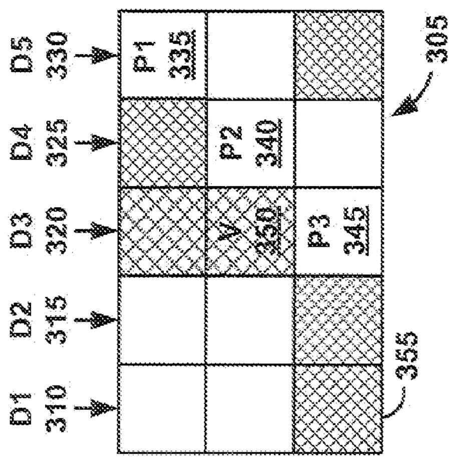


FIG. 3A

E1 440	E2 445	E3 450	E4 455	E5 460	E6 465	P1 470	P2 475	Q1 480	Q2 485
1	0	0	0	0	0	1	0	1	0
0	1	0	0	0	0	0	1	0	1
0	0	1	0	0	0	1	0	0	1
0	0	0	1	0	0	0	1	1	1
0	0	0	0	1	0	1	0	1	1
0	0	0	0	0	1	0	1	1	0

410

FIG. 4B

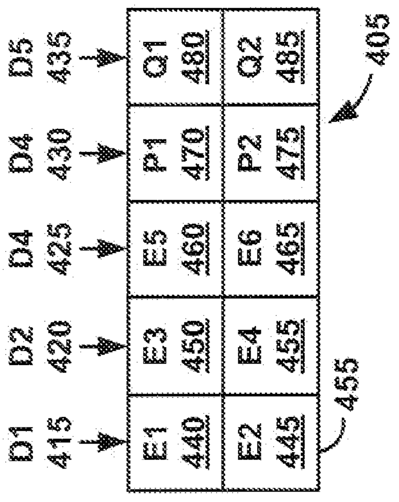


FIG. 4A

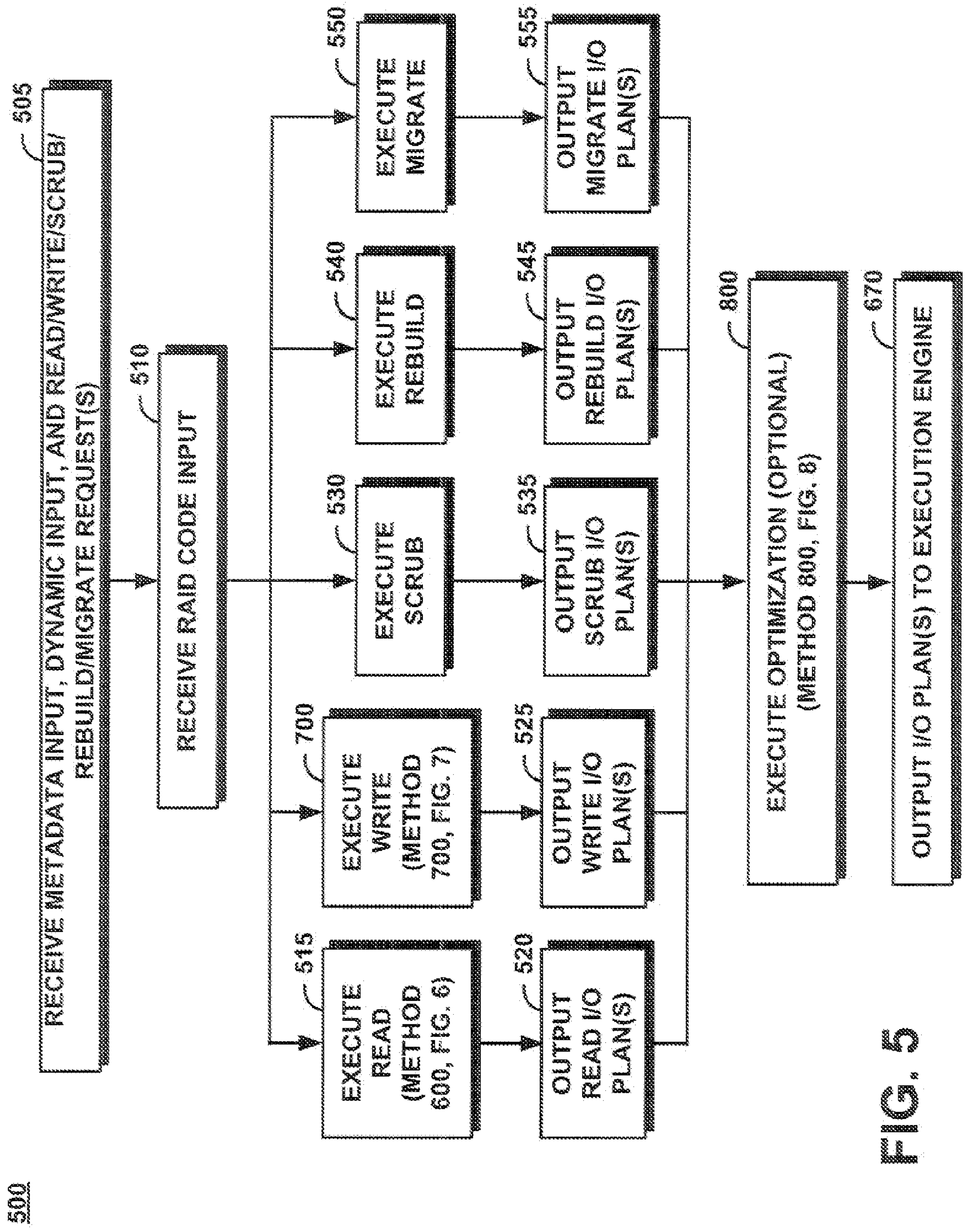

500
505
RECEIVE METADATA INPUT, DYNAMIC INPUT, AND READ/WRITE/SCRUB/REBUILD/MIGRATE REQUEST(S)
510
RECEIVE RAID CODE INPUT
515
EXECUTE READ (METHOD 600, FIG. 6)
700
EXECUTE WRITE (METHOD 700, FIG. 7)
530
EXECUTE SCRUB
540
EXECUTE REBUILD
550
EXECUTE MIGRATE
520
OUTPUT READ I/O PLAN(S)
525
OUTPUT WRITE I/O PLAN(S)
535
OUTPUT SCRUB I/O PLAN(S)
545
OUTPUT REBUILD I/O PLAN(S)
555
OUTPUT MIGRATE I/O PLAN(S)
800
EXECUTE OPTIMIZATION (OPTIONAL) (METHOD 800, FIG. 8)
670
OUTPUT I/O PLAN(S) TO EXECUTION ENGINE

FIG. 5

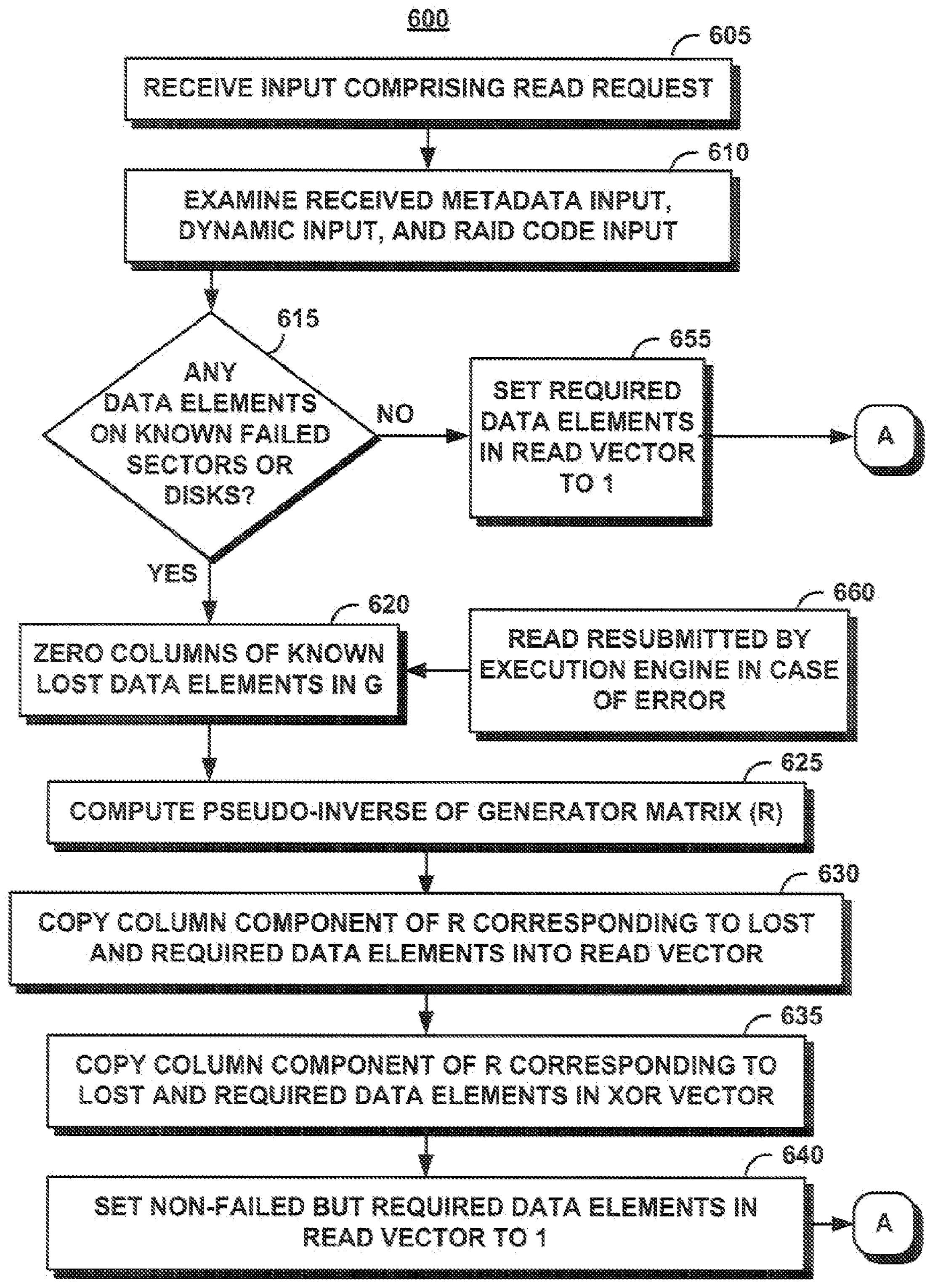

600
605
RECEIVE INPUT COMPRISING READ REQUEST
610
EXAMINE RECEIVED METADATA INPUT, DYNAMIC INPUT, AND RAID CODE INPUT
615
ANY DATA ELEMENTS ON KNOWN FAILED SECTORS OR DISKS?
NO
655
SET REQUIRED DATA ELEMENTS IN READ VECTOR TO 1
A
YES
620
ZERO COLUMNS OF KNOWN LOST DATA ELEMENTS IN G
660
READ RESUBMITTED BY EXECUTION ENGINE IN CASE OF ERROR
625
COMPUTE PSEUDO-INVERSE OF GENERATOR MATRIX (R)
630
COPY COLUMN COMPONENT OF R CORRESPONDING TO LOST AND REQUIRED DATA ELEMENTS INTO READ VECTOR
635
COPY COLUMN COMPONENT OF R CORRESPONDING TO LOST AND REQUIRED DATA ELEMENTS IN XOR VECTOR
640
SET NON-FAILED BUT REQUIRED DATA ELEMENTS IN READ VECTOR TO 1
A

FIG. 6A

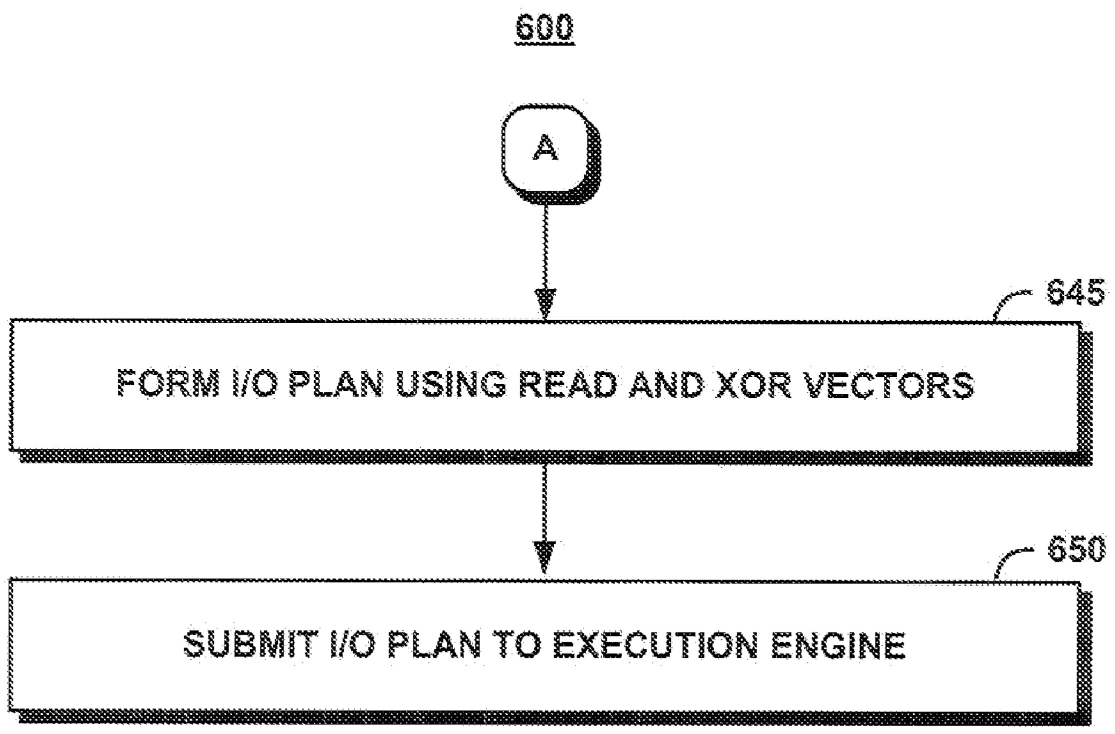

600
A
645
FORM I/O PLAN USING READ AND XOR VECTORS
650
SUBMIT I/O PLAN TO EXECUTION ENGINE

FIG. 6B

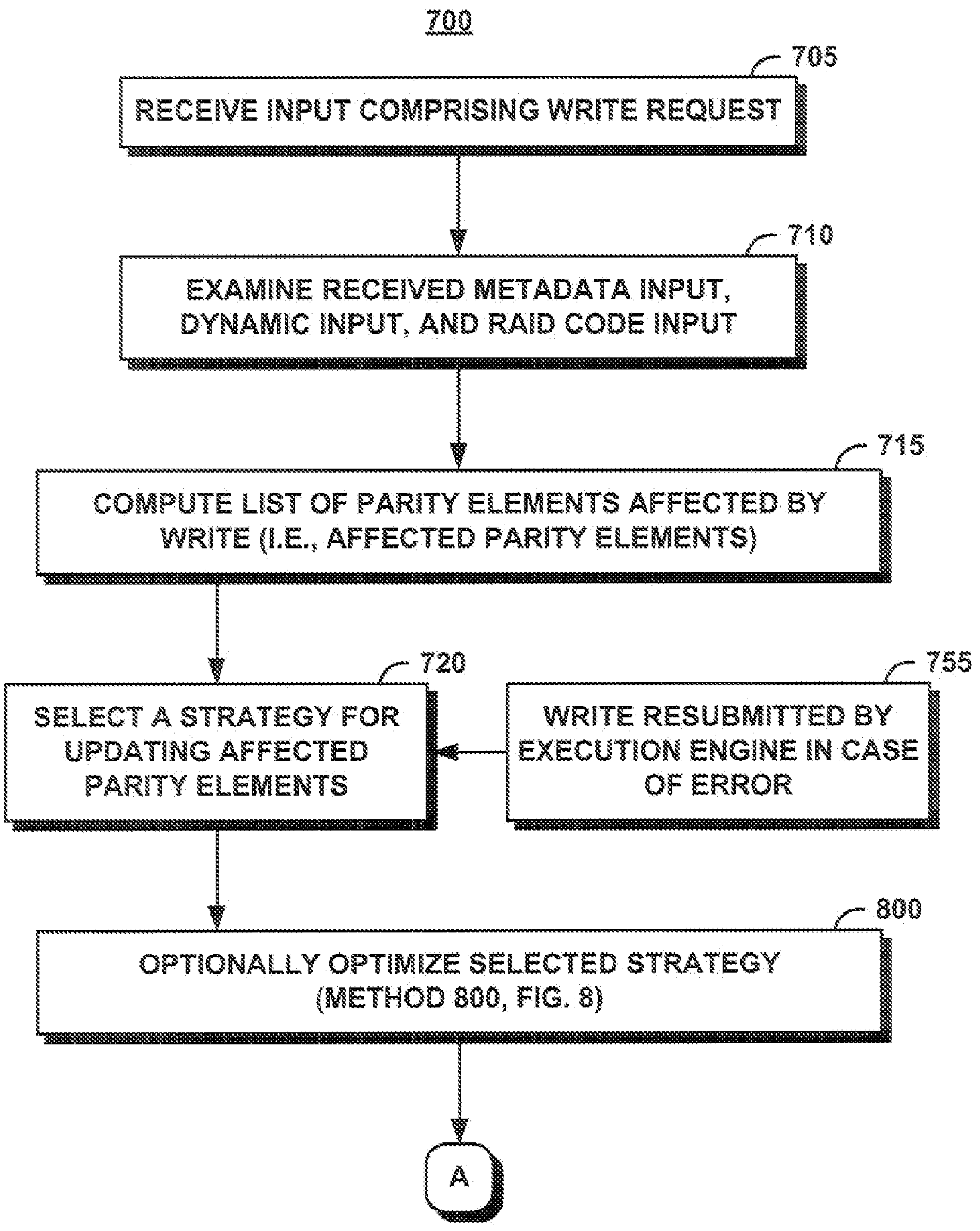

700
705
RECEIVE INPUT COMPRISING WRITE REQUEST
710
EXAMINE RECEIVED METADATA INPUT, DYNAMIC INPUT, AND RAID CODE INPUT
715
COMPUTE LIST OF PARITY ELEMENTS AFFECTED BY WRITE (I.E., AFFECTED PARITY ELEMENTS)
720
SELECT A STRATEGY FOR UPDATING AFFECTED PARITY ELEMENTS
755
WRITE RESUBMITTED BY EXECUTION ENGINE IN CASE OF ERROR
800
OPTIONALLY OPTIMIZE SELECTED STRATEGY (METHOD 800, FIG. 8)
A

FIG. 7A

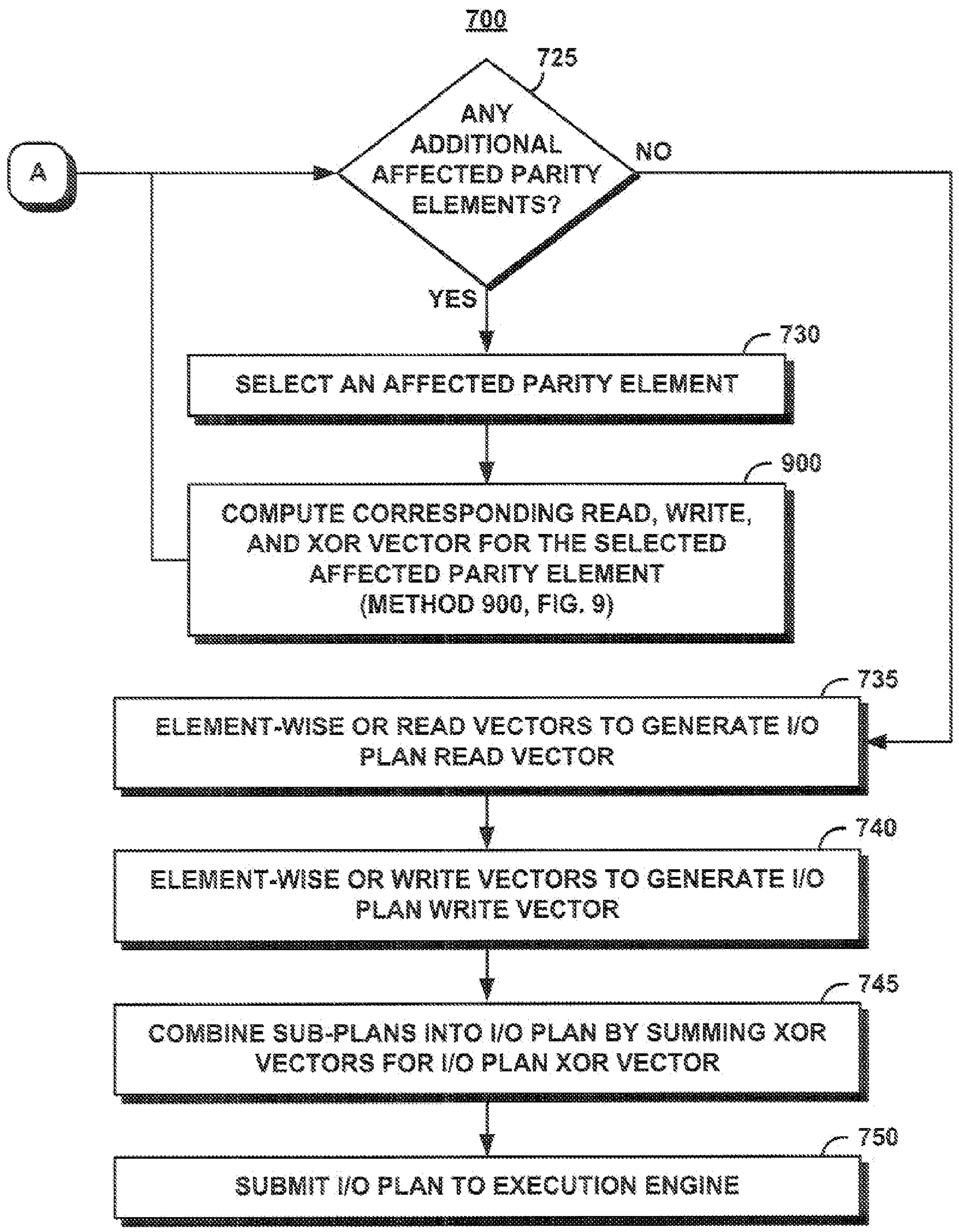

700
725
ANY ADDITIONAL AFFECTED PARITY ELEMENTS?
A
NO
YES
730
SELECT AN AFFECTED PARITY ELEMENT
900
COMPUTE CORRESPONDING READ, WRITE, AND XOR VECTOR FOR THE SELECTED AFFECTED PARITY ELEMENT (METHOD 900, FIG. 9)
735
ELEMENT-WISE OR READ VECTORS TO GENERATE I/O PLAN READ VECTOR
740
ELEMENT-WISE OR WRITE VECTORS TO GENERATE I/O PLAN WRITE VECTOR
745
COMBINE SUB-PLANS INTO I/O PLAN BY SUMMING XOR VECTORS FOR I/O PLAN XOR VECTOR
750
SUBMIT I/O PLAN TO EXECUTION ENGINE

FIG. 7B

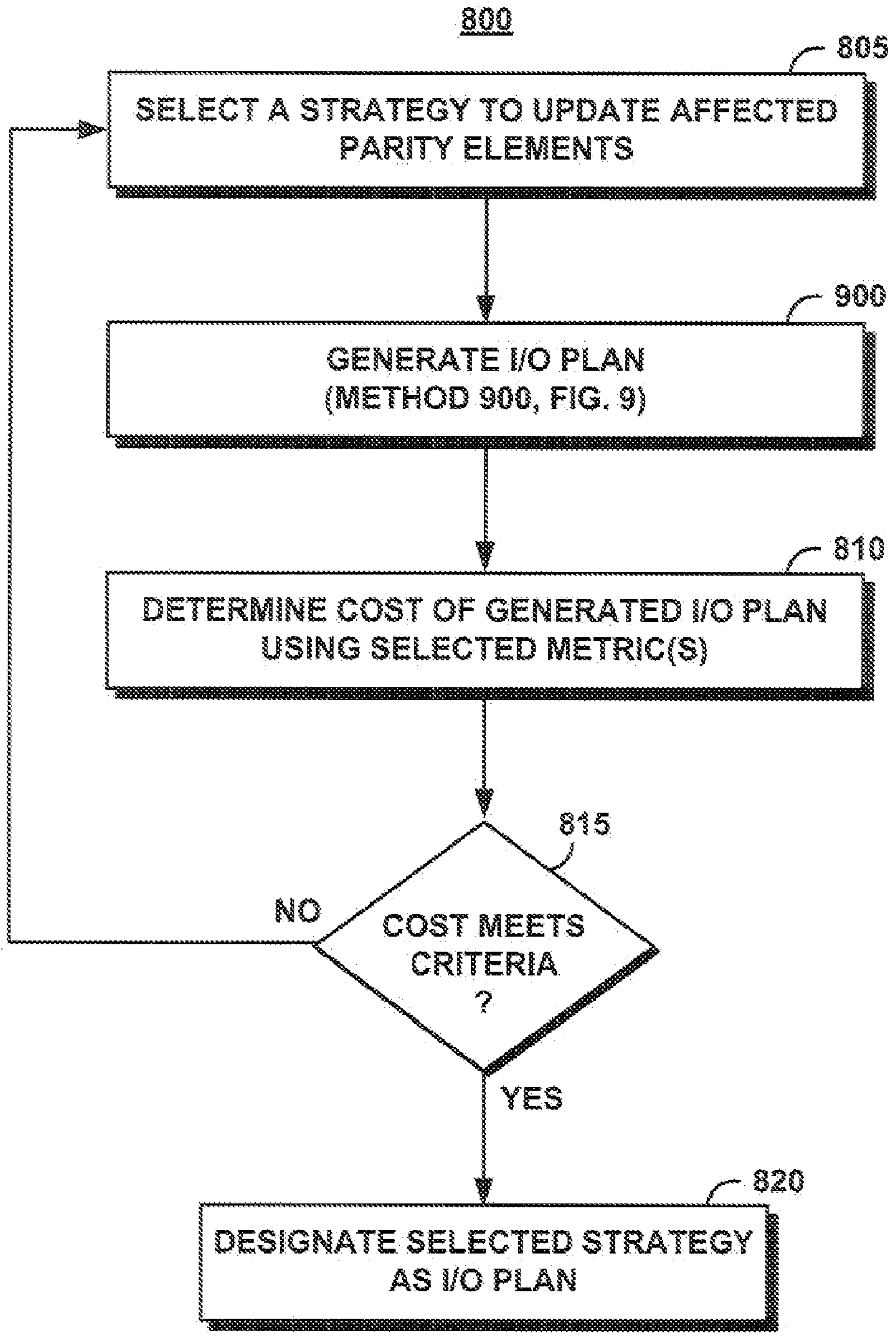

800
805
SELECT A STRATEGY TO UPDATE AFFECTED PARITY ELEMENTS
900
GENERATE I/O PLAN (METHOD 900, FIG. 9)
810
DETERMINE COST OF GENERATED I/O PLAN USING SELECTED METRIC(S)
815
COST MEETS CRITERIA ?
NO
YES
820
DESIGNATE SELECTED STRATEGY AS I/O PLAN

FIG. 8

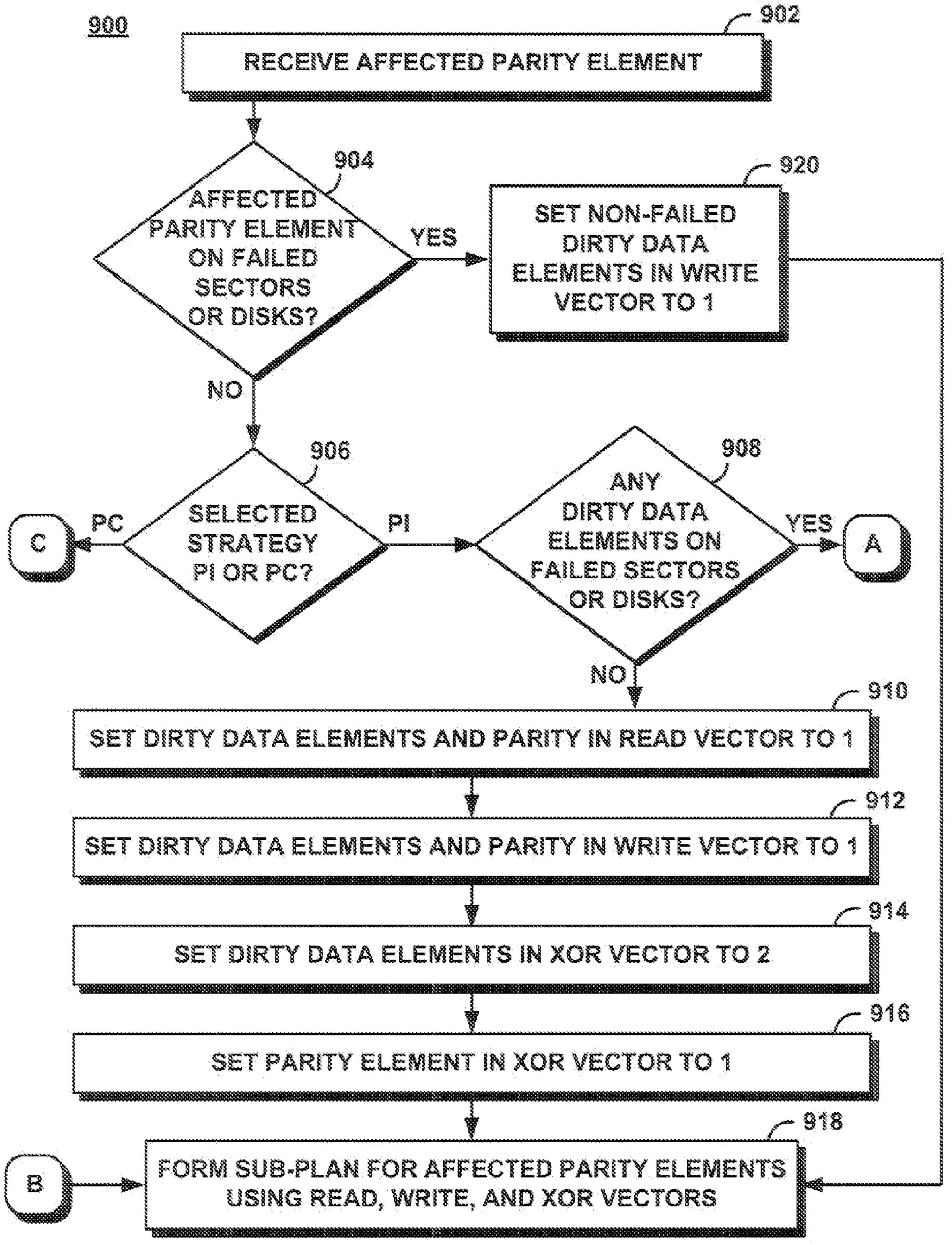

900
902
RECEIVE AFFECTED PARITY ELEMENT
904
AFFECTED PARITY ELEMENT ON FAILED SECTORS OR DISKS?
YES
NO
920
SET NON-FAILED DIRTY DATA ELEMENTS IN WRITE VECTOR TO 1
906
SELECTED STRATEGY PI OR PC?
PC
PI
C
908
ANY DIRTY DATA ELEMENTS ON FAILED SECTORS OR DISKS?
YES
A
NO
910
SET DIRTY DATA ELEMENTS AND PARITY IN READ VECTOR TO 1
912
SET DIRTY DATA ELEMENTS AND PARITY IN WRITE VECTOR TO 1
914
SET DIRTY DATA ELEMENTS IN XOR VECTOR TO 2
916
SET PARITY ELEMENT IN XOR VECTOR TO 1
918
B
FORM SUB-PLAN FOR AFFECTED PARITY ELEMENTS USING READ, WRITE, AND XOR VECTORS

FIG. 9A

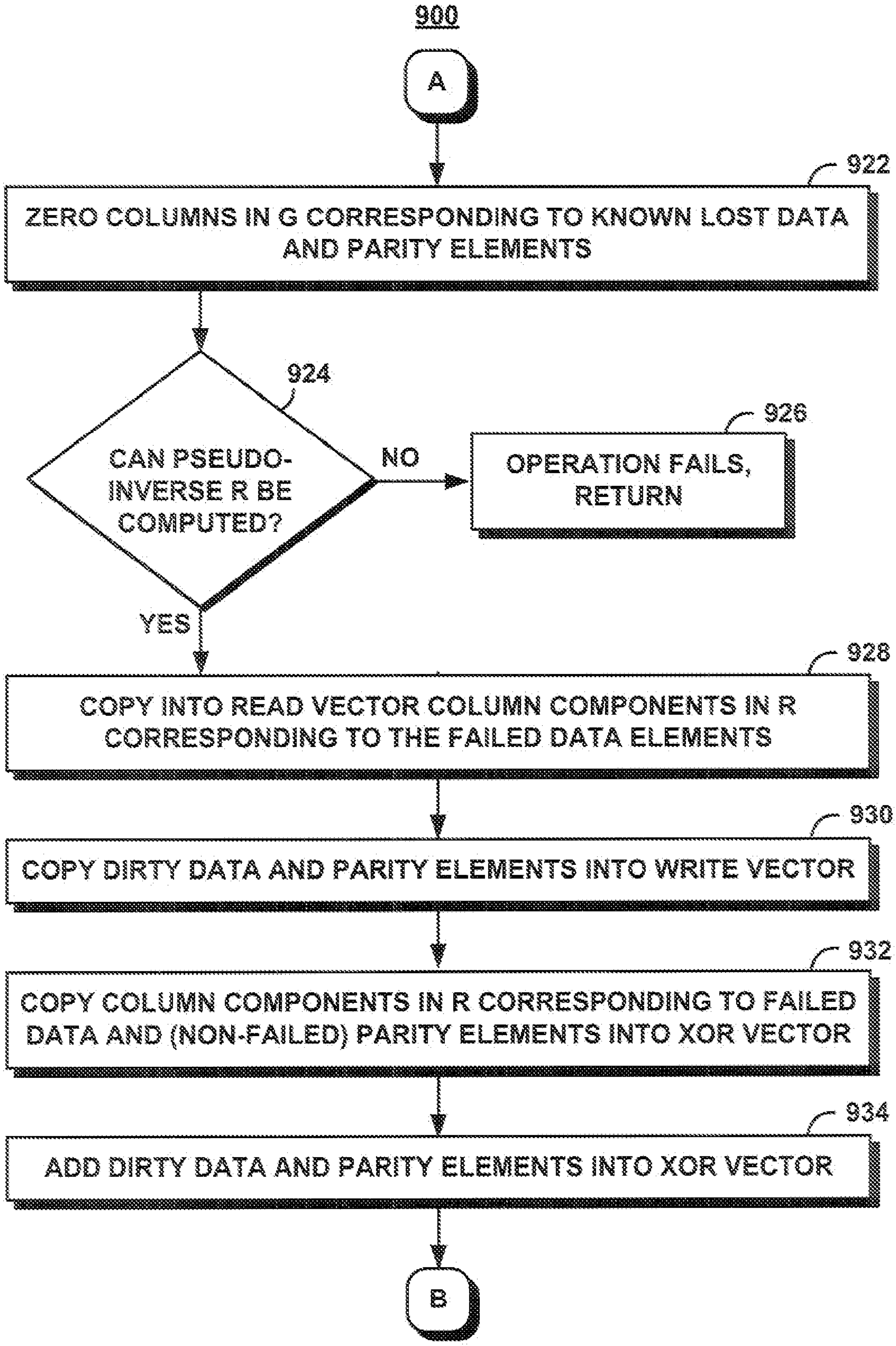

900
A
922
ZERO COLUMNS IN G CORRESPONDING TO KNOWN LOST DATA AND PARITY ELEMENTS
924
CAN PSEUDO-INVERSE R BE COMPUTED?
NO
926
OPERATION FAILS, RETURN
YES
928
COPY INTO READ VECTOR COLUMN COMPONENTS IN R CORRESPONDING TO THE FAILED DATA ELEMENTS
930
COPY DIRTY DATA AND PARITY ELEMENTS INTO WRITE VECTOR
932
COPY COLUMN COMPONENTS IN R CORRESPONDING TO FAILED DATA AND (NON-FAILED) PARITY ELEMENTS INTO XOR VECTOR
934
ADD DIRTY DATA AND PARITY ELEMENTS INTO XOR VECTOR
B

FIG. 9B

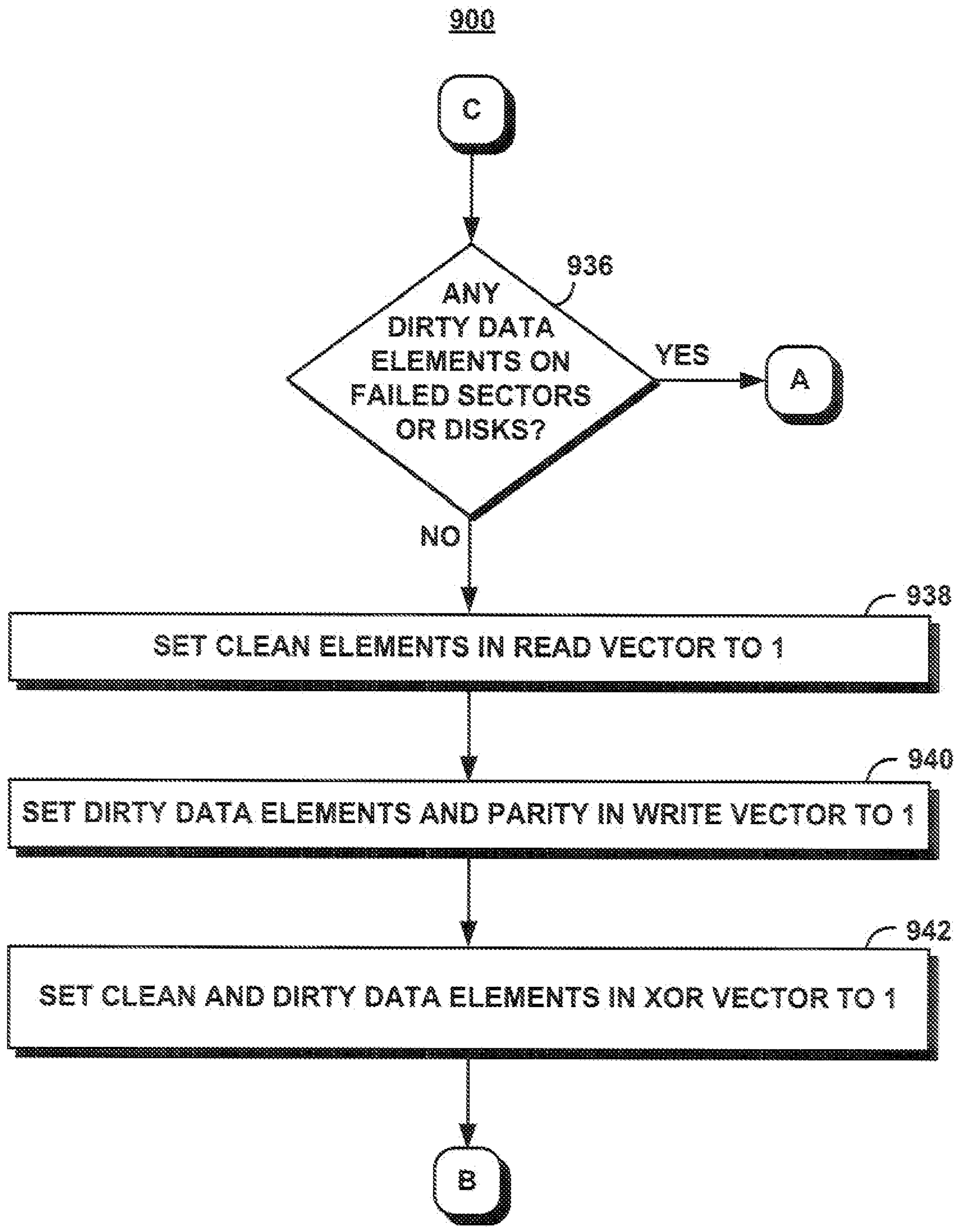

900
C
936
ANY DIRTY DATA ELEMENTS ON FAILED SECTORS OR DISKS?
YES
A
NO
938
SET CLEAN ELEMENTS IN READ VECTOR TO 1
940
SET DIRTY DATA ELEMENTS AND PARITY IN WRITE VECTOR TO 1
942
SET CLEAN AND DIRTY DATA ELEMENTS IN XOR VECTOR TO 1
B

FIG. 9C

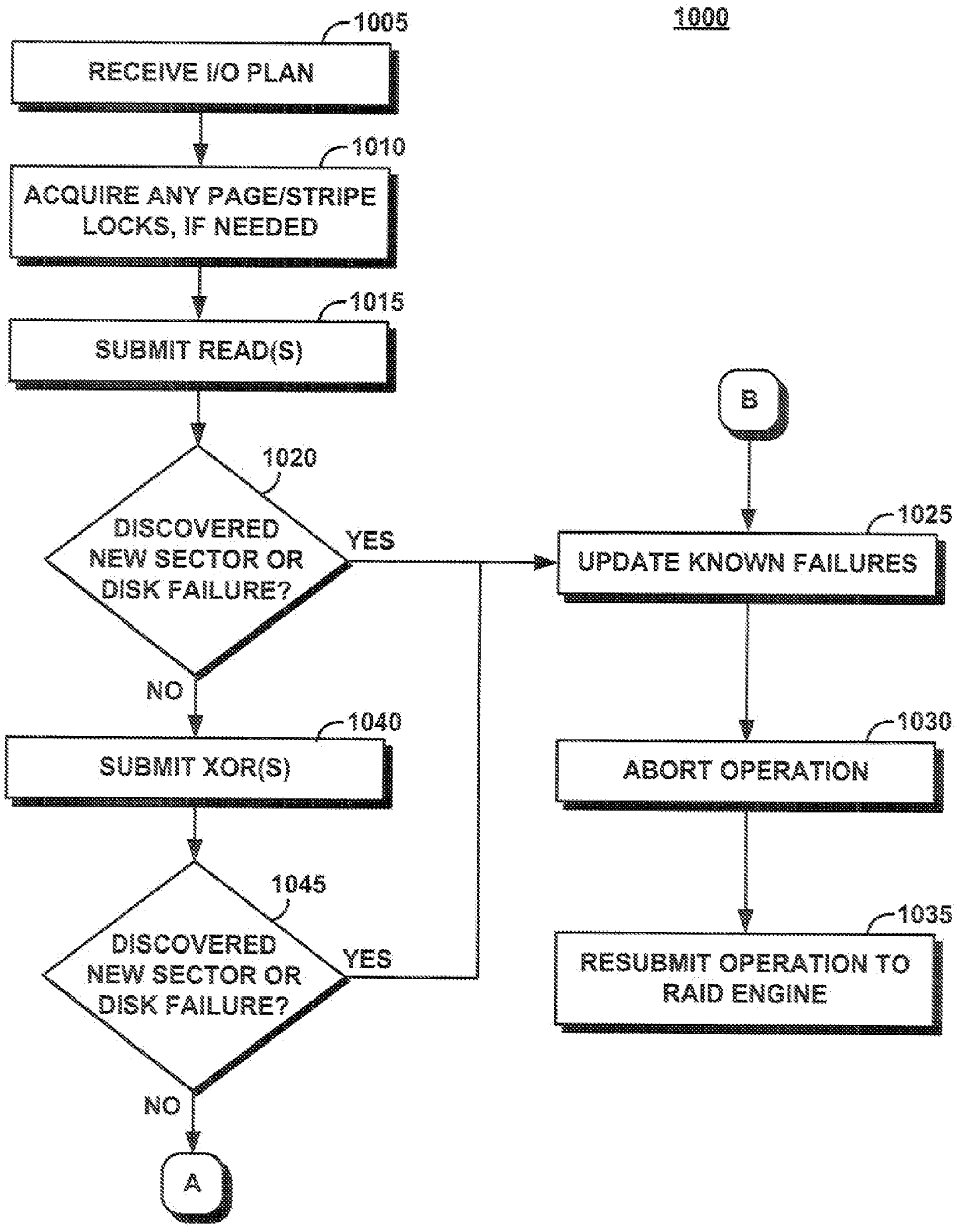

1000
1005
RECEIVE I/O PLAN
1010
ACQUIRE ANY PAGE/STRIPE LOCKS, IF NEEDED
1015
SUBMIT READ(S)
1020
DISCOVERED NEW SECTOR OR DISK FAILURE?
YES
NO
1040
SUBMIT XOR(S)
1045
DISCOVERED NEW SECTOR OR DISK FAILURE?
YES
NO
A
B
1025
UPDATE KNOWN FAILURES
1030
ABORT OPERATION
1035
RESUBMIT OPERATION TO RAID ENGINE

FIG. 10A

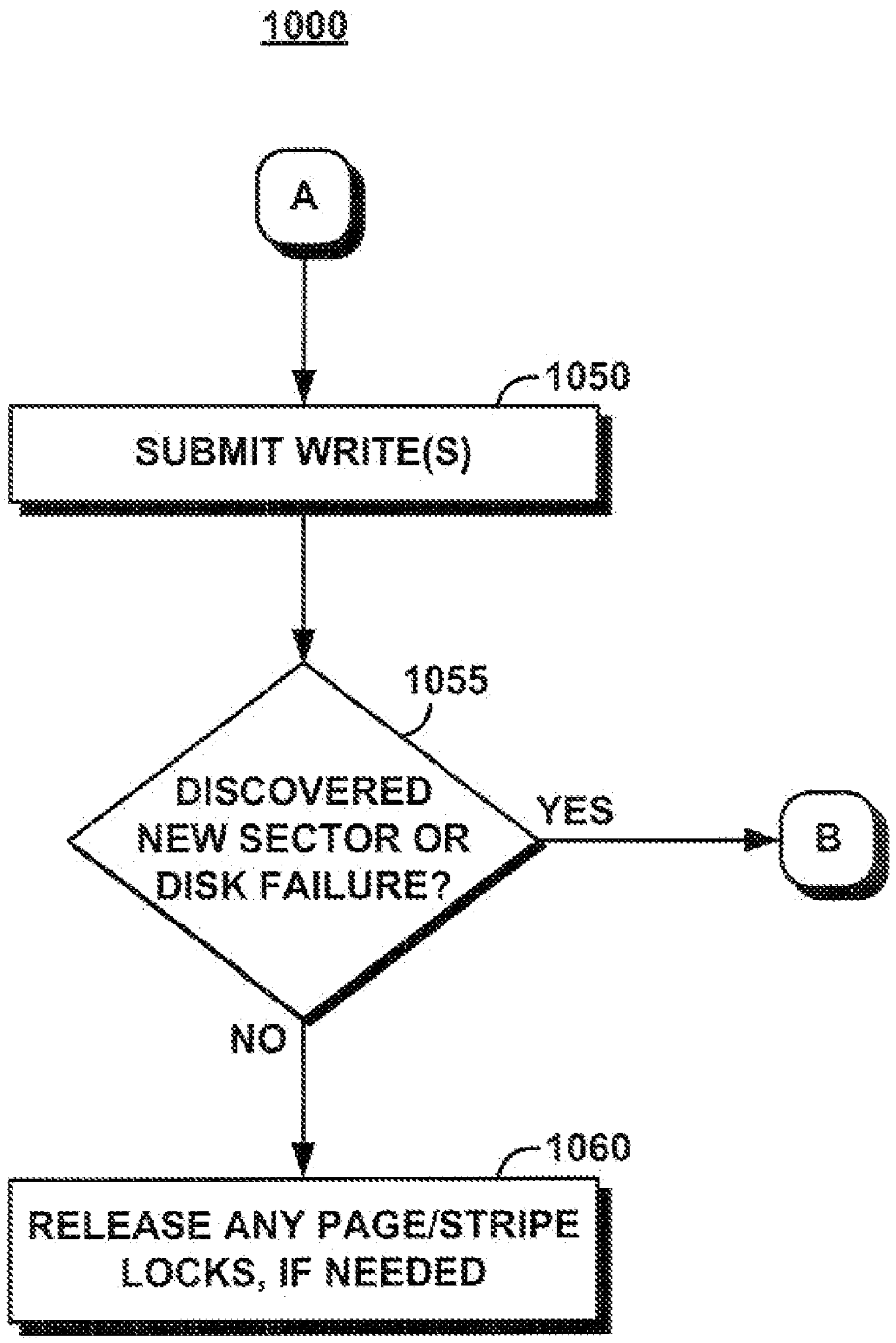

1000
A
1050
SUBMIT WRITE(S)
1055
DISCOVERED NEW SECTOR OR DISK FAILURE?
YES
B
NO
1060
RELEASE ANY PAGE/STRIPE LOCKS, IF NEEDED

FIG. 10B

SYSTEM, METHOD, AND SERVICE FOR PROVIDING A GENERIC RAID ENGINE AND OPTIMIZER

FIELD OF THE INVENTION

[0001] The present invention generally relates to data storage. More specifically, the present invention relates to providing fault tolerance for a storage system comprising RAID coded storage volumes.

BACKGROUND OF THE INVENTION

[0002] Conventional applications requiring reliable data storage typically use commonly available RAID (redundant array of independent disks) levels to protect against data loss due to media or disk failures. Although conventional RAID technology has proven to be useful, it would be desirable to present additional improvements. With a marked rise in the quantity of stored data and no commensurate improvement in disk reliability, a variety of RAID codes are becoming essential to containing data management costs. However, rolling out new RAID codes is challenging as well as cost prohibitive since the new RAID codes require significant development, testing, and tuning efforts.

[0003] Until recently, protecting customer data from loss due to media failure and/or device failures meant storing the using one of a basic set of RAID codes representing various levels of data protection and storage performance. To handle higher performance and reliability needs of customers, storage vendors deployed additional codes (e.g., RAID 51) as variations on that basic set. These additional codes were primarily offered as a result of juggling the inherent risk-reward trade-off from a software engineering standpoint as opposed to improving storage efficiency or performance. These additional codes can be composed by reusing (e.g., hierarchically) the basic RAID set, thus minimizing the amount of additional source code introduced. Consequently, product-marketing needs were satisfied with a low testing expense.

[0004] Only a few RAID codes were supported in traditional RAID implementations (firmware) for a variety of reasons: firmware complexity, software maintainability, and field upgrade difficulty. Firmware complexity, as measured by the number of paths that need to be tested, grows with every supported RAID code. Increased complexity increases development and test costs. The firmware becomes a collection of special cases making it hard to perform path length optimizations. In addition, performance tuning becomes difficult, if not prohibitively expensive.

[0005] From a software maintainability standpoint, a collection of "if . . . then . . . else . . . " code blocks makes firmware readability harder, making the firmware more prone to bugs. Each rollout of a RAID code requires field upgrades. Upgrading firmware and drivers is not a task that a storage administrator relishes, given the propensity of upgrades to trigger other problems.

[0006] Since deploying firmware changes is painful, there is a general mindset to avoid it all costs. However, recent trends in storage-technology and customer focus are forcing a re-evaluation of this status quo because of a need for supporting a variety of RAID codes in a system, growth in reference data, a growing popularity of modular systems, and a growing use of low cost serial disks to build high performance systems.

[0007] No single RAID code satisfies all aspects of data storage. In a world where the volume of customer data is rising due to various reasons from business transformation to regulatory requirements, it is becoming increasing important to store data at levels of reliability, performance and efficiency that are proportional to the "business" value of the data. Information life-cycle management (ILM) is becoming crucial to cost containment. Supporting a variety of RAID codes thus becomes integral to effective information life-cycle management.

[0008] The additive nature of reference data in organizations implies that the same storage manages a wide variety of scales of data sets from gigabytes to petabytes at the same reliability level. Using a single RAID code in this application is challenging. These data sets typically span many disks, indicating a relatively high probability of simultaneous failures. Furthermore, while disk capacities are increasing, the hard error rate (HER) due to media deterioration, channel errors, etc., has remains relatively constant. Combined, these trends raise the frequency of data loss events as data sets grow unless RAID codes with a higher fault tolerance are used.

[0009] The use of modular (or brick) systems to build storage systems that scale capacity, reliability and performance simultaneously is a trend that is gaining popularity. Many of these systems embrace deferred maintenance to reduce the cost of managing such systems. In a "fail in place" service strategy, software isolates failed components and rebuilds stored data on surviving bricks. As long as there is sufficient spare capacity, replacement of failed components can be deferred to bi-annual or multi-year cycles.

[0010] A further trend is the growing use of low cost serial ATA (SATA) disks to build high performance systems. SATA disks have hard error rates that are 10 times higher than comparable SCSI disks while costing about 35-55% less. Consequently, providing various data reliability levels using cheaper but less reliable disks requires a greater variety of RAID codes.

[0011] One conventional approach, RAIDframe, focuses on providing firmware environments that permit rapid prototyping and evaluation of redundant disk array architectures. Although this approach has proven to be useful, it would be desirable to present additional improvements. This approach modularizes the basic functions that differentiate RAID architectures: mapping, encoding, and caching. This modularization allows each aspect to be modified independently, creating new designs. In RAIDframe, array operations are modeled as directed acyclic graphs (DAGs) that specify the architectural dependencies (and execution) between primitives. RAIDframe provides no simplification or automation of error handling. Furthermore, RAIDframe has no ability to automatically tune performance.

[0012] Other conventional approaches utilize a RAID system-on-a-chip (SOC) product. Although these approaches have proven to be useful, it would be desirable to present additional improvements. For example, one such approach contains an embedded processor, DMA/XOR engines, and host and disk interface logic (FC and SATA). Since the processor is programmable, it is conceivable that this approach may support a variety of RAID codes. However, all error paths are specified as callbacks written by the developer. Further, tuning of this performance approach is only minimally automatic, if at all.

[0013] What is therefore needed is a solution to provide a variety of RAID codes without compromising the quality, performance, and maintainability of the firmware. Such a method allows for adding new RAID codes without bloating the firmware. Many RAID codes have been proposed such as, for example, EVEN ODD, generalized EVENODD, X-code, RDP, and WEAVER. A common trend in these RAID codes is to focus on XOR-based RAID codes since they can be efficiently implemented in hardware or software. Non-XOR codes such as LDPC and Reed-Solomon have been developed, but these have not become popular since they offer no special advantage over XOR based codes.

[0014] A solution is required to automatically handle any RAID code related error. An example of such an error path is, on a read, encountering a read error due to a failed sector or disk. Since error handling is a large fraction of a firmware, the solution should unify fault-free and fault-ridden cases into common code paths.

[0015] The solution is further required to simplify nested error paths inherent in firmware. An example of a nested error path is when, in the process of reconstructing a lost block due to a previous failure, a new sector or disk failure is discovered. If the RAID code encounters such nested error paths, the solution is required to automatically determine how to reconstruct the lost block.

[0016] Furthermore, the solution is required to automatically tune performance for every I/O operation performed by leveraging dynamic state such as currently cached pages.

[0017] What is therefore needed is a system, a service, a computer program product, and an associated method for providing a generic RAID engine and optimizer. Such a system should work for any XOR-based erasure (RAID) code and under any combination of sector or disk failures. The need for such a solution has heretofore remained unsatisfied.

SUMMARY OF THE INVENTION

[0018] The present invention satisfies this need, and presents a system, a service, a computer program product, and an associated method (collectively referred to herein as "the system" or "the present system") for providing a generic RAID engine and optimizer.

[0019] The present system accepts an access request, accepts a metadata input comprising a layout description and, optionally, a plurality of resource optimization objectives, accepts a dynamic input comprising a dynamic state of an I/O stack comprising the generic RAID engine and a fault configuration of a plurality of storage devices in the I/O stack, and accepts RAID code input comprising information about the RAID code used by the I/O stack. The present system utilizes the metadata input the dynamic input, and the RAID code input to transform the access request into individual device reads and individual device writes such that RAID code relationships for the storage devices are maintained at all times. An optional optimizer module of the present system selects strategies that meet the resource optimization objectives.

[0020] The layout description comprises a description of a rotation, a stripe size, and an element size of each of a plurality of disks in the storage devices.

[0021] The resource optimization objectives comprise minimizing disk I/O and minimizing memory bus bandwidth for the access request.

[0022] The dynamic input comprises a description of a data cache of the I/O stack regarding a description of clean pages in the data cache, a description of dirty pages in the data cache, the clean pages and the dirty pages being in a W-neighborhood of a page to be any of read and written.

[0023] The fault configuration comprises a description of known sector failures and a plurality of known disk failures.

[0024] Transforming a write request comprises constructing a plurality of affected parity vectors, preparing a failure vector appropriate to the degraded layout, computing a plurality of inverse matrices, and generating a plurality of subplans by combining individual vectors. Transforming a write request further comprises reblocking (according to the generator matrix for the RAID code) the read and write vectors and generating a write I/O plan comprising the matrices for performing individual device read and writes.

[0025] Transforming a read request comprises determining if any faults exist in the disks of the storage system that prevent a successful read, if faults exist, the present system zeroes column components in the generator matrix corresponding to the failed elements and computes its pseudo-inverse, translates this matrix for consideration to device reads, reblocks (as in the generator matrix for the RAID code) and generates a read I/O plan for performing individual device reads.

[0026] Transforming the access request further comprises any of executing a scrub, executing a rebuild, and executing a migrate.

[0027] The present system may be embodied in a utility program such as a generic RAID engine utility program. The present system also provides a method for the user to specifying input comprising metadata input, RAID code input, and dynamic input and then invoking the generic RAID code engine utility to execute read requests and write requests. The metadata input comprises disk layout information such as rotation, stripe size, element size, etc. The metadata input optionally comprises optimization criteria such as, for example, minimizing disk I/O or minimizing bus bandwidth. The dynamic input comprises information regarding a data cache such as a description of dean pages and dirty pages in a W-neighborhood of pages to be read or written. The dynamic input further comprises a current fault configuration comprising a description of known sector failures and disk failures. The RAID code input comprises a concise description of the RAID code.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] The various features of the present invention and the manner of attaining them will be described in greater detail with reference to the following description, claims, and drawings, wherein reference numerals are reused, where appropriate, to indicate a correspondence between the referenced items, and wherein:

[0029] FIG. **1** is a schematic illustration of an exemplary operating environment in which a generic RAID engine system of the present invention can be used;

[0030] FIG. **2** is a block diagram of the high-level architecture of the generic RAID engine system of FIG. **1**;

[0031] FIG. **3** is comprised of FIGS. **3**A, **3**B, and **3**C and represents a diagram illustrating possible strategies the generic RAID engine system of FIGS. **1** and **2** to perform an exemplary Hush operation;

[0032] FIG. **4** is comprised of FIGS. **4**A and **4**B and represents a diagram illustrating an exemplary stripe of a device utilizing an EVENODD code and a corresponding generator matrix of the stripe generated by of the generic RAID engine system of FIGS. **1** and **2**;

[0033] FIG. **5** is a process flow chart illustrating a method of operation of the generic RAID engine system of FIGS. **1** and **2**;

[0034] FIG. **6** is a process flow chart illustrating a method of operation of a generic read module of the generic RAID engine system of FIGS. **1** and **2**;

[0035] FIG. **7** is a process flow chart illustrating a method of operation of a generic write module of the generic RAID engine system of FIGS. **1** and **2**;

[0036] FIG. **8** is a process flow chart illustrating a method of operation of an optional optimizer module of the generic RAID engine system of FIGS. **1** and **2**;

[0037] FIG. **9** is a process flow chart illustrating a method of operation of the generic RAID engine system of FIGS. **1** and **2** in generating a sub-plan; and

[0038] FIG. **10** is a process flow chart illustrating a method of an execution engine of the generic RAID engine system of FIGS. **1** and **2**.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0039] The following definitions and explanations provide background information pertaining to the technical field of the present invention, and are intended to facilitate the understanding of the present invention without limiting its scope:

[0040] Element (interchangeably referenced as a page): fixed-size chunks of bits. An element typically comprises one or more consecutive pages on a disk and comprises data pages or parity pages but not both parity pages and data pages.

[0041] Page (interchangeably referenced as an element): fixed-size chunks of bits.

[0042] RAID (Redundant Array of Independent Disks): Any of a family of codes using XOR codes to achieve a virtual erasure coded storage volume. Examples of RAID codes comprise RAID 5, EVENODD, generalized EVENODD, X-code, RDP, and WEAVER.

[0043] Strategy: a sub-plan used by the present invention to develop an I/O plan based on metadata input, RAID code input, dynamic input, and one or more read requests or one or more write requests.

[0044] Stripe: the set of data elements and ail related parity elements. The number of elements that a stripe comprises depends on the number of disks in the storage system and the coding scheme.

[0045] FIG. **1** portrays an exemplary overall environment in which a system, a service, a computer program product, and an associated method (the generic RAID engine system **10** or the "system 10") for providing a generic RAID engine and optimizer according to the present invention may be used. System **10** comprises a software programming code or a computer program product that is typically embedded within, or installed on an I/O stack **15**. Alternatively, system **10** can be saved on a suitable storage medium such as a diskette, a CD, a hard drive, or like devices.

[0046] System **10** can take the form of an entirely hardware embodiment, an entirely software embodiment or an embodiment containing both hardware and software elements. In a preferred embodiment, system **10** is implemented in software, which includes but is not limited to firmware, resident software, microcode, etc.

[0047] Furthermore, system **10** can take the form of a computer program product accessible from a computer-usable or computer-readable medium providing program code for use by or in connection with a computer or any instruction execution system. The computer program product comprises the instructions that implement a method of system **10**. For the purposes of this description, a computer-usable or computer readable medium can be any apparatus that can contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device.

[0048] The medium can be an electronic, magnetic, optical, electromagnetic, Infrared, or semiconductor system (or apparatus or device) or a propagation medium. Examples of a computer-readable medium comprise a semiconductor or solid-state memory, magnetic tape, a removable computer diskette, a random access memory (RAM), a read-only memory (ROM), a rigid magnetic disk, and an optical disk. Current examples of optical disks comprise compact disk-read only memory (CD-ROM), compact disk-read/write (CD-R/W), and DVD.

[0049] A data processing system suitable for storing and/or executing program code comprises at least one processor coupled directly or indirectly to memory elements through a system bus. The memory elements comprise local memory employed during actual execution of the program code, bulk storage, and cache memories that provide temporary storage of at least some program code to reduce the number of times code is retrieved from bulk storage during execution.

[0050] Input/output or I/O devices (including but not limited to keyboards, displays, pointing devices, etc.) can be coupled to the system either directly or through intervening I/O controllers.

[0051] Network adapters may also be coupled to the system to enable the data processing system to become coupled to other data processing systems or remote printers or storage devices through intervening private or public networks. Modems, cable modems, and Ethernet cards are just a few of the currently available types of network adapters.

[0052] FIG. **1** illustrates a high-level diagram of a typical deployment of system **10** within the I/O stack **15**. One or more applications **20** generate an access request comprising read or write calls (interchangeably referenced herein as read requests or reads and write requests or writes) to a RAID coded storage volume such as a storage system **25**. While described for illustration purposes only as read requests and write requests, the applications **20** may also generate for consideration by system **10** a file read request, a file write request, a block read request a block write request, etc.

[0053] The storage system **25** comprises, for example, a storage device **1**, **30**, a storage device **2**, **35**, through a storage device H, **40** (collectively referenced as storage devices **45**). A device driver operates each of the storage devices **45**. For example, a device driver **1**, **50**, operates the storage device **1**, **30**. A device driver **2**, **55**, operates the storage device **2**, **35**. A device driver N, **40**, operates the storage device N, **40**. The device driver **1**, **50**, the device driver **2**, **55**, through the device driver N, **60**, are collectively referenced as device drivers **65**.

[0054] The read and write requests are initially served by a data cache **70**. System **10** is invoked if a read miss occurs or a page needs to be flushed. System **10** provides generic support of any RAID code under any set of sector or disk failures. System **10** generates disk reads and writes by considering the current (dynamic) state of the data cache **70**.

[0055] System **10** is invoked by the data cache **70** when reading or writing data to a virtualized erasure coded storage volume such as, for example, RAID 5, EVENODD, etc. Applications **20** generate read and write requests to the I/O stack **15**. The read and write requests are serviced by the data cache **70** that manages cached data in pages. With write-back caching, application writes are copied to pages in the data cache **70** and marked dirty. At a later time, as determined by the page replacement policy of the I/O stack **15**, dirty pages are flushed (written out) to the storage devices **45**. With read caching, application reads are served out of the data cache **70** when possible. Otherwise, on a read miss, the data cache **70** has to fetch the data from the storage devices **45** and then return this data to the applications **20**. In one embodiment, the data cache **70** dynamically partitions pages into a write-back portion and a read portion to handle a wide variety of application workloads.

[0056] While FIG. **1** illustrates a deployment of system in which locally running applications **20** submit I/Os, is should be clear that system **10** is applicable to a variety of deployments. For example, applications **20** may operate on hosts connected to the I/O stack **15** via a network, such as, for example, a storage area network, the internet, etc., to a (block or file) controller. The data cache **70** and system **10** are deployed within this controller. In many controllers the write-back cache is battery backed to protect content of dirty pages from loss due to unexpected power failure. Other controllers employ a fire-hose dump to a reserved disk.

[0057] FIG. **2** illustrates a high-level hierarchy of system **10**. System **10** comprises a generic raid engine module **205**, an optional optimizer module **210**, and an execution engine **215**. The generic raid engine module **205** comprises a generic read module **220**, a generic write module **225**, a generic scrub module **230**, a generic rebuild module **235**, and a generic migrate module **240**. Input to system **10** comprises a metadata input **245**, a RAID code input **250**, a dynamic input **255**, and one or more read/write requests **260** (further referenced herein as access requests **260**). The access requests **260** comprises any request for access to the storage devices **25** such as, for example, a read request, a write request, a file read request, a file write request, a block read request, a block write request, etc. System **10** generates as output one or more I/O plans **265**. The I/O plans **265** are provided to the execution engine **215** for execution.

[0058] The I/O plan **265** comprises a set of pages that are read from the storage system **25**, a set of pages that must be XORed, and a set of pages that are written to the storage system **25**. Depending on the operation and associated arguments, some of sets of pages in the I/O plan **265** can be empty. The execution engine **215** generates and manages error handling during execution of the I/O plan **265**. If the execution engine **215** encounters any errors, the execution engine **215** aborts the I/O plan **265**, modifies a fault configuration vector, and re-submits the operations of the I/O plan **265** to the generic RAID engine module **205**. The optimizer module **210** selects strategies that meet one or more resource optimization objective(s).

[0059] The metadata input **245** comprises a description of the physical arrangement of blocks in the RAID code called the layout, available from the meta-data for the storage devices **45**. Layout of the storage devices **45** comprises, for example, rotation, stripe size, element size, etc. The metadata input **245** optionally comprises any resource optimization objectives for use by the optimizer module **210**. The resource optimization objectives comprise optimization criteria such as minimizing disk I/O or minimizing memory bus bandwidth. This input guides the optimizer module **210** in selecting I/O strategies for a given read or write.

[0060] The optimizer module **210** has few options for fault-free reads where the only reasonable option is to read the required page directly from the appropriate disk in the storage devices **45**. The optimizer module **210** has many options for writes. Each of these options can require a different number of disk reads and/or XOR operations. In such cases, the optimizer module **210** uses the input resource optimization objectives to guide selection of the desired I/O plan.

[0061] The dynamic input **255** comprises information regarding the data cache **70** such as, for example, a description of clean pages and dirty pages in the data cache **70** that are in a W-neighborhood of the page(s) to be read or written. This description is available from a directory of the data cache **70**, the data cache directory. The clean pages are designated as cv. The dirty pages are designated as dv. The dynamic input **255** further comprises information regarding the storage devices **45** such as, for example, a current fault configuration. The current fault configuration (designated as f) comprises a description of known sector failures and disk failures.

[0062] The RAID code input **250** comprises a concise description of the RAID code, available from the meta-data for the storage devices **45**.

[0063] The read/write requests **260** comprise the type of operation (read or write) and arguments associated with the operation. The arguments comprise a block address of the page(s), a starting virtual block address, and a number of bytes to be read or written.

[0064] Scenarios under which the data cache **70** invokes system **10** comprise a read on a miss, a flush of a dirty page, a rebuild of a lost page, a scrub of every stripe, and a migrate of a page.

[0065] The generic read module **220** responds to the "read on a miss" scenario. The generic read module **220** translates a virtualized block address of the requested page(s) to a corresponding physical block address within an identified disk. In the fault-free case, one or more disk read(s) are issued. If the identified disk (or particular sectors within the identified disk) has failed, system **10** performs a reconstruction by reading related blocks as directed by the RAID code. If reconstruction fails, a read error is returned.

[0066] The generic write module **225** responds to the flush of a dirty page scenario. When the cache replacement policy has selected a victim (dirty) page for writing to an identified disk, the generic write module **225** translates the virtual block address of the victim page to a corresponding physical block address within the identified disk. The generic write module **225** identifies one or more dependent (parity) block(s) as determined by the RAID code. The generic write module **225** determines how to update the dependent (parity) blocks and issues that determination with a write I/O plan.

[0067] The generic rebuild module **235** responds to the "rebuild a lost page" scenario. The "rebuild a lost page" scenario is generated by an internal housekeeping routine to repair lost data due to sector or disk failure. The generic rebuild module **235** reconstructs the lost page using the redundant information within the RAID code and then writes the lost page to a new location. The rebuild process of the generic rebuild module **235** can be viewed as a composition: reconstruct read followed by write.

[0068] The generic migrate module **240** responds to the "migrate a page" scenario. Triggered by an administrative action, migration is invoked to change the RAID code of a page. Changes comprise varying the span (rank) of disks. For example, the span may be changed from an 8-disk RAID 5 to a 5-disk RAID 5. Changes further comprise changing the RAID code. For example, the RAID code may be changed from RAID 5 to EVENODD. The migration process of the migration module **240** can be viewed as a composition: read, using the old code, followed by write, using the new code.

[0069] The generic RAID engine module **205** transforms the input into the I/O plan **235** that comprises a set of blocks to be read, a set of blocks, to be XORed, and a set of blocks to be written. The I/O plan **265** is input to the execution engine **215** that issues the necessary disk reads and writes and monitors or computes XOR operations.

[0070] The execution engine **215** executes the I/O plan **265** in the following phases: disk reads are submitted, the XOR operations are performed, and the disk writes are submitted. Serialization mechanisms such as, for example, stripe locking, are localized to the execution engine **215**. One aspect of the execution engine **215** comprises error handling, specifically when encountering new failed sectors or disks during execution. The execution engine **215** modifies the fault configuration based on this new information and re-submits the operation to the generic RAID engine module **205**. The generic RAID engine module **205** computes a new I/O plan **265** that is handed to the execution engine **215**. Thus, system **10** unifies the error path with the main path. Consequently, the recovery code is no different from the main path.

[0071] By incorporating the RAID code information, the physical arrangement of the storage system **25**, the current fault configuration, and the dynamic state of the data cache **70**, system **10** determines an optimum way to perform a given read or write. The fault-free and fault-ridden code paths utilized by system **10** provide a simplification for nested error handling and recovery that plagues many RAID implementations.

[0072] FIG. **3** (FIGS. **3**A, **3**B, **3**C) illustrates the options for the I/O plans **265** generated by system **10** and the cost of the different I/O plans **265** with respect to the number of XORs required and the number of disk reads and writes. The example of FIG. **3** applies to a write request with a left-symmetric RAID 5 code.

[0073] FIG. **3**A illustrates a stripe **305** for a disk **1** (D**1**), **310**, a disk **2** (D**2**), **315**, a disk **3** (D**3**), **320**, a disk **4** (D**4**), **325**, and a disk **5** (D**5**) **330**. Stripe **305** comprises a parity element **1** (P**1**), **335**, a parity element **2** (P**2**), **340**, and a parity element **3** (P**3**), **345**. The dirty pages within a one-stripe neighborhood of a victim page (V **350**) are shaded as indicated by element **355**. The shaded pages are flushed in one operation.

[0074] FIG. **3**B and FIG. **3**C illustrate possible strategies for performing the flush operation. FIG. **3**B shows stripe **305** as a block of pages **360** with pages to be read indicated with left diagonal shading as illustrated by a page **365**. FIG. **3**B further shows stripe **306** as a block of pages **370** with pages to be written indicated with a right diagonal shading as illustrated by a page **370**. The strategy illustrated by FIG. **3**B requires 4 read I/Os, 6 write I/Os, and 14 pages of memory bus usage for XOR. A strategy is a sub-plan that system **10** uses to develop the I/O plan **265**.

[0075] FIG. **3**C shows stripe **305** as a block of pages **380** with pages to read indicated with a left diagonal shading as illustrated by page **375**. FIG. **3**C further shows stripe **305** as a block of pages **385** with pages to be written indicated by a right diagonal shading as illustrated by page **375**. The strategy illustrated by FIG. **3**C requires 3 read I/Os, 6 write I/Os, and 15 pages of memory bus usage.

[0076] System **10** can select a strategy based on the input resource optimization objectives. For example, system **10** selects the strategy illustrated by FIG. **3**B if memory bus usage is to be minimized. Otherwise, system **10** selects the strategy illustrated by FIG. **3**C if disk I/O is to be minimized. The strategies shown in FIG. **3**B and FIG. **3**C are from a possible eight strategies available for the write request illustrated by FIG. **3**A.

[0077] In XOR-based erasure codes (i.e., RAID codes) any redundant bit is an XOR of a number of data bits. For efficiency, this relationship is applied to fixed-size chunks of bits called elements. An element typically comprises one or more consecutive pages on disk. An element can have either data or parity pages but not a mix of the two. A stripe is the set of data elements and all related parity elements. A parity element in a stripe is a XOR of some subset of data elements within that stripe. The parity element depends on those data elements. The number of elements that a stripe comprises depends both on the number of disks in the storage system **25** (called the rank) and the coding scheme.

[0078] For example, FIG. **4** (FIGS. **4**A, **4**B) illustrates an exemplary stripe **405** of a device utilizing an EVENODD code and a corresponding generator matrix **410** of stripe **405** generated by system **10**. The stripe **405** comprises **10** elements for a 2-fault tolerant EVENODD code over 5 devices. The devices comprise a disk **1** (D**1**), **415**, a disk **2** (D**2**), **420**, a disk **3** (D**3**), **425**, a disk **4** (D**4**), **430**, and a disk **5** (D**5**), **435**. Within each stripe **405**, e consecutive elements are arranged contiguously on each of the storage devices **25**, forming a strip. The elements comprise data elements and parity elements. The data elements comprise an E**1**, **440**, an E**2**, **445**, an E**3**, **450**, an E**4**, **455**, an E**5**, **460**, and an E**6**, **465**. The parity elements comprise a P**1**, **470**, a P**2**, **475**, a Q**1**, **480**, and a Q**2**, **485**.

[0079] FIG. **4**B illustrates a matrix representation of the stripe **405**, the generator matrix **410**. A matrix representation of a RAID code is obtained by expressing the XOR relationships between data elements and parity elements as a system of equations. The matrix from such an organization is called its generator matrix, G. The generator matrix is an N×M binary matrix, where N is the number of data elements in a stripe and M is the combined number of data and parity elements in a stripe. A column of G corresponds to an (data or parity) element in the stripe. A column component of G corresponding to a data element typically comprises a single 1. For a parity element, the corresponding column component has additional 1s, one for each data element to which the corresponding parity element relates.

[0080] If each element comprises k pages, then G can be rewritten in terms of pages instead of elements by replacing each element entry by an identity matrix of size k. For exemplary purposes only, each element is assumed to correspond to a single page. The terms element and page are used interchangeably.

[0081] Layout is the physical (on disk) arrangement of data parity pages within a stripe. Besides configuration parameters such as the size of each page, much of the layout can be discerned from the generator matrix G for the RAID code and e, the number of pages per strip. As illustrated by FIG. **4**B and described previously, G can be visualized as blocks of e columns, each block corresponding to physical arrangement of a strip on the disk. When parity pages are interspersed with data pages, the layout is interleaved.

[0082] The location of parity pages within a stripe is summarized in a vector of column indices corresponding to parity pages in G. This vector is referred to as the parity arrangement vector, denoted by parity of dimension 1×(M−N).

[0083] To allow for even distribution of load across all disks, many layouts are cyclically shifted; i.e., columns of the basic code word are rotated, distributing the parity elements evenly on ail disks. This shifting can be represented by a signed number s that defines the cyclical shift of strips per stripe. The sign encodes the shift direction: negative for left symmetric and positive for right symmetric.

[0084] The failure state of a page can he derived from a failure state of the disks and a bad sector table. The bad sector table is a persistent data structure that is updated whenever a read error is encountered by a read operation.

[0085] System **10** encodes the failure state of a set of n pages as the fault configuration vector f of dimension 1×n, where an entry for page i is marked 1 if that page has failed, otherwise 0.

[0086] System **10** modifies the fault configuration vector f as new errors are discovered in the process of executing the I/O plan **265**.

[0087] FIG. **5** illustrates a method **500** of system **10** in generating I/O plans for execution by the execution engine **215**. The generic RAID engine **205** receives the metadata input **245**, the dynamic input **255**, and the read/write requests **260** (step **505**). The generic raid engine **205** receives the RAID code input **250** (step **510**).

[0088] The generic read module **220** executes a read (method **600**, further illustrated in FIG. **6**) (step **600**). The generic read module **220** outputs one or more read I/O plans (step **515**). The generic write module **225** executes a write (method **700**, further illustrated in FIG. **7**) (step **700**). The generic write module **225** outputs one or more write I/O plans (step **525**).

[0089] The generic scrub module **230** executes a scrub (step **530**) and outputs one or more scrub I/O plans (step **535**). The generic rebuild module **235** executes a rebuild (step **540**) and outputs one or more rebuild I/O plans (step **545**). The generic migrate module **249** executes a migrate (step **550**) and outputs one or more migrate I/O plans (step **550**). The optimizer module **210** optionally executes an optimization (method **800**, further illustrated in FIG. **8**) to select an optimum I/O plan **265** (step **800**). System **10** provides the output I/O plan (s) **265** to the execution engine **215** (step **560**).

[0090] In the data cache **70**, a victim (dirty) page is determined by the replacement policy for the victim page. While flushing the victim, it is efficient to collectively flush dirty pages that belong to the same stripe as the victim. System **10** defines a W-neighborhood for a victim page, as illustrated by the shaded blocks in FIG. **3**A. The W-neighborhood is defined as the set of all pages, clean or dirty, in the data cache **70** that are in a 2W+1 stripe window centered around the stripe of the victim. By choosing W>0, system **10** can batch the flush requests of one or more pages that are presumably physically close, thereby improving the throughput of the disks.

[0091] The set of pages in the W-neighborhood of a victim page can be partitioned into clean and dirty page sets. Each set can be encoded as a binary vector, with a 1 in an entry denoting whether the page is in cache. The clean data vector is denoted cv and the dirty data vector is denoted dv.

[0092] The I/O plan **265** is a 3-tuple (r, X, w). The vector r is a vector encoding of the set of disk read operations required by the I/O plan **265**. A non-zero entry denotes that the corresponding page is to be read. Similarly, w is a vector encoding of the set of disk write operations required by the I/O plan **265**. The vector X is the set of XOR operations, each of which is a list of pages to be XORed yielding a resultant data or parity page. The vector X can be encoded as a square matrix of dimension M×M where a column component i describes the set of pages to be XORed to compute page i of the stripe.

[0093] If the requested pages can be read from good disk(s), then it is trivial to set r to the corresponding pages on the disk(s). In this scenario, both X and w are zero.

[0094] The challenging case for the generic read module **220** is when reconstruction is required due to sector or disk failures. From the generator matrix G, a modified matrix $\hat{G}$ is derived as follows. For every failed sector, the entries corresponding to that row in G are zeroed. For every failed disk, the columns corresponding to pages on disk are zeroed. Formally, $\hat{G}$ is computed as follows:

$$\hat{G}=G(I_M-\mathrm{diag}(f))$$

where I_M is the identity matrix of size M, and diag(f) is the matrix derived by applying the fault configuration vector f as the diagonal of the M×M matrix.

[0095] Next, using a variant of Gaussian elimination, a pseudo-inverse $R(G^{-1})$ is computed. R is of dimension M×N where the column component i corresponds to a description of the set of surviving pages (data or parity) that are required to be read and XORed to reconstruct data page i.

[0096] If the RAID code allows, the pseudo-inverse technique finds a reconstruction scheme using only the surviving pages. From linear algebra, since G describes an over-specified system of equations, its inverse R is not unique (hence the name pseudo-inverse). Each pseudo-inverse, R, of $\hat{G}$ defines a read strategy. Given resource optimization objectives, the optimizer module **210** picks a suitable strategy and the relevant pseudo-inverse R. The columns of R that correspond to the lost and required pages are extracted to r and X. Since some of the required pages may already he in cache, r is logically ANDed with the clean cache vector cv to yield the set of pages that the execution engine **215** is required to read from disk. In the case of reconstruct reads, w is zero.

[0097] FIG. **6** illustrates a method **600** of the generic read module **220** in executing the read. System **10** receives input comprising a read request (step **605**). The generic read module **220** examines received metadata input, dynamic input, and RAID code input (step **610**). The generic read module **220** determines if any data elements required by the read reside on known failed disks or sectors (decision step **615**). If yes, the generic read module **220** sets to zero the columns of the known lost data elements in G (step **620**).

[0098] The generic read module **220** computes a pseudo-inverse of the generator matrix R (step **625**). The generic read module **220** copies a column component of R corresponding to lost and required data elements into the read vector (step **630**). The generic read module **220** copies a column component corresponding to lost and required data elements in XOR vector (step **635**). The generic read module **220** sets non-failed but required data elements in read vector to 1 (step **640**). The generic read module **220** forms an I/O plan using read and XOR vectors (step **645**). System **10** submits the I/O plan to the execution engine **215** (step **650**.

[0099] If, at decision step **615**, no data elements required by the read reside on known failed sectors or disks, the generic read module **220** sets required data elements in read vector to 1 (step **655**). Processing proceeds to step **645** and step **650**, previously described.

[0100] In case of error, a read may be resubmitted by the execution engine **215** (step **660**), with processing proceeding from step **620** to step **650**, as previously described.

[0101] FIG. **7** illustrates a method of the generic write module **225** executing a write. System **10** receives input comprising a write request (step **705**). The generic write module **225** examines received metadata input, dynamic input, and RAID code input (step **710**). The generic write module **225** computes a list of parity elements affected by the write (further referred to herein as affected parity elements) (step **715**). The generic write module **225** selects a strategy for updating affected parity elements (step **720**). The optimizer module **210** optionally optimizes the selected strategy (step **800**, further described by method **800**, FIG. **8**).

[0102] The generic write module **225** determines if any additional affected parity elements exist (decision step **725**). If yes, the generic write module **225** selects an affected parity element (step **730**). The generic write module **225** computes a sub-plan from the corresponding read, write, and XOR vectors for the selected affected parity element (step **900**, further described by method **300** of FIG. **9**). The generic write module **225** repeats steps **725**, **730**, and **900** until no additional affected parity elements remain for processing.

[0103] If, at decision step **725**, no additional affected parity elements remain for processing or if no affected parity elements corresponded to the write request, the generic write module **225** element-wise ORs read vectors to generate an I/O plan read vector (step **735**). The generic write module **225** element-wise ORs write vectors to generate an I/O plan write vector (step **740**). The generic write module combines subplans into an I/O plan by summing XOR vectors for the I/O plan XOR vector (step **745**). System **10** submits the I/O plan to the execution engine (step **750**). The execution engine **215** resubmits a write in case of error (step **755**) and processing proceeds at step **720**.

[0104] The generic write module **225** constructs affected parity vectors (step **715**). Recollect that the victim page to be written out is expanded to include the W-neighborhood of dirty pages. The dirty data vector dv is then the set of pages to be written out; dv includes the victim. In any RAID code, the changed content of data pages is reflected to corresponding dependent parity pages. Consequently, the generic write module **225** identifies all dependent parity pages. This can be determined by logically ANDing the dirty data vector with each column component of a parity page in $\hat{G}$. Every resultant non-zero vector implies that that surviving parity page requires updating as part of writing dv. Parity pages with a resulting zero column imply that either the parity page is unaffected or that the parity page cannot be written to due a sector or disk failure.

[0105] The generic write module **225** encodes the list of affected parity pages as a binary vector where an entry for a parity page is set to 1 if that page is affected, 0 otherwise. This binary vector is referenced as the affected parity vector.

[0106] The generic write module **225** determines whether the layout is degraded (decision step **904**). If no, the generic write module **225** computes inverse matrix (step **924**). When computing the inverse matrix in step **924**, the write module determines how each affected parity page is updated. With erasure-coded data, any parity element can be updated using parity increment or parity compute. Parity increment is referred to as read-modify-write in RAID 5 firmware. In parity increment, on-disk versions of the modified data and parity pages are initially read and a parity difference (referred to as delta parity) between the new and old version of the data page is computed. The delta parity is applied to the old version of the parity to derive the new parity. Parity compute is referred to as full-stripe-write in RAID 5 firmware. In parity compute, all unmodified data pages on which a parity page depends are read from disk. The unmodified data pages are XORed with the dirty pages to compute the updated parity page.

[0107] For a fault-free write, as indicated by a no response to decision any correct update of dirty pages in any erasure coded stripe is some combination of parity increment or parity compute for each of the affected parity pages. Updates that reuse results from one parity update (delta parity) for another can be re-written as if each parity page were updated separately. Each instantiation of a parity increment or parity compute for non-zero entries in the affected parity vector is a write strategy.

[0108] For any write, if p parity pages are affected there are 2^p write strategies for selection by system **10**. Since each write strategy translates to a different I/O plan, system **10** can select a write strategy that meets the resource optimization objectives.

[0109] It at decision step **615**, the layout is degraded, the generic write module **225** prepares failure vectors. In the presence of sector or disk failures, the generic write module **225** reconstructs the pages needed for parity increment or parity compute before updating the parity page itself. In case of parity increment, the on-disk version of the modified data is reconstructed, if lost. For parity compute, the on-disk version of the unmodified data is reconstructed, if lost. The inverse matrix is then computed as before (step **924**).

[0110] Given a write strategy, for each affected parity page, the generic write module **225** can compute the pages to be read, XOR-ed and written independently. The generic write module **225** calculates each sub-plan, the I/O plan corresponding to each affected parity page, using column components from the pseudo-inverse to translate the write strategy (parity increment or parity compute) into reads, XORs, and writes. In computing the read set, the dean page vector cv is used to cull out pages that can be readily served from **745** the read cache.

[0111] The generic write module **225** generates one or more sub-plans by combining individual r, w, X vectors (step). If the sub-plan for affected parity page k is denoted by (r_k, X_k, w_k), the generic write module **225** derives the combined I/O plan by summing the individual sub-plans.

$$r = \sum_{k \in parity} r_k$$

$$X = \sum_{k \in parity} X_k$$

$$w = \sum_{k \in parity} w_k$$

The generic write module **225** adjusts for physical layout (step **735**). The generic write module **225** generates the write I/O plan(s) comprising the R, W, X matrices (step **750**).

[0112] An example for write, assuming a fault-free configuration of the EVENODD code with a rank of 5 disks, is described as follows. A sketch of the physical arrangement is illustrated by stripe **405** in FIG. **4**A; the generator matrix **410** for this code is shown in FIG. **4**B. This code has two pages per strip (e=2), 6 data pages (N=6) and a total of 10 pages per stripe (M=10). The physical arrangement of parity pages is parity=(7, 8, 9, 10)^t.

[0113] In this example, there are no clean pages available for this stripe. Being fault-free, f=0. Hence,

$$\hat{G}=G(I_M-\mathrm{diag}(f))=G$$

[0114] For the purposes of this example, pages D**1** and D**3** are dirty. Then,

$$dv=\begin{pmatrix}1\\0\\1\\0\\0\\0\end{pmatrix}$$

[0115] The generic write module **225** computes the set of affected parity pages by ANDing the dirty page vector with Ĝ for each parity page **715**. Below is a tabulation of this calculation for each parity page in the stripe.

P1	P2	Q1	Q2
1	0	1	0
0	0	0	0
1	0	0	1
0	0	0	0
0	0	0	0
0	0	0	0

[0116] In this example, P**2** is unaffected as is seen by a corresponding zero column.

[0117] The generic write module **225** generates a write I/O plan **720**. For example, the generic write module **225** selects, as a strategy for the write I/O plan, strategy$_A$:

$$strategy_A=\begin{pmatrix}P1\\P2\\Q1\\Q2\end{pmatrix}=\begin{pmatrix}\text{parity compute}\\ \text{—}\\ \text{parity compute}\\ \text{parity increment}\end{pmatrix}$$

[0118] The generic write module **225** generates sub-plans for each affected parity page. The sub-plan for P**1** is:

$$r_{P1}=\begin{pmatrix}0\\0\\0\\0\\1\\0\\0\\0\\0\\0\end{pmatrix};\quad X_{P1}=\begin{pmatrix}1\\0\\1\\0\\1\\0\\0\\0\\0\\0\end{pmatrix};\quad w_{P1}=\begin{pmatrix}1\\0\\1\\0\\0\\0\\1\\0\\0\\0\end{pmatrix}$$

[0119] The sub-plan for Q**1** is:

$$r_{Q1}=\begin{pmatrix}0\\0\\0\\1\\1\\1\\0\\0\\0\\0\end{pmatrix};\quad X_{Q1}=\begin{pmatrix}1\\0\\0\\1\\1\\1\\0\\0\\0\\0\end{pmatrix};\quad w_{Q1}=\begin{pmatrix}1\\0\\0\\0\\0\\0\\0\\0\\1\\0\end{pmatrix}$$

[0120] The sub-plan for Q**2** is:

$$r_{Q2}=\begin{pmatrix}0\\0\\0\\1\\0\\0\\0\\0\\0\\1\end{pmatrix};\quad X_{Q2}=\begin{pmatrix}0\\0\\2\\0\\0\\0\\0\\0\\0\\1\end{pmatrix};\quad w_{Q2}=\begin{pmatrix}0\\0\\1\\0\\0\\0\\0\\0\\0\\1\end{pmatrix}$$

[0121] The generic write module **225** combines the sub-plans to generate the write I/O plan (step **745**):

$$r=\begin{pmatrix}0\\0\\1\\1\\2\\1\\0\\0\\0\\1\end{pmatrix};\quad X=\left(\begin{array}{ccc}7&9&10\\ \hline 1&1&0\\0&0&0\\1&0&2\\0&1&0\\1&1&0\\0&1&0\\0&0&0\\0&0&0\\0&0&0\\0&0&1\end{array}\right);\quad w=\begin{pmatrix}2\\0\\2\\0\\0\\0\\1\\0\\1\\1\end{pmatrix}$$

[0122] For brevity, only the non-zero columns of X are shown. The number atop the horizontal line in X denotes the column index.

[0123] The generic rebuild module **235** performs rebuild (step **535**, FIG. **5**). Rebuild is the operation of reconstructing failed pages within a stripe and writing the reconstructed pages to new disk locations. The rate at which rebuild is performed primarily determines the data availability. The generic rebuild module **235** makes rebuild generic to the RAID code.

[0124] The generic rebuild module **235** performs rebuild when there is a sector failure or a disk failure. In the former case, rebuild is typically performed for the affected stripe. This affected stripe can be scattered over a storage volume. In the case of a disk failure, the generic rebuild module **235** batches rebuilds. Within each batch, one or more stripes are rebuilt simultaneously since rebuilding stripes translates to sequential disk reads and writes.

[0125] To perform a rebuild for a set of lost pages within a stripe, the generic rebuild module **235** executes a read for the set of lost pages. The generic rebuild module **235** selects an optimal I/O read plan for reconstructing the failed pages. The execution engine **215** executes the resultant I/O plan **265**. The generic rebuild module **235** submits to the execution engine **215** a rebuild I/O plan with the vector w set to the reconstructed pages. The vectors rand X of the submitted rebuild I/O plan are zero.

[0126] In one embodiment, the generic rebuild module **235** directs the execution engine **215** to read and write out the entire stripe instead of just the minimum pages required for reconstruction. This is done to detect any lurking sector failures.

[0127] In some layouts, spare space for rebuild is interleaved within the stripe. Such information is captured in the layout input of the metadata input **245**.

[0128] Most RAID implementations also support RAID migration, a process performed by the generic migrate module **240**. The migration process re-lays data that was stored in one layout in another layout. Migration comprises changing stripe size or stripe rank; i.e., re-layout a 5-disk RAID 5 code to a 7-disk RAID 5 code. Migration further comprises changing the RAID code itself; i.e., re-layout a 5-disk 1-fault tolerant RAID 5 code into a 5-disk 2-fault tolerant EVENODD code, or a combination of the two.

[0129] In RAID migration, a volume written in a source layout is re-written in a target layout. Typically, for space efficiency, this migration is performed in-place; i.e., the same set of sectors and disks in the source layout are reused for the target layout. Migration proceeds in some multiples of stripes.

[0130] Typically, this multiple is either determined by the least common multiple of stripe sizes of the source and target layouts, or by the stripe size target layout alone. A staging area on disk may be used to store temporary results if cache memory is limited.

[0131] The generic migrate module **240** directs the reading of all data pages from the source layout using read. System **10** performs any reconstructions, if needed, during this process. The generic migrate module **240** inputs to write the list of data pages for the target layout as if all the parity pages were lost.

[0132] In one embodiment, the generic migrate module **240** reads all pages (data and parity) in the source layout. If possible, the generic migrate module **240** reuses parity pages from this layout as partial results for computing parity pages of the target page. Reusing parity pages from the source layout can reduce the memory bandwidth needed for the migration.

[0133] System **10** performs initialization. Initialization is layout independent in that all regions of a volume are zeroed. Initialization is typically performed in batches by writing sufficiently large writes with zeroes.

[0134] The generic scrub module **230** performs scrubbing as a periodic scan of every stripe to check for latent hard errors. The generic scrub module **230** implements scrubbing by using a "parity check matrix" H for a RAID code that is computed from its generator matrix G. H is a M×(M−N) matrix where each column component corresponds to a parity page in the RAID code. If all pages with entry 1 in that column are XORed, the result is a zero page. A resultant non-zero page implies an inconsistent parity. Overwriting the erroneous parity page with the correct value rectifies this inconsistent parity.

[0135] H is derived from G by rearranging column blocks of G into row blocks in H and including an identity matrix (corresponding to the parity pages). An exemplary parity check matrix for the 5-disk 2-fault tolerant EVENODD code is as follows:

$$H = \left(\begin{array}{cccc} P1 & P2 & Q1 & Q2 \\ \hline 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ \hline 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 \\ \hline 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ \hline 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{array}\right)$$

[0136] The optimizer module **210** selects one strategy over another as guided by specified resource optimization objectives. To translate the resource optimization objectives into optimization metrics that can be used by the optimizer module **210** to improve strategy selection, the optimizer module **210** uses optimization metrics comprising the number of distinct disk read and write commands needed to execute an I/O plan and the number of cache pages input to and output from XOR operations in executing an I/O plan.

[0137] The number of distinct disk read and write commands needed to execute an I/O plan measures disk overhead; i.e., distinct seeks and/or rotations. In a simple cost model, this metric assumes that disk seeks are equal cost. Minimizing distinct disk read and write commands leads to lower disk overhead in service requests, effectively improving the throughput of the disk.

[0138] The number of cache pages input to and output from XOR operations in executing an I/O plan measures the memory overhead incurred. Minimizing XOR leads to lower memory bandwidth usage.

[0139] In one embodiment, the optimization module **210** utilizes second order optimization metrics such as, for example, variance in the number of distinct read and write commands among all disks. Additional optimization metrics can be defined that allow for variable seeks. Further optimization metrics can relate to CPU costs. Furthermore, optimization metrics can comprise customization's based on architecture.

[0140] FIG. **8** illustrates a method **800** of the optimizer module **210**, given optimization metrics for an I/O plan, selecting among competing strategies by costing I/O plans. The optimizer module **210** selects a strategy to update affected parity elements (step **805**). The optimizer module **210** generates an I/O sub-plan (step **900**, further described by method **900** of FIG. **9**).

[0141] The optimizer module **210** determines a cost of the selected strategy (step **810**). The optimizer module **210** determines whether a determined cost meets predetermined criteria (decision step **815**). If no, the optimizer module **210**

returns to step **806** to select another strategy, if yes, the optimizer module **210** designates the selected strategy as the I/O plan (step **820**).

[0142] To compute the number of distinct read and write commands needed to execute an I/O plan, the optimizer **210** restructures both r and w into matrices of the shape of G. The optimization module **210** turns runs of e entries into columns. The optimization module **210** exchanges columns based on the parity arrangement vector parity. The optimization module **210** rotates the columns by the cyclical shift s. In the resulting matrices (one for reads and one for writes) the optimization module **210** counts the number of vertical runs of non-zero entries to compute the number of distinct read and write commands needed to execute the I/O plan. A run of non-zero entries in either matrix represents sequential I/Os.

[0143] To compute XOR for an I/O plan, the optimization module **210** sums the entries in X.

[0144] Given a set of metrics and a definition of the space of all possible strategies, the optimization module **210** can use any search technique to find an I/O plan that suits the resource optimization objectives.

[0145] For reconstruct reads, each pseudo-inverse matrix, R, leads to a strategy. Each strategy can be measured by the number of distinct read and write commands needed to execute the I/O plan or XOR.

[0146] For writes, an exhaustive enumeration of all strategies can be CPU intensive especially for higher fault tolerant codes and larger W-neighborhoods. Consequently, heuristics are used to reduce CPU load. Exemplary heuristics used by the optimization module **210** comprise BASELINE and GRADIENT. BASELINE is a heuristic taken from existing (where possible) RAID implementations. GRADIENT is a greedy heuristic.

[0147] The optimization module **210** employs a simple majority rule to determine whether to perform parity increment or parity compute. If a majority of pages for a stripe are clean or dirty then the optimization module **210** selects parity compute. Otherwise, the optimization module selects parity increment. Under degraded mode, the optimization module **210** uses parity increment The complexity of the BASELINE heuristic is O(p), where p is the number of affected parity elements. BASELINE uses a window size of 1; i.e., a 0-neighborhood where only pages in the victim stripe are considered.

[0148] The GRADIENT heuristic selects a write strategy by incrementally assigning parity increment or parity compute to each non-zero entry in the affected parity vector. As each affected parity is assigned, the GRADIENT heuristic favors the assignment that results in a lower cost (based on the number of distinct read and write commands needed or XOR),

[0149] GRADIENT improves on BASELINE since the optimization module **210** selects a strategy for the next affected parity page based on the assignments to previously assigned parity pages. The complexity of the GRADIENT heuristic is O(p), where p is the number of affected parity elements.

[0150] The execution engine **215** executes an I/O plan from a read or write. Reads are submitted and completed. XORs are calculated. Writes are submitted. Prior to submission and completion of reads, the execution engine **215** transforms r and w in the I/O plan **265** to a matrix in the shape of G, in a manner similar to that previously described. The resultant read and write matrices are used by the execution engine **215** to coalesce runs of non-zero entries into single sequential I/O commands.

[0151] The execution engine **215** is responsible for the following:

- **[0152]** Ensuring that phases of the I/O plan **265** are executed as part of a single transaction; i.e., there are no interleaving of two concurrently executing **10** plans that overlap on pages on disk. Either all or none of the reads, XORs, and writes of the I/O plan **265** are performed.
- **[0153]** Retrying operations in case of timeouts from disks or during XOR operations.
- **[0154]** Updating the fault configuration vector f if any new sector or disk failures are discovered while executing a plan. In such an event, the I/O plan **265** is aborted and the I/O resubmitted to the RAID engine (with the updated fault configuration vector f).

[0155] Ensuring that the phases of the I/O plan **265** are executed as part of a single transaction ensures that if one or more I/O plans **265** have overlapping pages, the execution engine **215** ensures (some) consistent ordering. Any robust solution to this problem employs use of an on-disk log or reliance on persistent memory (NVRAM). The latter approach is common among commercial RAID controllers since most commercial RAID controllers perform write-back caching that requires persistent memory. In these implementations, a stripe lock table, kept in persistent memory, maintains the lock state of stripes being touched by concurrent I/O plans. The execution engine **215** acquires all locks for stripes in the W-neighborhood before beginning execution.

[0156] The execution engine **215** requires resources necessary to complete the I/O plan **265** either in advance of the execution or in a pre-ordered sequence. This is necessary to avoid deadlocks. The execution engine **215** is responsible for simple retries such as, for example, re-submitting timed out disk reads and writes and/or any errors during XORs.

[0157] System **10** unifies the error path with the main path through parameterization of the fault configuration vector f. If the execution engine **215** discovers any new failures (sector or disk) during execution of the I/O plan **265**, the execution engine **215** updates the fault configuration vector f, aborts the I/O plan **265**, and resubmits the I/O plan **265** the generic RAID engine module **205**. The generic RAID engine module **205** computes a new I/O plan **265** based on the updated fault state.

[0158] Traditional RAID controllers comprise hardware support for XOR. An XOR engine, typically built into the memory controller, allows the embedded processor to offload XOR calculations. The processor submits a scatter-gather list of memory addresses that form the inputs to the operation and an address to store the result to the XOR engine. Once this task is submitted, the processor is free to work on other I/Os until the XOR engine signals completion. The XOR engine uses direct memory access (DMA) to fetch the operands and store the result.

[0159] The approach to computing XOR the cost metric used by system **10** reflects the presence of an XOR engine. XOR engines are expensive since they require support in the memory controller. A recent trend to reduce this cost utilizes a commodity processor to perform the XOR as well as I/O handling. This change allows system **10** to take advantage of the 12 caches in these processors by combining one or more memory fetches for a set of XOR operations with overlapping inputs into a single fetch (for each) of the operands. Chunks of operand pages are fetched into the L2 cache and the resultant pages are stored info the L2 cache.

[0160] In one embodiment, system **10** is adapted to this XOR architecture. While computing the total XOR cost for an I/O plan, system **10** counts the number of non-zero entries in X in lieu of summing up all entries in X. This change in costing reflects memory bandwidth used when the processor calculates XOR.

[0161] Hierarchical RAID schemes are structured in layers where one RAID code is used at the top level and another at the lower level. Such layering can boost fault-tolerance at the cost of reduced storage efficiency. Currently, commercial RAID controllers support-RAID 51, a hierarchical scheme that layers a RAID 5 layout over a RAID 1 layout.

[0162] Of greater relevance to future RAID systems are infra-disk redundancy schemes. The goal of such schemes (called SPIDRE) is to build intra-disk redundancy aimed at reducing hard error rates in presence of correlated failures.

[0163] In one embodiment, system **10** is adapted to handle this hierarchy in a RAID scheme. System **10** computes the composite generator matrix of such a scheme by multiplying generator matrices. An exemplary combined generator matrix G' for a system using EVENODD over disks, that infernally use SPIDRE is:

$$G'=G_{EVENODD}\times G_{SPIDRE}$$

[0164] Working off G', system **10** can generate I/O plans for the hierarchical RAID scheme. Any hierarchical RAID scheme increases the number of affected parity pages for a given read or write, underlying the need for an efficient heuristic for strategy selection.

[0165] An emerging trend in storage architectures is the rise of clustered storage systems, etc. In these systems, data is striped across nodes, each of which has a network connection, a processor (and memory), and a group of disks. Layouts span across nodes instead of disks as in traditional RAID systems. Such architectures can allow for scaling of capacity, reliability and performance at a low cost.

[0166] In one embodiment, system **10** is adapted for such distributed architectures. This adaptation is limited to changes to the execution engine **215**. Access and updates to data striped using distributed RAID comprise some serialization and recovery protocol to handle (a) access to data from one or more clients, (b) transient errors from the network and/or nodes, and (c) untrusted nodes. Any suitable protocol can be implemented within the execution engine **215** of system **10**. The unification of the main path with the error path in system **10** allows for simplifying implementation of schemes that rely on retries for detecting out of order execution between one or more clients.

[0167] System **10** is generic in that it works for any XOR-based erasure (RAID) code and under any combination of sector or disk failures. In a typical deployment, the data cache **70** invokes system **10** to read, write, scrub, rebuild, or migrate data stored on one or more disks using a RAID code. Using a matrix representation of the RAID code and its physical arrangement on disks, system **10** can systematically deduce a reconstruction strategy when an application requests blocks that are lost due to failure or an update strategy when the data cache flushes dirty blocks. Furthermore, the optimizer module **210** can select a least cost strategy from the set of possible reconstruction or update strategies for every read or write, respectively. The optimizer module **210** can be configured to minimize, for example, disk I/O or memory bus usage. Another aspect of system **10** is unification of fault-free and fault-ridden code paths. By eliminating nested error code paths, system **10** qualitatively simplifies the RAID implementation.

[0168] FIG. **9** illustrates a method **900** of system **10** in generating a sub-plan. System **10** receives an affected parity element (step **902**). System **10** determines whether the affected parity element exists on failed sectors or disks (decision step **904**). If no, system **10** determines which strategy has been selected, parity compute (PC) or parity increment (PI) (decision step **906**). If parity increment, system **10** determines if any dirty data elements exist on failed sectors or disks (decision step **908**). If not, system **10** sets dirty elements and parity in the read vector to 1 (step **910**). System **10** sets dirty data elements and parity in the write vector to 1 (step **912**). System **10** sets dirty data elements in the XOR vector to 2 (step **914**). System **10** sets the parity element in the XOR vector to 2 (step **916**). System **10** forms a sub-plan for the affected parity elements using the read, write, and XOR vectors (step **918**).

[0169] If at decision step **908** dirty elements exist on failed sectors or disks, system **10** zeros columns in G corresponding to known lost data and parity elements (step **922**). System **10** determines whether a pseudo inverse can be computed (decision step **924**). If, at decision step **922** a pseudo-inverse R cannot be computed, the operation fails and system **10** returns (step **926**). If yes at decision step **924**, system **10** copies into the read vector column components in R corresponding to the failed data elements (step **928**). System **10** copies dirty data and parity elements into the write vector (step **930**). System **10** copies column components in R corresponding to failed data and (non-failed) parity elements into the XOR vector (step **932**). System **10** adds dirty data and parity elements into the XOR vector (step **934**). System **10** proceeds to step **918** and forms a sub-plan for the affected parity elements using the read, write, and XOR vectors.

[0170] If, at decision step **906**, system **10** determines that the selected strategy is parity compute, system **10** determines whether any dirty data elements exist on failed sectors or disks (decision step **935**). If yes, system **10** proceeds to step **922** and performs step **922** through **934** and step **918** as previously described. If no, system **10** sets the clean elements in the read vector to 1 (step **938**). System **10** sets dirty data elements and parity in the write vector to 1 (step **940**). System **10** sets clean and dirty data elements in the XOR vector to 1 (step **945**). System **10** proceeds to step **918** and forms a sub-plan for the affected parity elements using the read, write, and XOR vectors,

[0171] FIG. **10** illustrates a method **1000** of the execution engine **215**. The execution engine **215** receives an I/O plan (step **1005**). The execution engine **215** acquires any page locks, or stripe locks, if needed (step **1010**). The execution engine submits one or more read(s) (step **1015**). The execution engine **215** determines if any new sector or disk failures have been discovered (decision step **1020**). If yes, the execution engine **215** updates known failures (step **1025**), aborts the operation (step **1030**), and resubmits the operation to system **10** (step **1035**).

[0172] If at decision step **1020** no new sector or disk failures have been discovered, the execution engine **215** submits XORs (step **1040**). The execution engine **215** determines if any new sector or disk failures have been discovered (decision step **1045**). If yes, the execution engine **215** performs steps **1025** through **1035**, as previously described.

[0173] The execution engine **215** submits writes (step **1050**). The execution engine **215** determines if any new sector or disk failures have been discovered (decision step **1055**). If yes, the execution engine **215** performs steps **1025** through **1035**, as previously described. The execution engine **215** releases any page locks or stripe locks, if needed (step **1060**). At this point, the operation has been successfully executed by the execution engine **215**.

[0174] It is to be understood that the specific embodiments of the invention that have been described are merely illustrative of certain applications of the principle of the present invention. Numerous modifications may be made to the system, method, and service for providing a generic RAID engine and optimizer described herein without departing from the spirit and scope of the present invention. Moreover, while the present invention is described for illustration purpose only in relation to RAID, it should be clear that the invention is applicable as well to, for example, any linear code or XOR based code used to achieve a virtual erasure coded storage volume.

1. A method of providing a RAID engine in an I/O stack that comprises a data cache and a storage system having a plurality of storage devices, the method comprising:

accepting an access request directed towards performing I/O operations affecting selected pages of the plurality of storage devices, the access request comprising any of the following I/O operations:

a read request,

a write request,

a file read request,

a file write request,

a block read request,

a block write request,

a stripe rebuild request,

a stripe scrub request,

and a stripe migrate request;

accepting a metadata input comprising a layout description and, optionally, a plurality of resource optimization objectives: the layout description further comprising a description of a rotation, a stripe size, and an element size of each of the plurality of storage devices: each resource optimization objective further comprising for the access request the objective of minimizing the I/O operations for each of the plurality of storage devices and the objective of minimizing memory bus bandwidth;

accepting a dynamic input comprising

a dynamic state of the I/O stack containing the RAID engine,

a fault configuration of the plurality of storage devices, the fault configuration further comprising a description of all known sector failures and a description of all known storage device failures, and

a description of the data cache that includes a description of clean pages in the data cache and a description of dirty pages in the data cache, the clean pages and the dirty pages being in a W-neighborhood of at least one of the selected pages;

accepting a RAID code generator matrix input comprising information about a RAID code used by the I/O operations;

transforming the access request into a plurality of individual operations, each individual operation selected from an operations group consisting of an individual device read request, an XOR calculation, an individual device write request, a RAID scrub request, a rebuild request, and a RAID migrate request, each such transformation of the access request being performed through and being dependent upon the metadata input, the dynamic input, and the RAID code generator matrix input while maintaining for each individual operation a plurality of RAID code relationships for the storage devices;

the transforming of the access request into the individual device read request comprising the steps of:

determining if at least one fault exists in the plurality of storage devices that prevent a successful read:

if the at least one fault exists, then performing further the following steps for each fault:

computing a pseudo-inverse matrix of the generator matrix for the RAID code,

translating the pseudo-inverse for consideration to device reads, and XORs, and

generating a read I/O plan for performing individual device reads and XORs:

the transforming of the access request into the individual device write request comprising the following steps:

constructing a plurality of affected party vectors, preparing a plurality of failure vectors as required by a degraded layout,

computing a plurality of inverse matrices,

generating a plurality of sub-plans by combining individual vectors,

reblocking the vectors as per the physical layout, and generating a write I/O plan comprising the matrices for performing individual device reads, XORs and writes;

the transforming of the access request into the RAID scrub request comprises generating a party check matrix based on the generator matrix for the RAID code; and

the transforming of the access request into the RAID migration request comprises employing different generator matrices for each of a source target RAID layout and a target RAID layout;

utilizing the party check matrix to ensure that all elements in the RAID code maintain the necessary RAID relationship at all times; and

providing an optimizer for optimizing I/O plans for available hardware resources;

wherein the RAID engine automatically optimizes individual read, individual write, and XOR operations necessary to complete the read, write, rebuild, scrub, and migrate operations.

2-20. (canceled)

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