US008572138B2

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Sundar et al.

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(54) **DISTRIBUTED COMPUTING SYSTEM HAVING AUTONOMIC DEPLOYMENT OF VIRTUAL MACHINE DISK IMAGES**

(75) Inventors: **Jagane Sundar**, Saratoga, CA (US); **Sanjay Radia**, Fremont, CA (US); **David A. Henseler**, Maplewood, MN (US)

(73) Assignee: **CA, Inc.**, Islandia, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1339 days.

(21) Appl. No.: **11/694,483**

(22) Filed: **Mar. 30, 2007**

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Related U.S. Application Data

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(51) **Int. Cl.**
G06F 12/00 (2006.01)
G06F 17/30 (2006.01)

(52) **U.S. Cl.**
USPC **707/828**; 707/831; 718/1

(58) **Field of Classification Search**
None
See application file for complete search history.

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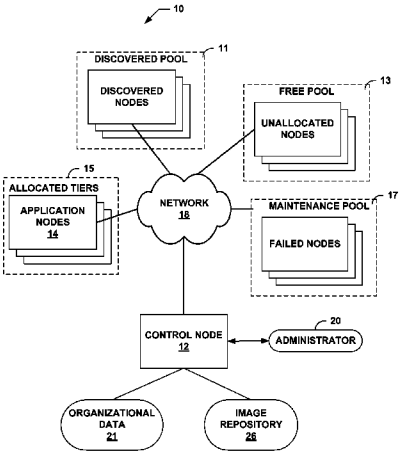
Primary Examiner — Angelica Ruiz
(74) *Attorney, Agent, or Firm* — Baker Botts, L.L.P.

(57) **ABSTRACT**

One or more control nodes provide for the efficient and automated allocation and management of computing functions and resources within the distributed computing system. The distributed computing system includes a software image repository storing: (i) one or more image instances of a virtual machine manager that is executable on the application nodes, wherein when executed on the applications nodes, the image instances of the virtual machine manager provide one or more virtual machines, and (ii) one or more image instances of one or more software applications that are executable on the virtual machines. The distributed computing system also includes a control node that comprises an automation infrastructure to provide autonomic deployment of the image instances of the virtual machine manager on the application nodes and to provide autonomic deployment of the image instances of the software applications on the virtual machines.

26 Claims, 29 Drawing Sheets



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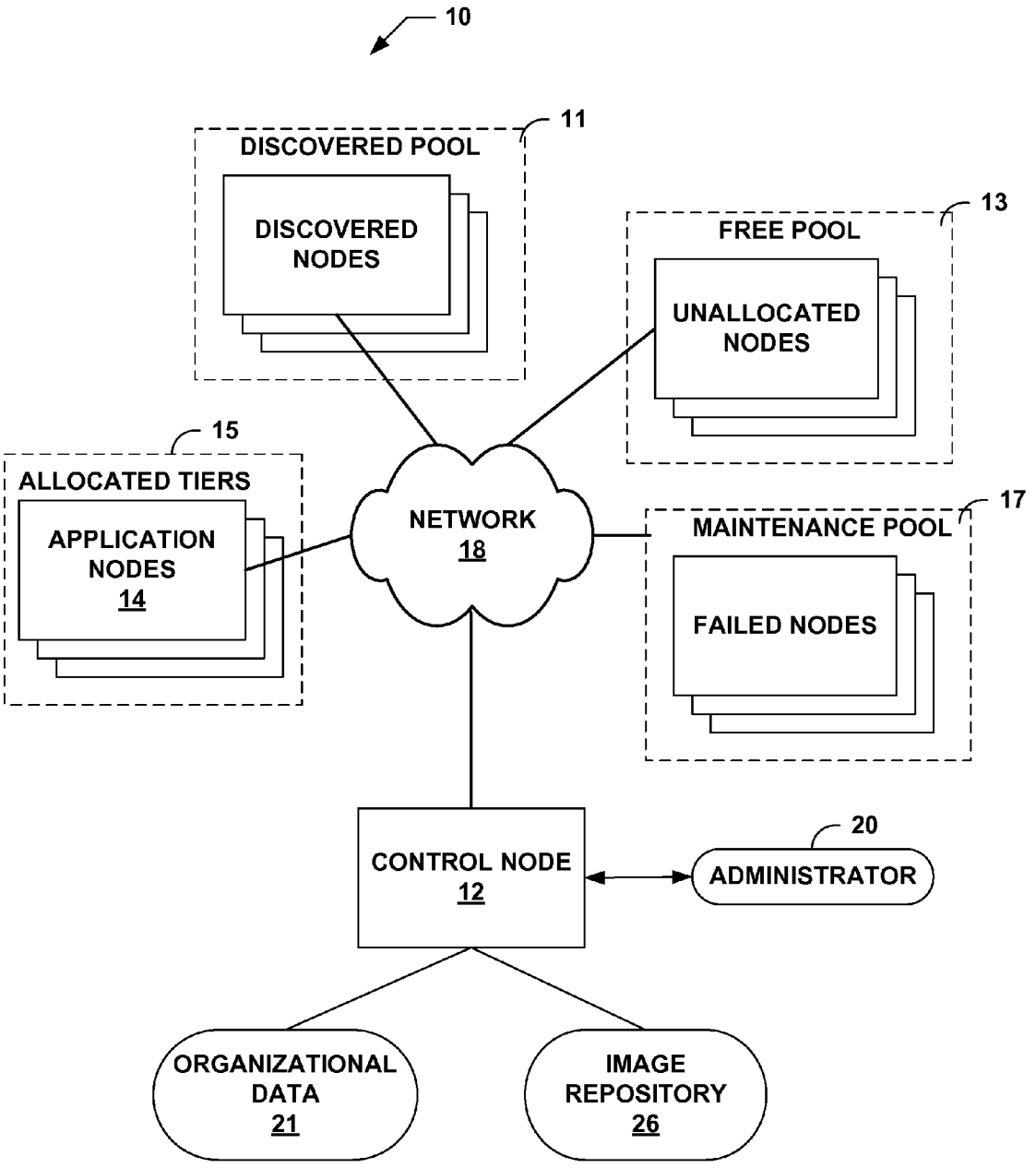
10
11
DISCOVERED POOL
DISCOVERED NODES
13
FREE POOL
UNALLOCATED NODES
15
ALLOCATED TIERS
APPLICATION NODES 14
NETWORK 18
17
MAINTENANCE POOL
FAILED NODES
CONTROL NODE 12
20
ADMINISTRATOR
ORGANIZATIONAL DATA 21
IMAGE REPOSITORY 26

FIG. 1

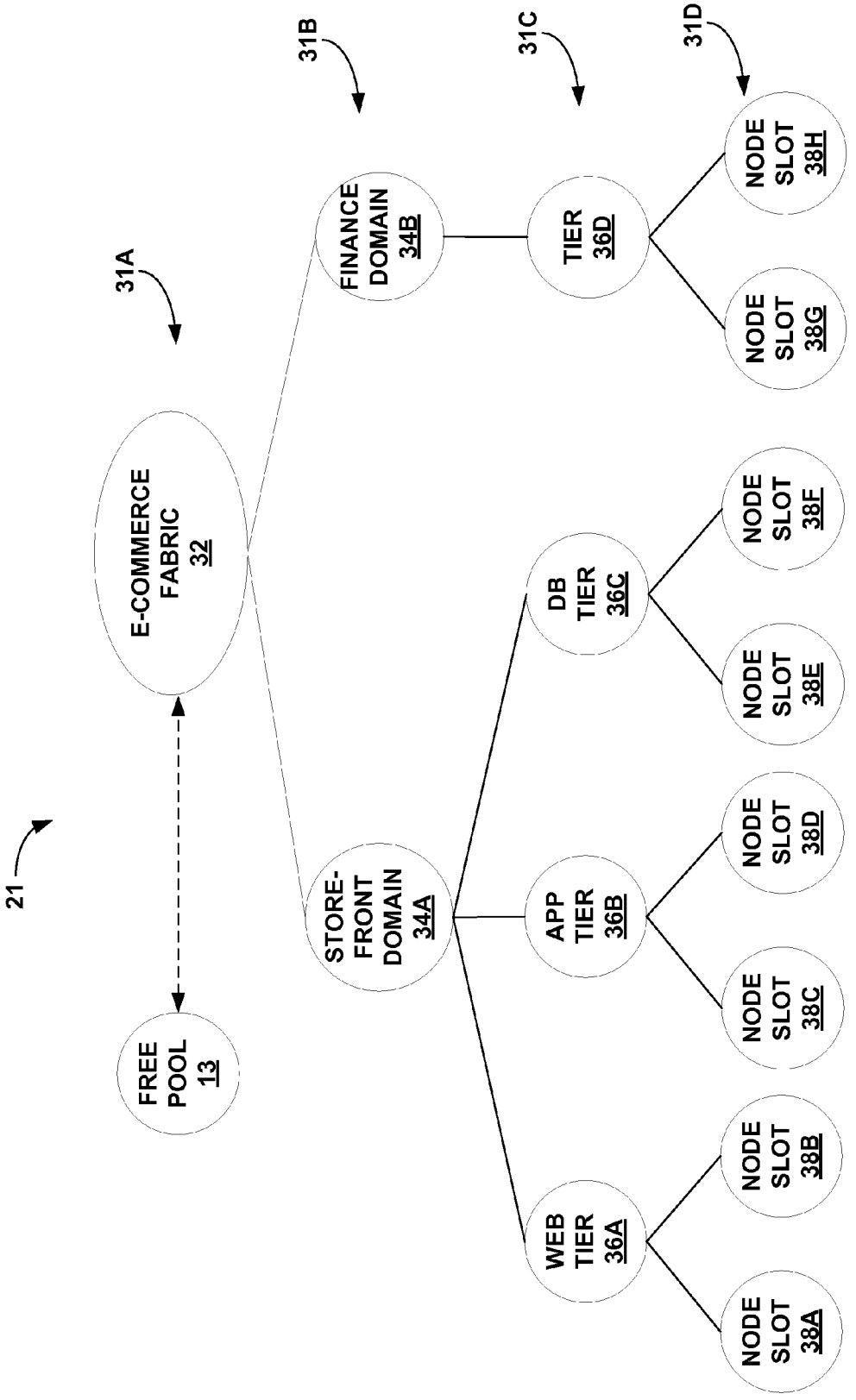
21
E-COMMERCE FABRIC 32
FREE POOL 13
31A
31B
31C
31D
FINANCE DOMAIN 34B
STORE-FRONT DOMAIN 34A
TIER 36D
DB TIER 36C
APP TIER 36B
WEB TIER 36A
NODE SLOT 38H
NODE SLOT 38G
NODE SLOT 38F
NODE SLOT 38E
NODE SLOT 38D
NODE SLOT 38C
NODE SLOT 38B
NODE SLOT 38A

FIG. 2

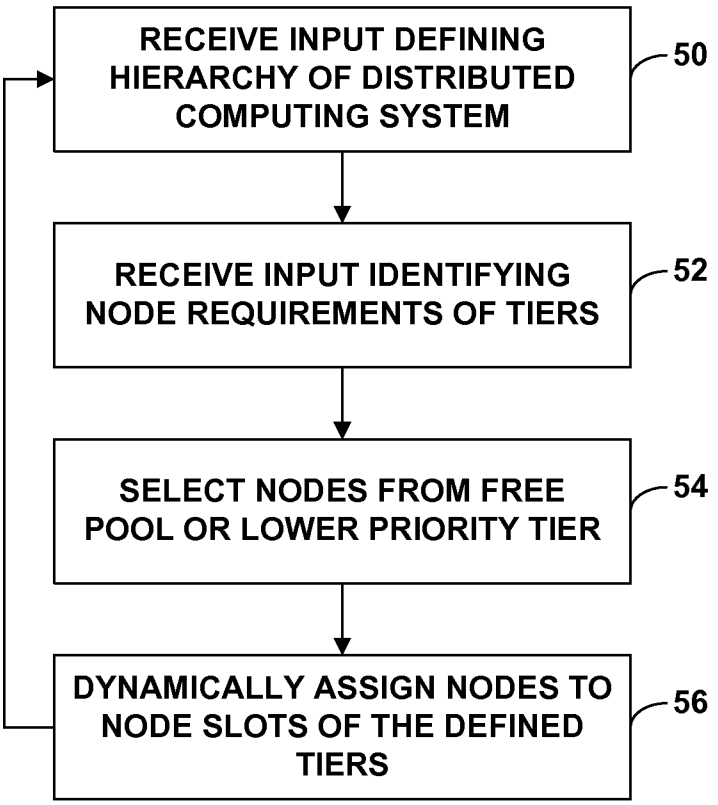
RECEIVE INPUT DEFINING HIERARCHY OF DISTRIBUTED COMPUTING SYSTEM
50
RECEIVE INPUT IDENTIFYING NODE REQUIREMENTS OF TIERS
52
SELECT NODES FROM FREE POOL OR LOWER PRIORITY TIER
54
DYNAMICALLY ASSIGN NODES TO NODE SLOTS OF THE DEFINED TIERS
56

FIG. 3

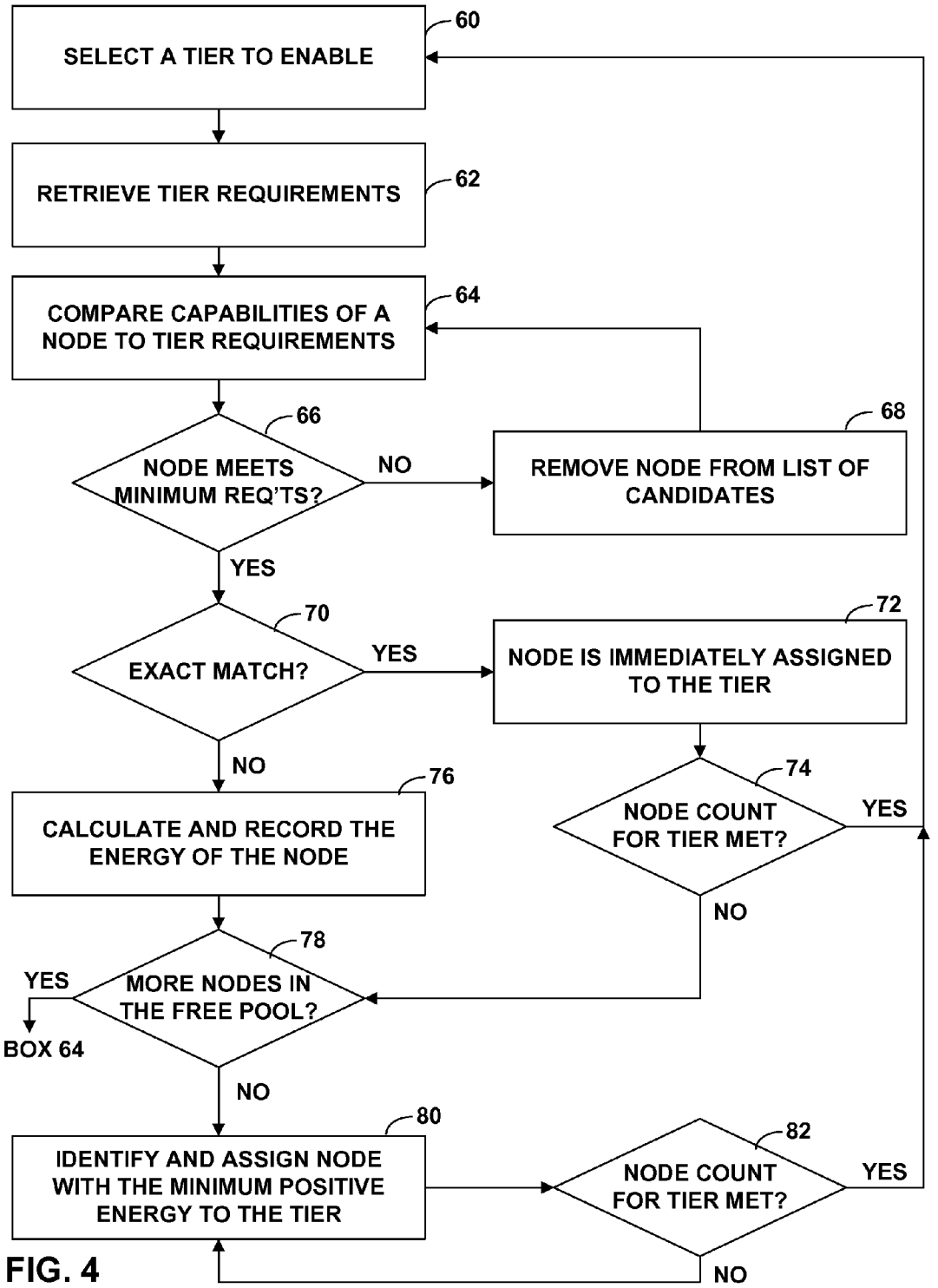
SELECT A TIER TO ENABLE
60
RETRIEVE TIER REQUIREMENTS
62
COMPARE CAPABILITIES OF A NODE TO TIER REQUIREMENTS
64
NODE MEETS MINIMUM REQ'TS?
66
NO
REMOVE NODE FROM LIST OF CANDIDATES
68
YES
EXACT MATCH?
70
YES
NODE IS IMMEDIATELY ASSIGNED TO THE TIER
72
NO
CALCULATE AND RECORD THE ENERGY OF THE NODE
76
NODE COUNT FOR TIER MET?
74
YES
NO
MORE NODES IN THE FREE POOL?
78
YES
BOX 64
NO
IDENTIFY AND ASSIGN NODE WITH THE MINIMUM POSITIVE ENERGY TO THE TIER
80
NODE COUNT FOR TIER MET?
82
YES
NO

FIG. 4

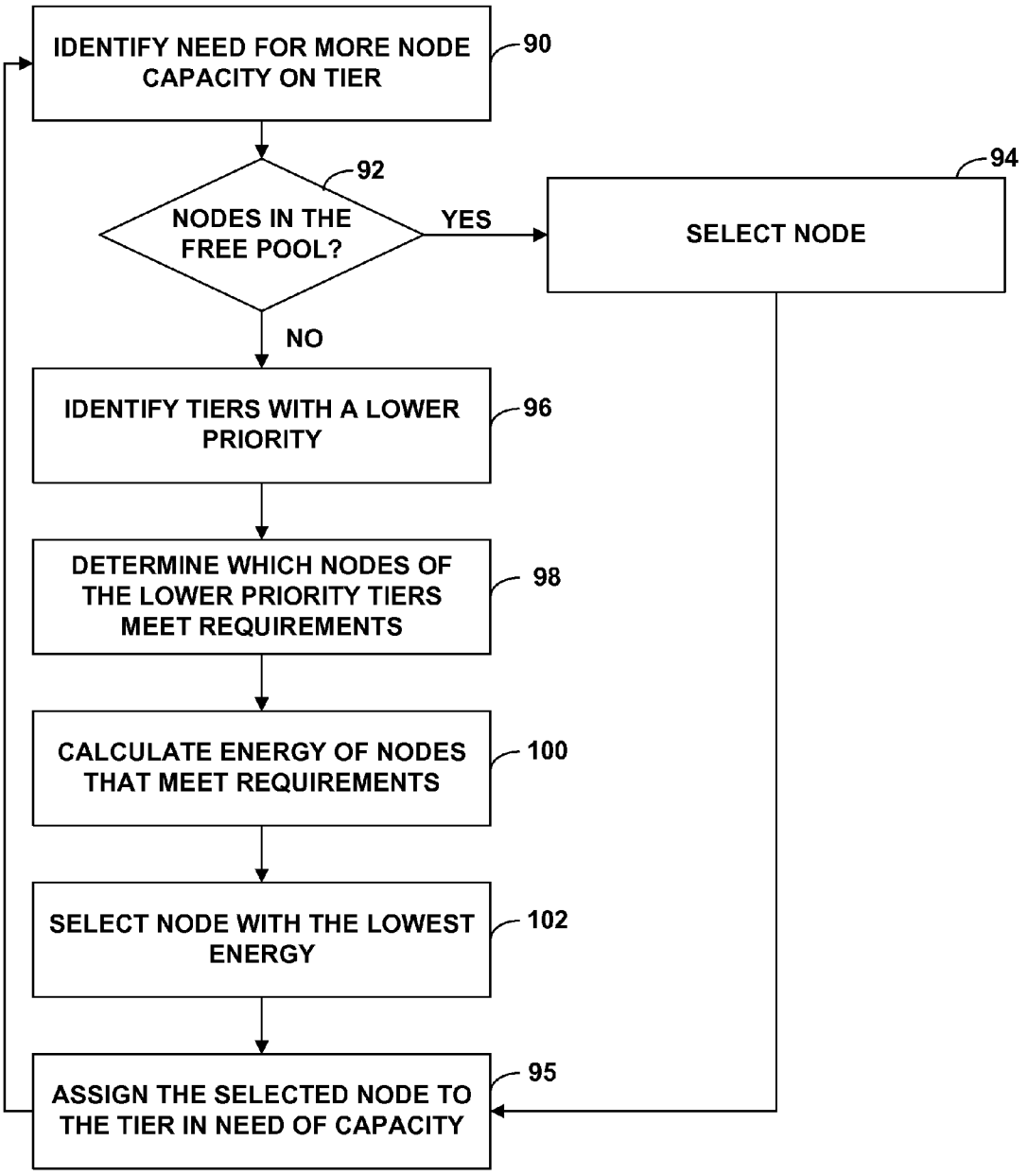
IDENTIFY NEED FOR MORE NODE CAPACITY ON TIER
90
NODES IN THE FREE POOL?
92
YES
SELECT NODE
94
NO
IDENTIFY TIERS WITH A LOWER PRIORITY
96
DETERMINE WHICH NODES OF THE LOWER PRIORITY TIERS MEET REQUIREMENTS
98
CALCULATE ENERGY OF NODES THAT MEET REQUIREMENTS
100
SELECT NODE WITH THE LOWEST ENERGY
102
ASSIGN THE SELECTED NODE TO THE TIER IN NEED OF CAPACITY
95

FIG. 5

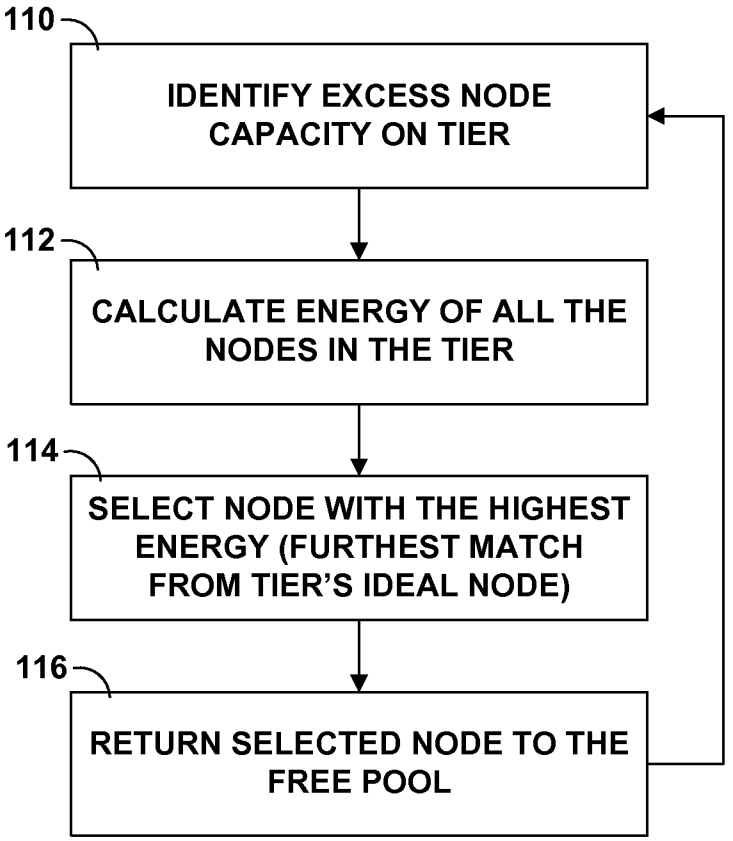
110
IDENTIFY EXCESS NODE CAPACITY ON TIER
112
CALCULATE ENERGY OF ALL THE NODES IN THE TIER
114
SELECT NODE WITH THE HIGHEST ENERGY (FURTHEST MATCH FROM TIER'S IDEAL NODE)
116
RETURN SELECTED NODE TO THE FREE POOL

FIG. 6

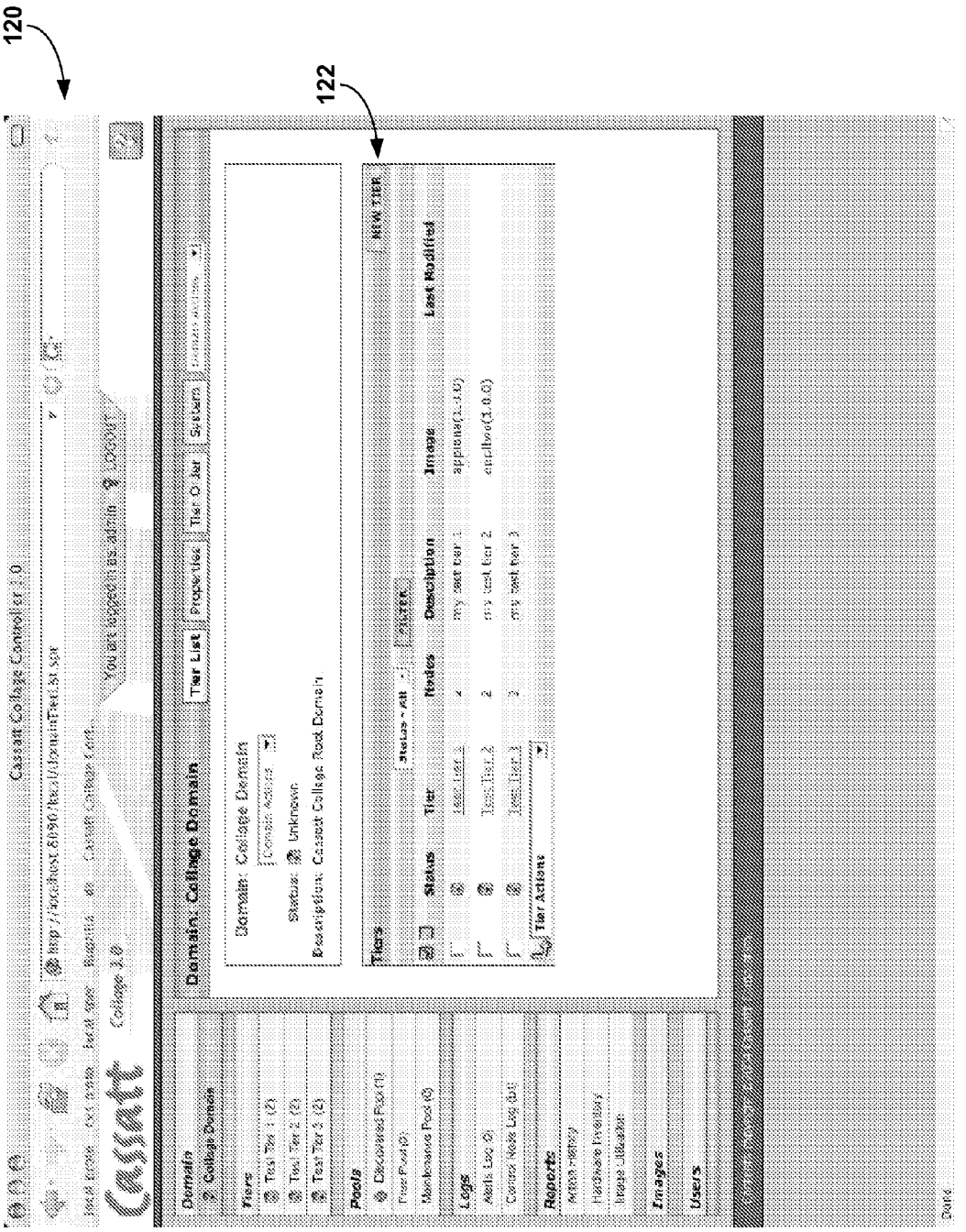
120
122
Cassat Collage Controller 1.0
Cassat
Collage 1.0
You are logged in as: admin
Logout
Domain
College Domain
Tiers
Test Tier 1 (2)
Test Tier 2 (2)
Test Tier 3 (2)
Pools
Decommissioned Pool (0)
Free Pool (0)
Maintenance Pool (0)
Logs
Alerts Log (0)
Control Node Log (0)
Reports
Activity History
Hardware Inventory
Image Utilization
Images
Users
Domain: College Domain
Tier List
Properties
Tier Of Jar
System
Domain: College Domain
Owner Access
Status: Unknown
Description: Cassat College Pool Domain
Tiers
NEW TIER
Status - All
FILTER
Status
Tier
Nodes
Description
Image
Last Modified
Test Tier 1
1
my test tier 1
appliance(1.0.0)
Test Tier 2
2
my test tier 2
appliance(1.0.0)
Test Tier 3
3
my test tier 3
Tier Actions

FIG. 7

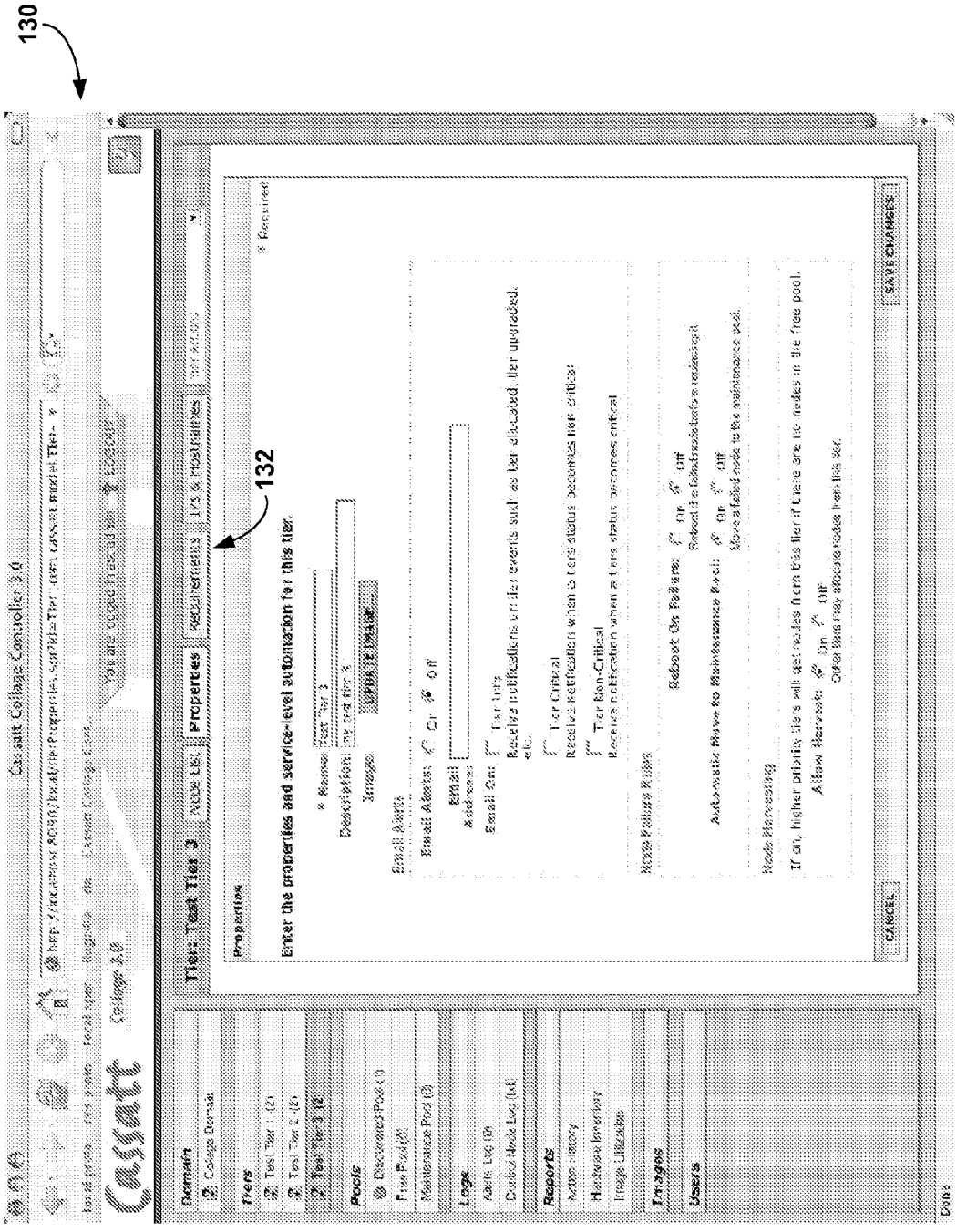
130
132
Cisco Collage Controller 3.0
Cisco Collage 3.0
Tiers
Test Tier 1 (2)
Test Tier 2 (2)
Test Tier 3 (2)
Pools
Disconnected Pool (1)
Free Pool (2)
Maintenance Pool (0)
Logs
Admin Log (0)
Device Mode Log (14)
Reports
Action History
Hardware Inventory
Image Utilization
Images
Users
Tier: Test Tier 3
Node List
Properties
Requirements
IPs & Hostnames
Properties
Enter the properties and service-level automation for this tier.
* Required
* Name:
Test Tier 3
Description:
Image:
Email Alerts
Email Alerts:
On
Off
Email:
Email On:
Tier Info
Receive notifications when other events such as tier allocated, tier unprovisioned, etc.
Tier Critical
Receive notification when a tier's status becomes non-critical
Tier Non-Critical
Receive notification when a tier's status becomes critical
Node Failure Policy
Reboot On Failure:
On
Off
Reboot the failed node before redeploy
Automatic Move to Maintenance Pool:
On
Off
Move a failed node to the maintenance pool.
Node Harvesting
If an higher priority tier's will get nodes from this tier if there are no nodes in the free pool.
Allow Harvesting:
On
Off
Other tiers may allocate nodes from this tier.
CANCEL
SAVE CHANGES
Done

FIG. 8

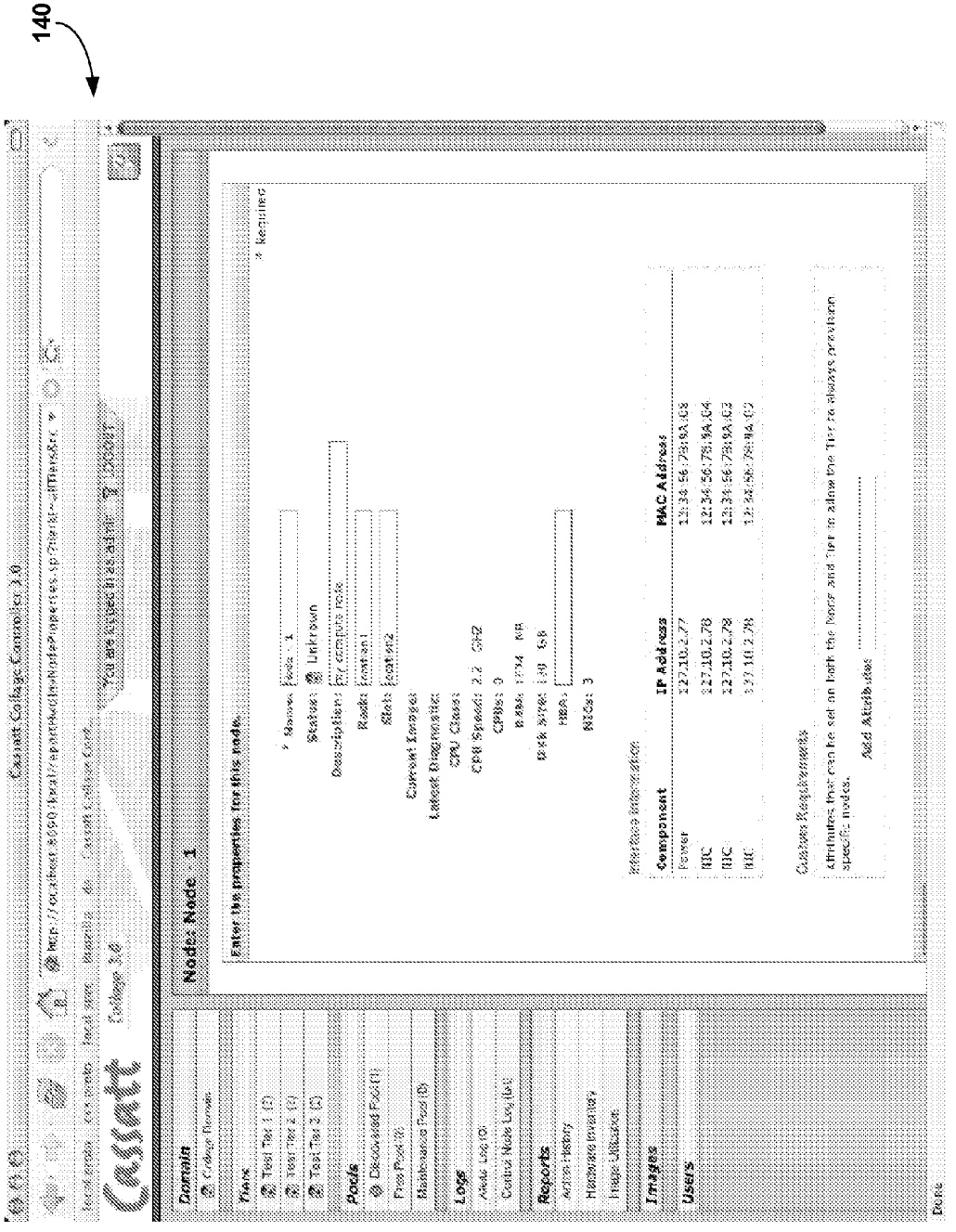
140
Cavatt
Node: Node_1
Enter the properties for this node.
Domain
Runs
Pools
Logs
Reports
Images
Users
Component
IP Address
MAC Address

FIG. 9

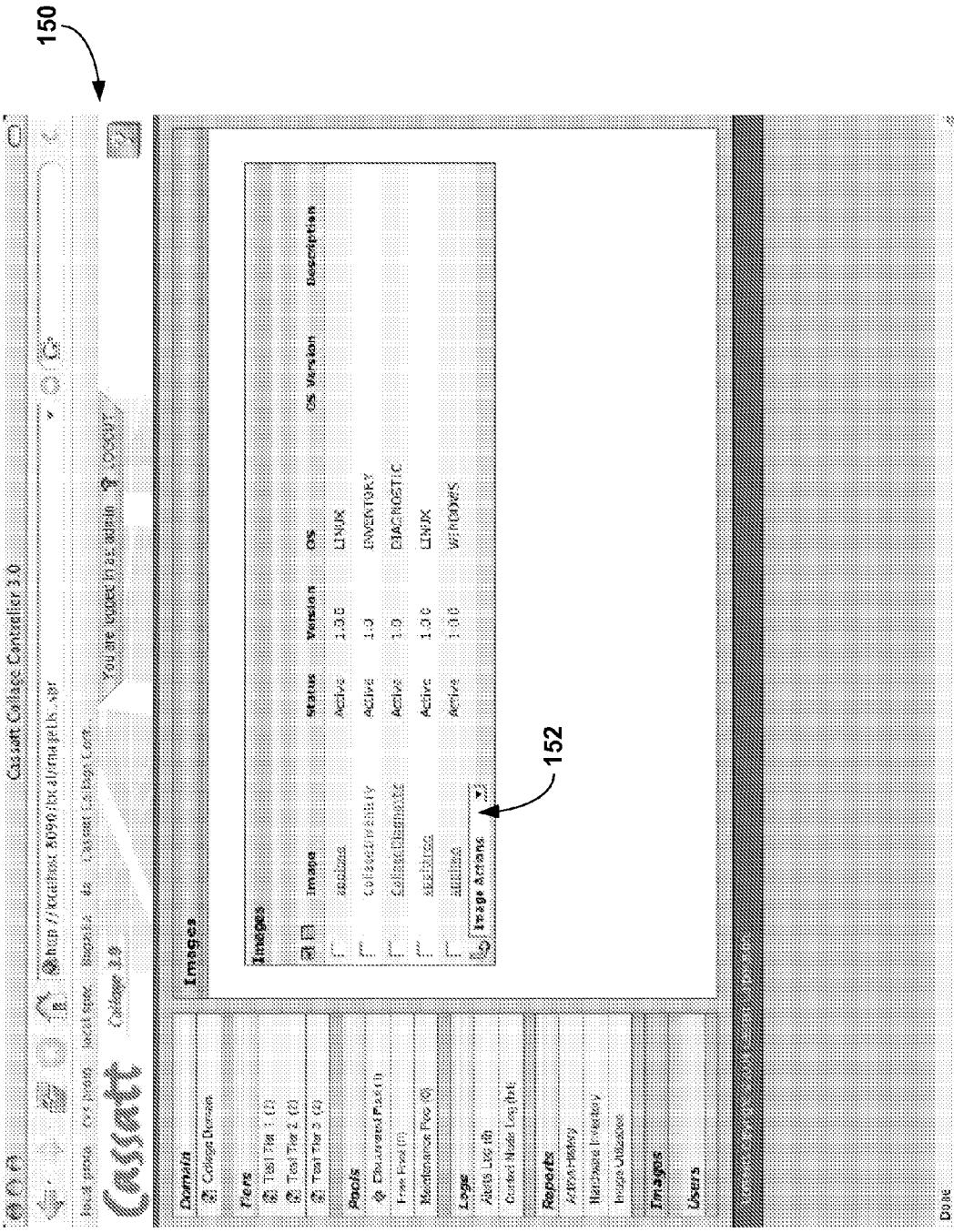
150
Cassatt Collage Controller 3.0
Cassatt
Collage 3.0
You are logged in as admin
LOGOUT
Domain
Collage Domain
Tiers
Test Tier 1 (0)
Test Tier 2 (0)
Test Tier 3 (0)
Pools
Clustered Pool (0)
Free Pool (0)
Maintenance Pool (0)
Logs
Alerts Log (0)
Control Node Log (0)
Reports
Action History
Hardware Inventory
Image Utilization
Images
Users
Images
Images
Image
Status
Version
OS
OS Version
Description
Active
1.0.0
LINUX
Active
1.0
INVENTORY
Active
1.0
DIAGNOSTIC
Active
1.0.0
LINUX
Active
1.0.0
WINDOWS
Image Actions
152
Done

FIG. 10

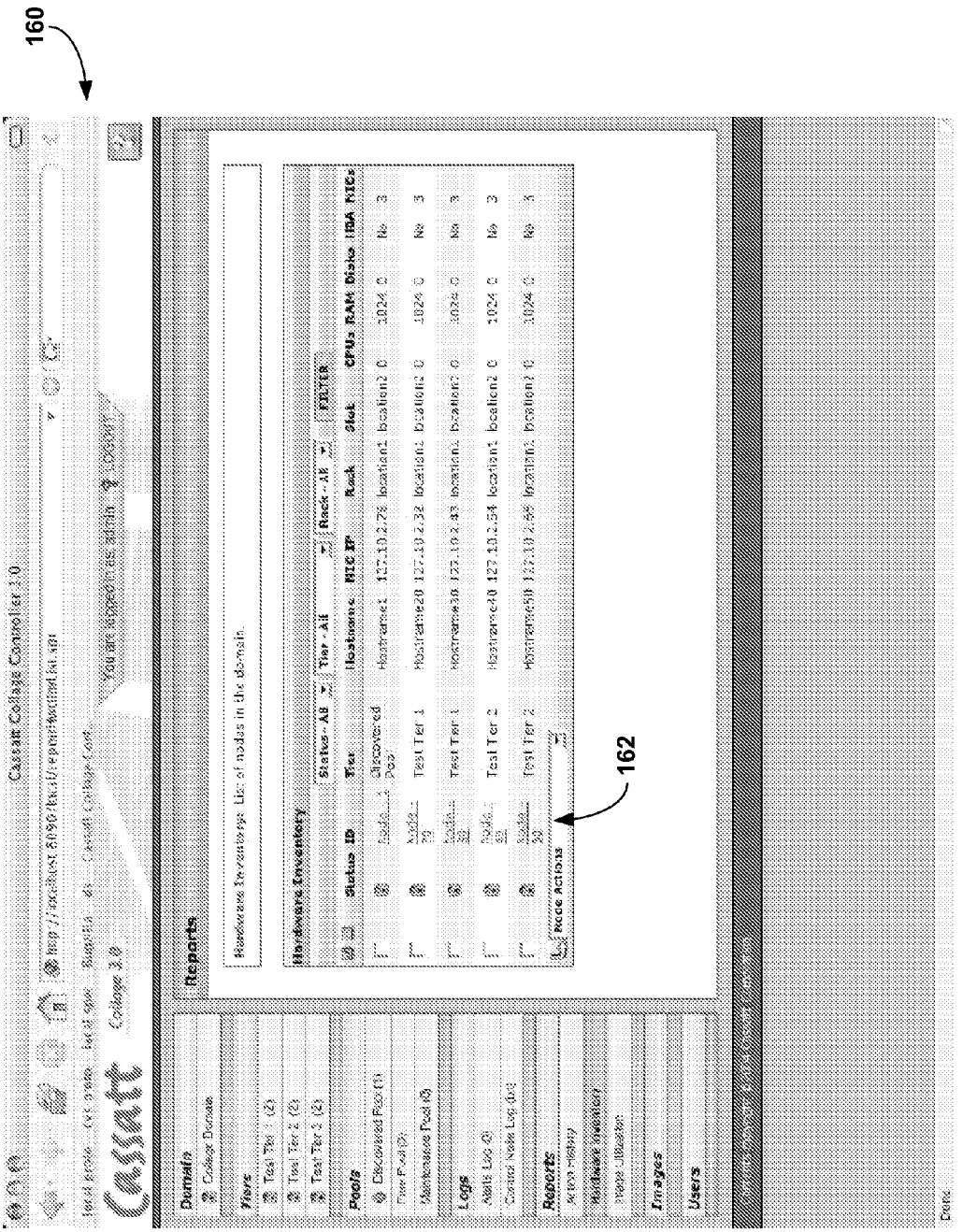
160
Cisco Collage Controller 1.0
Cisart
Collage 2.0
You are logged in as admin
Domain
Reports
Hardware Inventory: List of nodes in the domain.
Hardware Inventory
Status - All
Tier - All
Rack - All
Filter
Status ID
Tier
Hostname
NIC IP
Rack
Slot
CPUs
RAM
Disks
HBA NICs
Pools
Discovered Pool (1)
Test Pool (0)
Maintenance Pool (0)
Logs
Alert Log (0)
Control Node Log (0)
Reports
Action History
Hardware Inventory
Image Utilization
Images
Users
Node Actions
162
Done

FIG. 11

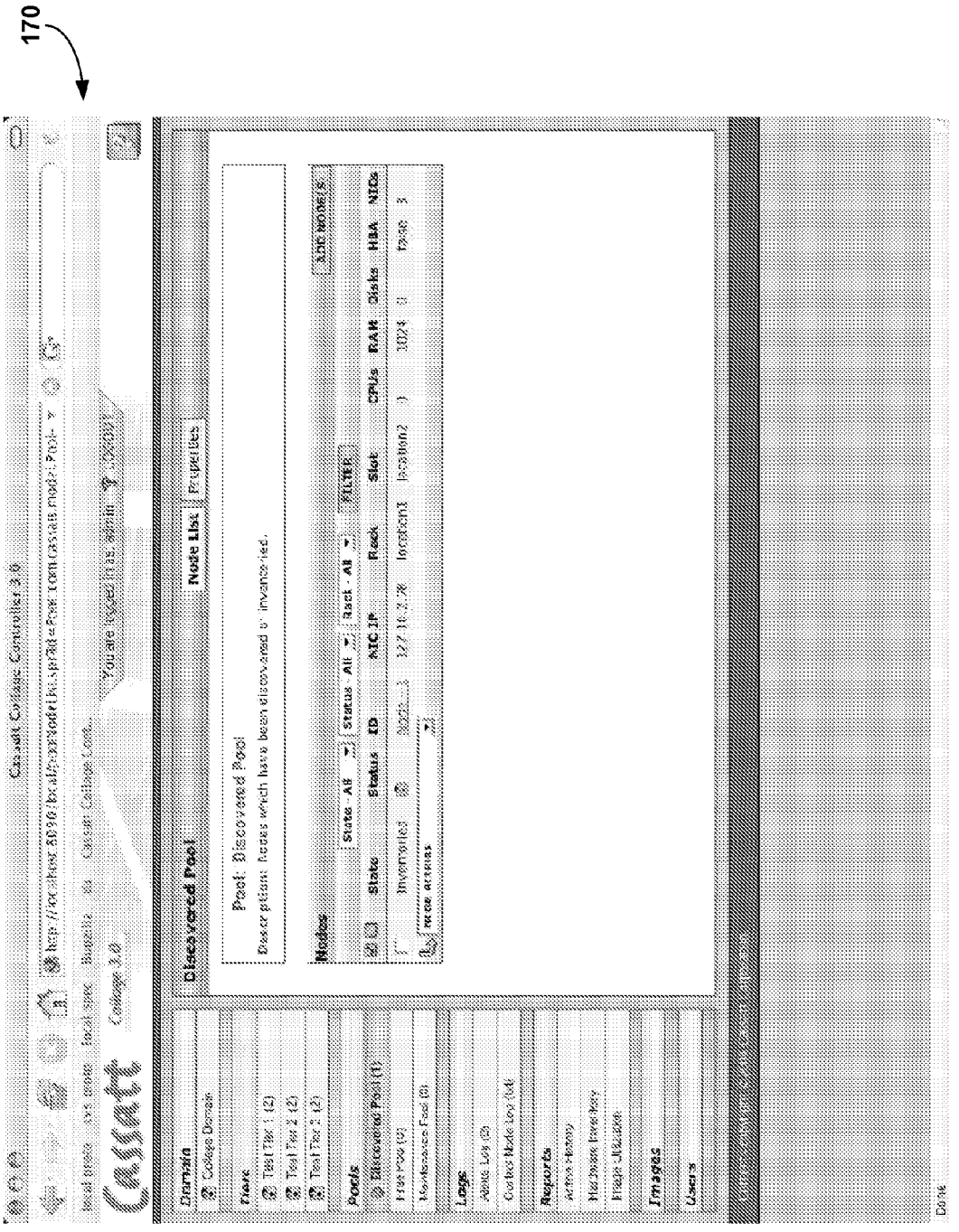
170
Cassatt Collage Controller 3.0
Cassatt
Collage 3.0
Domain
College Domain
Plan
Test Tier 1 (2)
Test Tier 2 (2)
Test Tier 3 (2)
Pools
Discovered Pool (1)
Free Pool (0)
Maintenance Pool (0)
Logs
Admin Log (0)
Control Node Log (14)
Reports
Action History
Hardware Inventory
Image Utilization
Images
Users
Discovered Pool
Node List
Properties
Pool: Discovered Pool
Description: Nodes which have been discovered or inventoried.
Nodes
Add Nodes
State
Status
ID
NIC IP
Rack
Slot
CPUs
RAM
Disks
HBA
NICs
Inventoried
Rack Servers
Done

FIG. 12

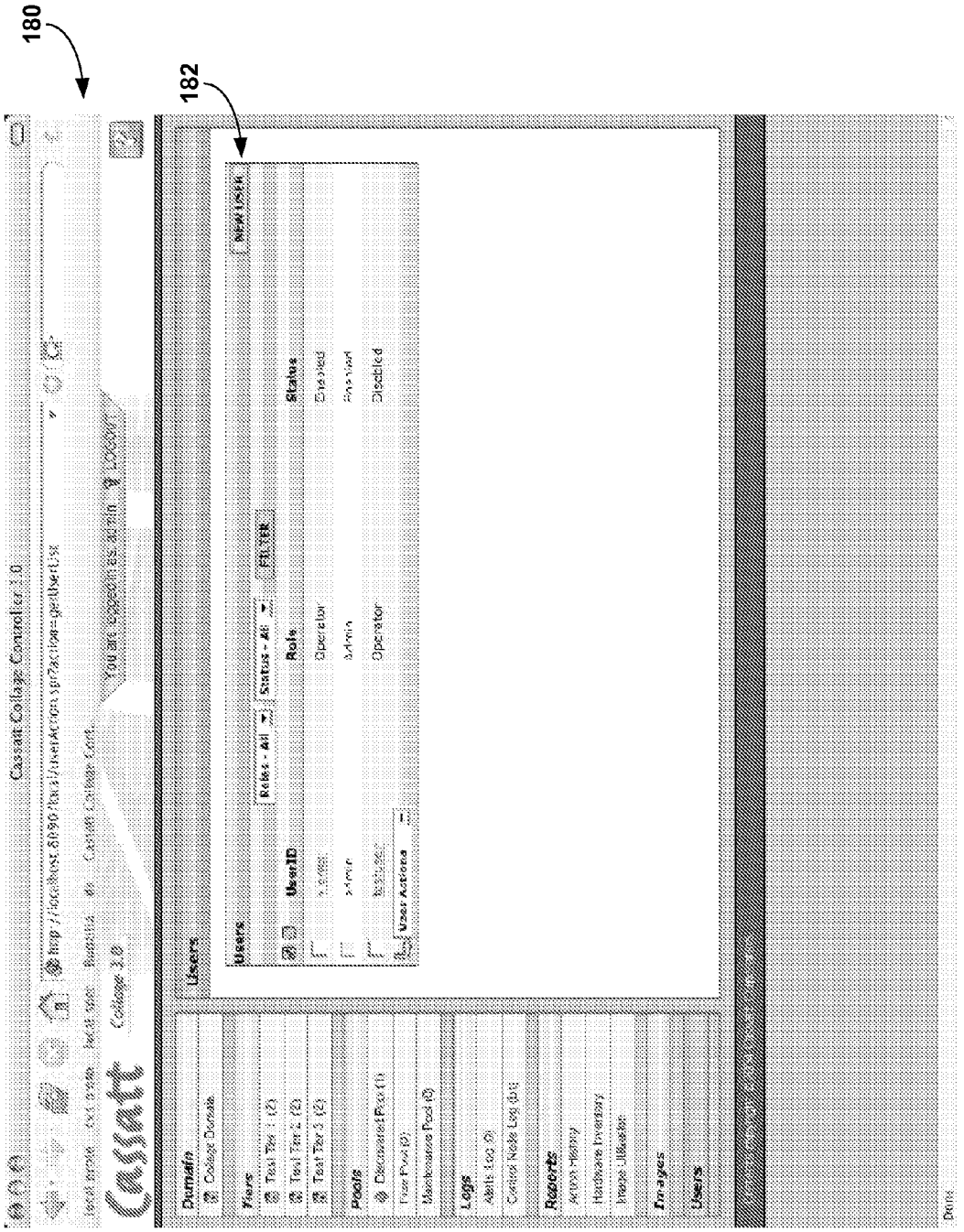
180
182
Cassat Collage Console 3.0
Cassat
Collage 3.0
Domain
Users
Pools
Logs
Reports
Images
Users
Status - All
FILTER
UserID
Role
Status
Operator
Disabled
Admin
Operator
Disabled
User Actions
Done

FIG. 13

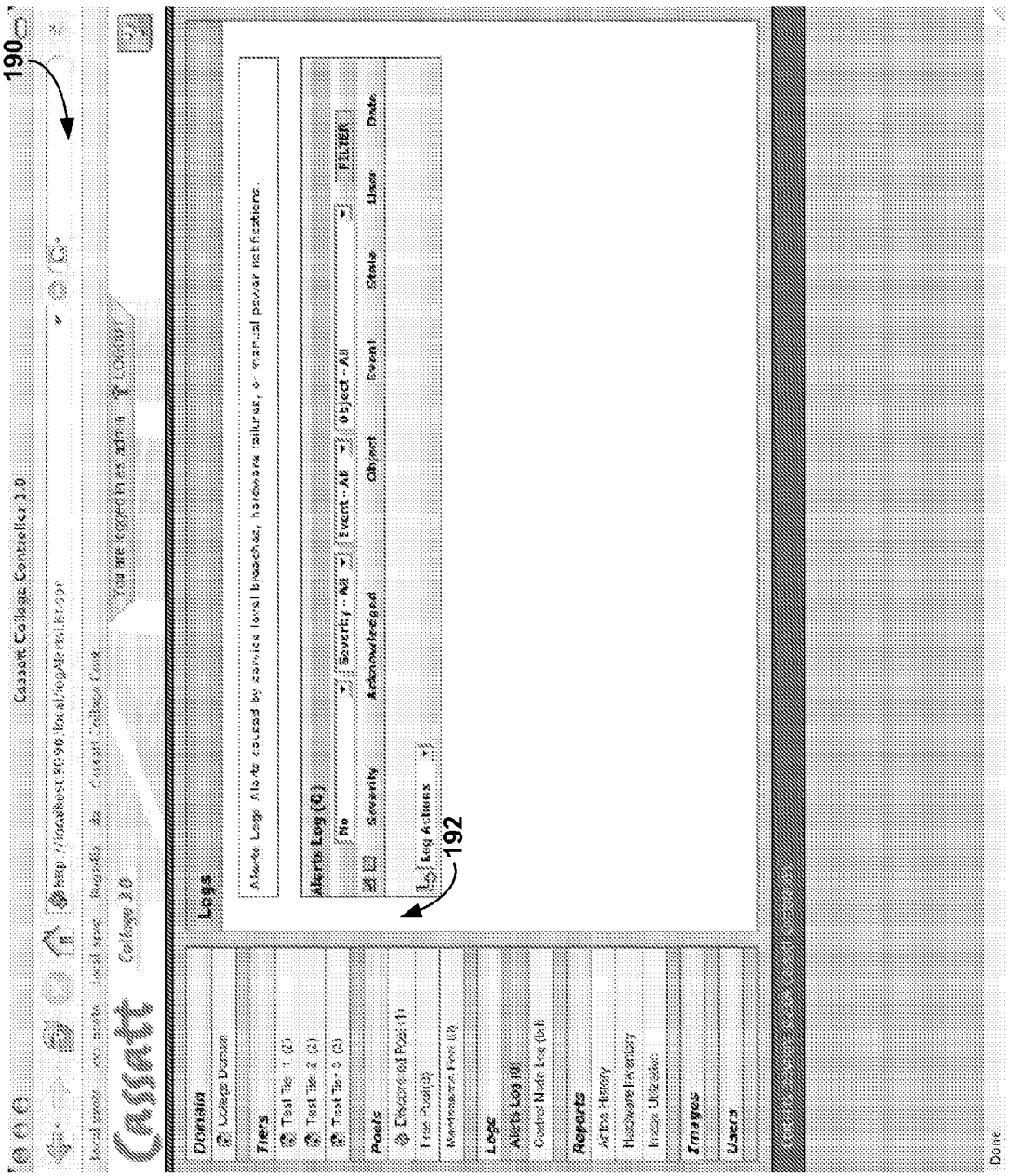
190
192
Cassat Collage Controller 3.0
Cassat
Collage 3.0
Domain
Logs
Tiers
Pools
Logs
Reports
Images
Users
Alerts Log (0)
Severity
Acknowledged
Object
Event
State
User
Date
FILTER
Log Actions
Done

FIG. 14

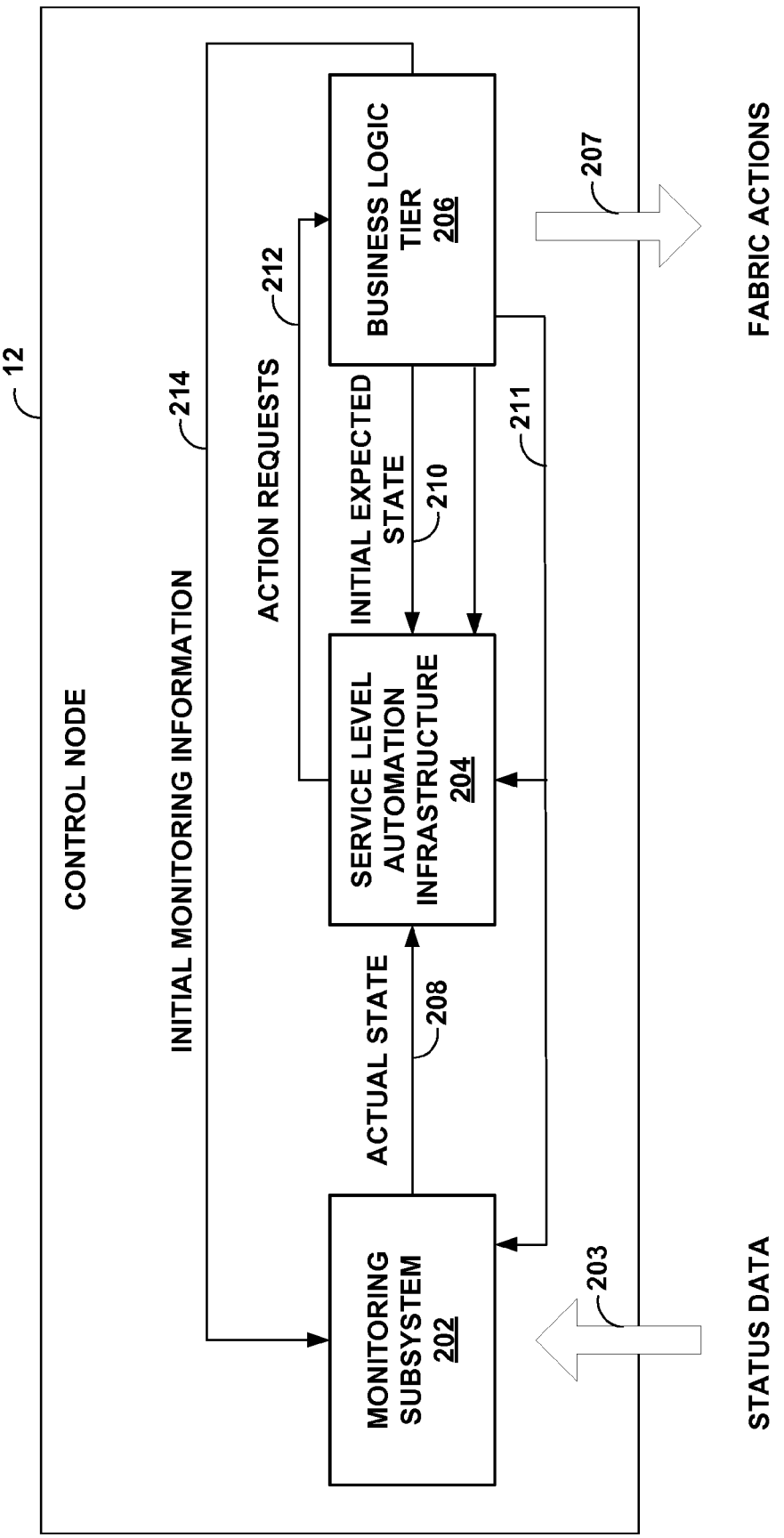
12
CONTROL NODE
214
INITIAL MONITORING INFORMATION
212
ACTION REQUESTS
BUSINESS LOGIC TIER 206
207
FABRIC ACTIONS
INITIAL EXPECTED STATE
210
211
SERVICE LEVEL AUTOMATION INFRASTRUCTURE 204
ACTUAL STATE
208
MONITORING SUBSYSTEM 202
203
STATUS DATA

FIG. 15

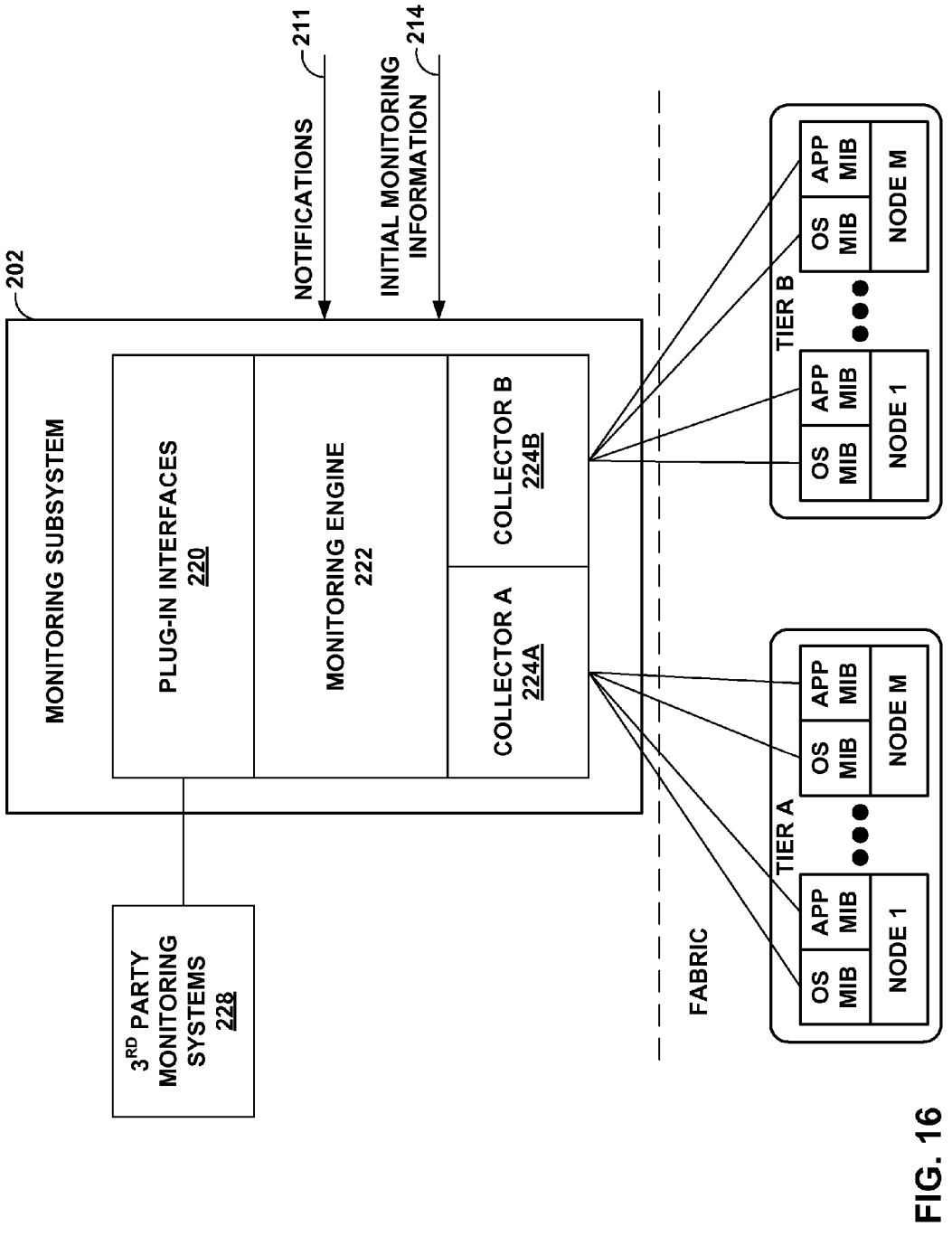
202
MONITORING SUBSYSTEM
PLUG-IN INTERFACES 220
MONITORING ENGINE 222
COLLECTOR A 224A
COLLECTOR B 224B
NOTIFICATIONS 211
INITIAL MONITORING INFORMATION 214
3RD PARTY MONITORING SYSTEMS 228
FABRIC
TIER A
TIER B
OS MIB
APP MIB
NODE 1
NODE M

FIG. 16

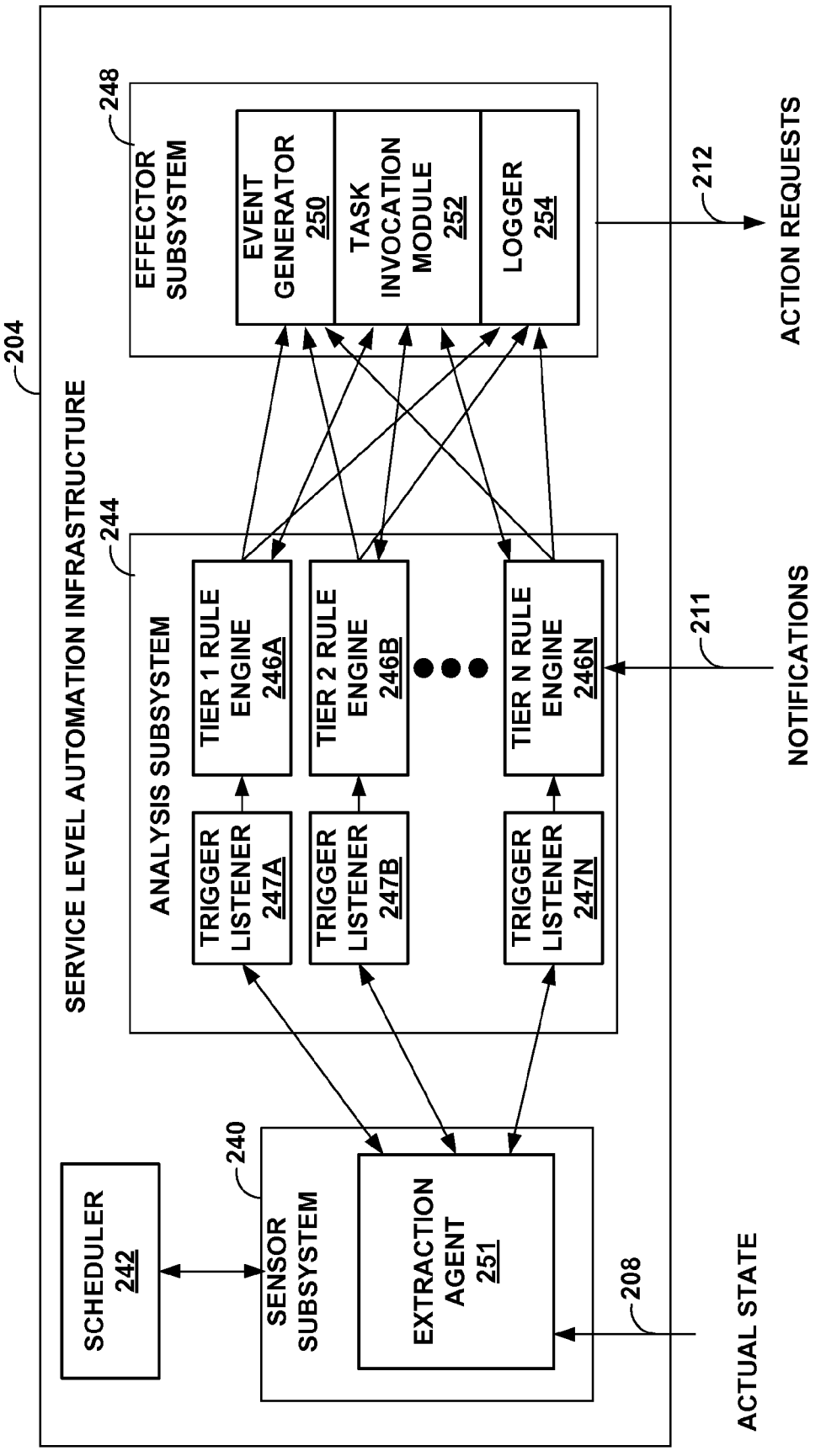
204
SERVICE LEVEL AUTOMATION INFRASTRUCTURE
248
EFFECTOR SUBSYSTEM
EVENT GENERATOR 250
TASK INVOCATION MODULE 252
LOGGER 254
212
ACTION REQUESTS
244
ANALYSIS SUBSYSTEM
TIER 1 RULE ENGINE 246A
TIER 2 RULE ENGINE 246B
TIER N RULE ENGINE 246N
211
NOTIFICATIONS
TRIGGER LISTENER 247A
TRIGGER LISTENER 247B
TRIGGER LISTENER 247N
240
SCHEDULER 242
SENSOR SUBSYSTEM
EXTRACTION AGENT 251
208
ACTUAL STATE

FIG. 17

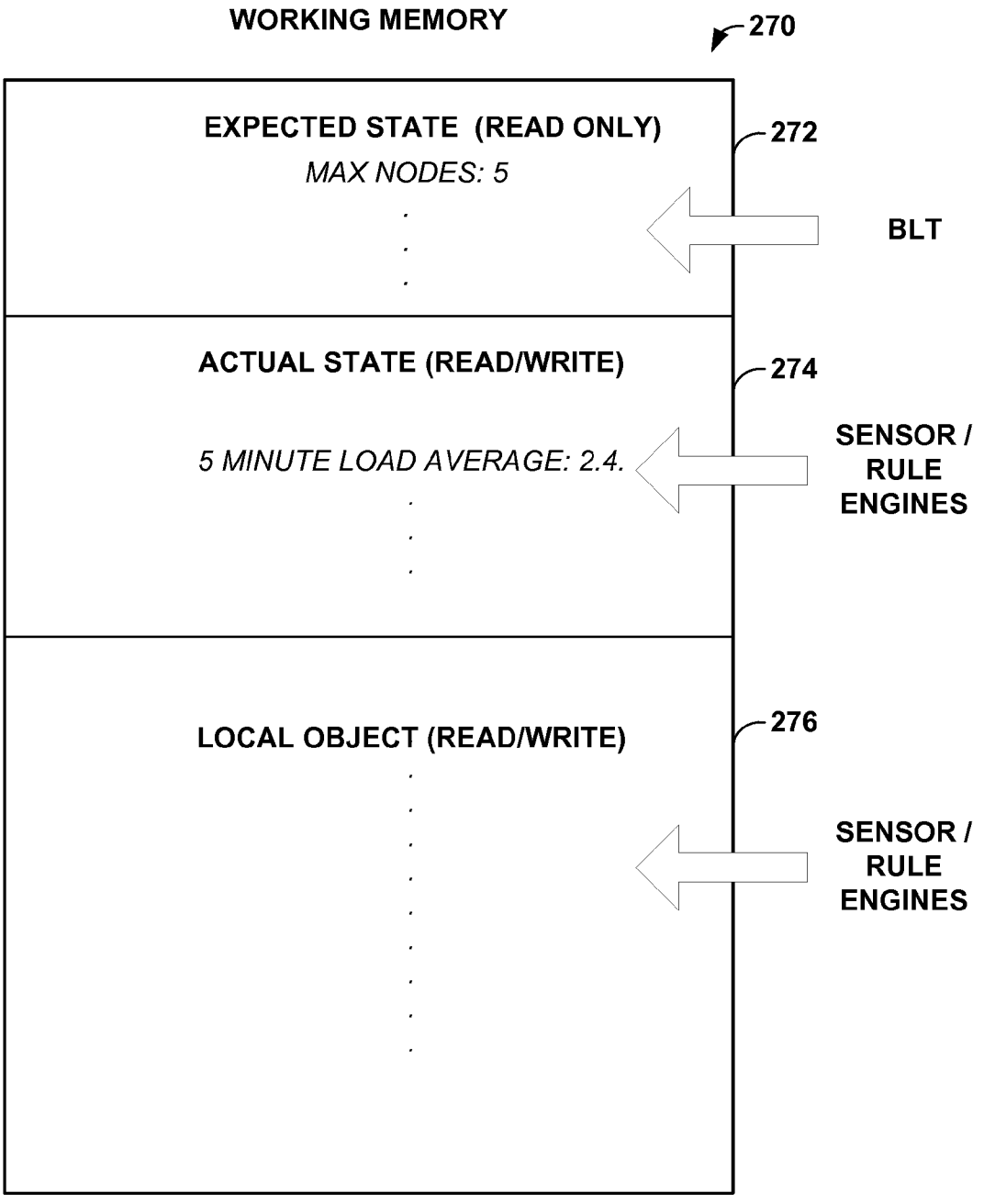
WORKING MEMORY
270
EXPECTED STATE (READ ONLY)
MAX NODES: 5
272
BLT
ACTUAL STATE (READ/WRITE)
274
5 MINUTE LOAD AVERAGE: 2.4.
SENSOR / RULE ENGINES
LOCAL OBJECT (READ/WRITE)
276
SENSOR / RULE ENGINES

FIG. 18

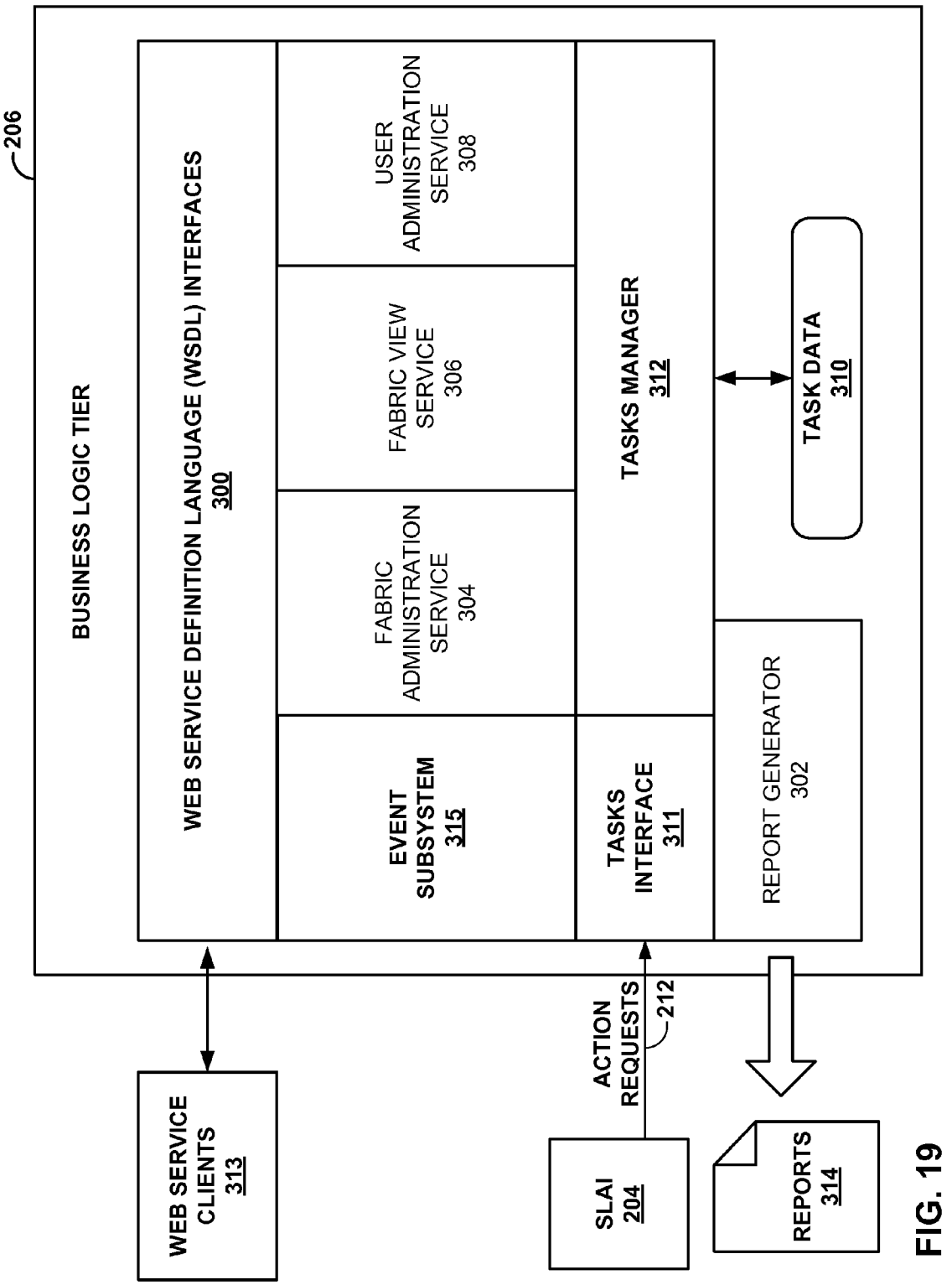
206
BUSINESS LOGIC TIER
WEB SERVICE DEFINITION LANGUAGE (WSDL) INTERFACES 300
USER ADMINISTRATION SERVICE 308
FABRIC VIEW SERVICE 306
FABRIC ADMINISTRATION SERVICE 304
EVENT SUBSYSTEM 315
TASKS MANAGER 312
TASKS INTERFACE 311
REPORT GENERATOR 302
TASK DATA 310
WEB SERVICE CLIENTS 313
ACTION REQUESTS 212
SLAI 204
REPORTS 314

FIG. 19

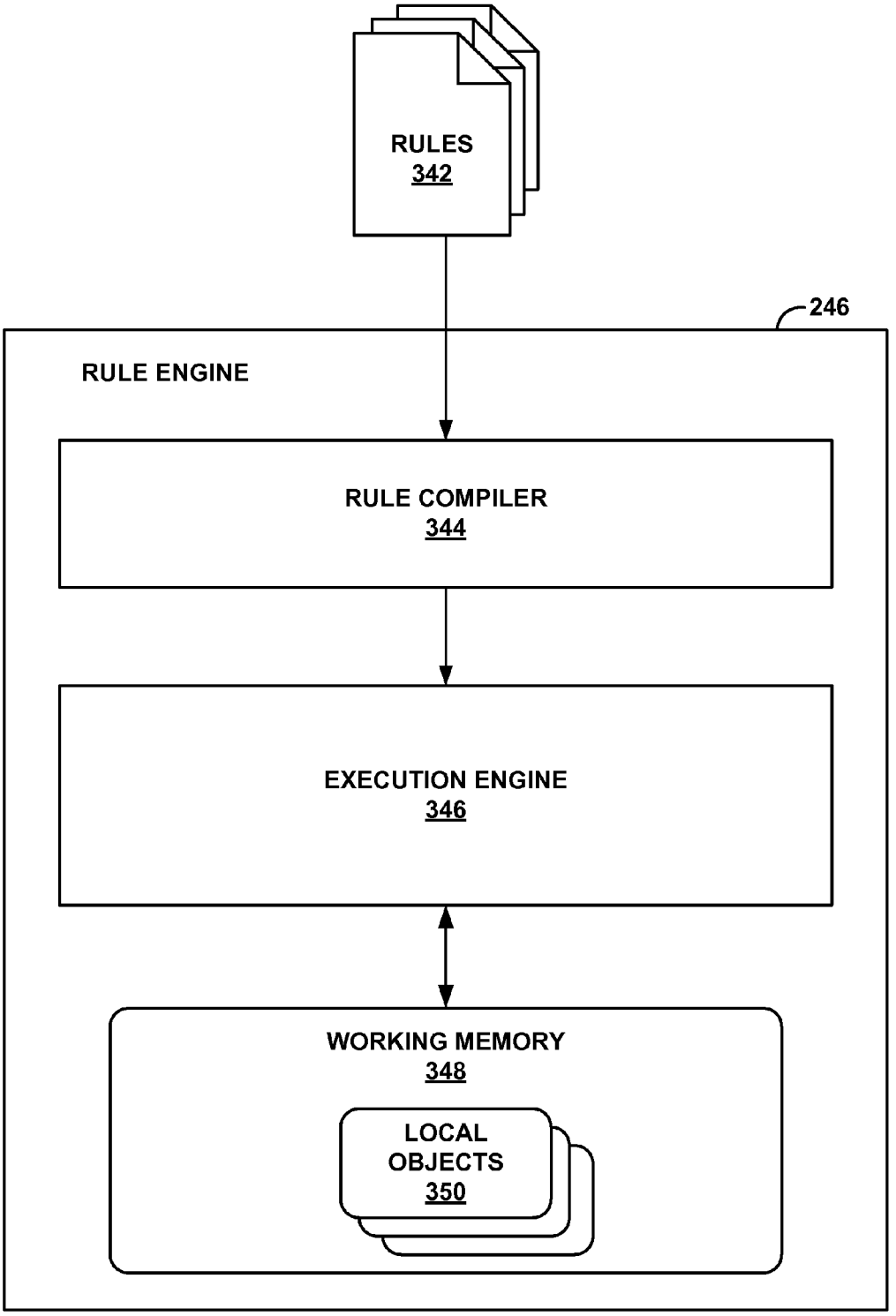
RULES
342
246
RULE ENGINE
RULE COMPILER
344
EXECUTION ENGINE
346
WORKING MEMORY
348
LOCAL
OBJECTS
350

FIG. 20

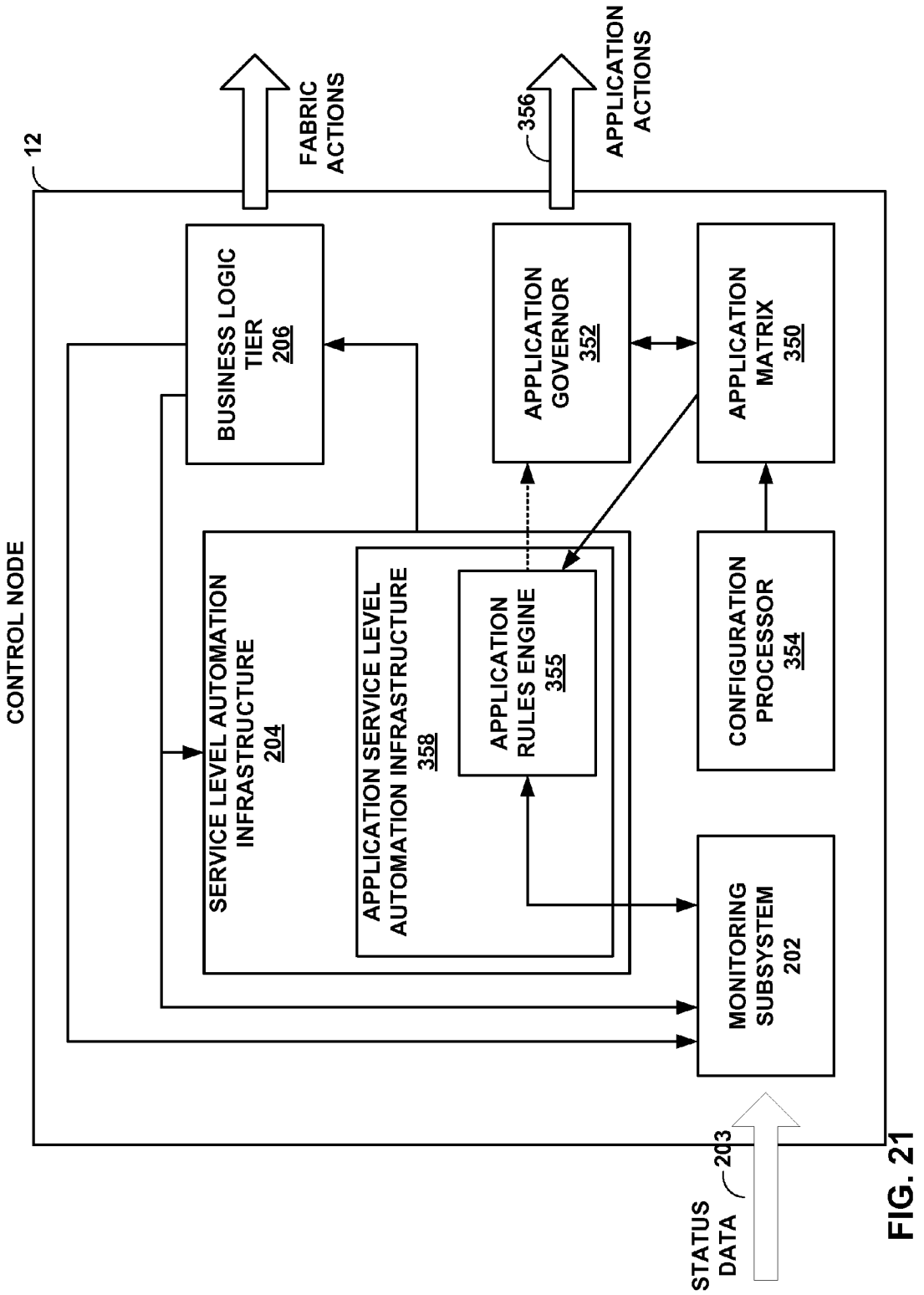
12
CONTROL NODE
FABRIC ACTIONS
356
APPLICATION ACTIONS
BUSINESS LOGIC TIER 206
APPLICATION GOVERNOR 352
APPLICATION MATRIX 350
SERVICE LEVEL AUTOMATION INFRASTRUCTURE 204
APPLICATION SERVICE LEVEL AUTOMATION INFRASTRUCTURE 358
APPLICATION RULES ENGINE 355
CONFIGURATION PROCESSOR 354
MONITORING SUBSYSTEM 202
203
STATUS DATA

FIG. 21

APPLICATION (360)	APPLICATION NODES (362)	SERVICES (364)	NODE MONITORED VALUES (366)	SERVICE MONITORED ATTRIBUTES (368)	SERVICE LEVELS (370)	DEPLOYMENT CONSTRAINTS (372)
Name= DataDomain **adminIP=** "172.31.64.201" **adminPort=** "1100" **adminTier=** "Web Admin" **clusterName=** "PathCluster" **expectedStartupDelay=**120 **loadDelay=**120 **maxNodes=**2 **minNodes=**1	**IP=** 172.31.64.201 **Name=** managedServer_0 **IP=** 172.31.64.202 **Name=** managedServer_1	**name=**"AI Design-time" **path=**"/lib/ai-designtime.ear" **name=**"System EJBs" **path=**"/lib/ejbs.ear" **name=**"Worklist Worker User Interface" **path=**"/lib/worklist/worklist.ear" **name=**"DBMS_ADK" **path=**"/lib/DBMS_ADK.ear" **name=**"App" **path=**"/user_projects/domains/data.ear"	**name=** Load5Average **name=** PercentFree-Memory	**name=** PendRequests **name=** ExecuteThread-IdleCount **name=** ExecuteThread-TotalCount	**attribute=** "BusyThread-Percentage" **expression=** "(ExecuteThreadTotalCount-ExecuteThreadIdleCount)*100/ExecuteThreadTotalCount" **frequency=**"15" **maxThreshold=**"20.0" **minThreshold=**"5.0" **period=**"30" **attribute=** "PendingRequests" **expression=** "PendingRequests" **frequency=**"15" **maxThreshold=**"20" **minThreshold=**"5" **period=**"30"	**attribute=** "LoadAverage" **expression=** "Load5Average" **frequency=**"15" **maxThreshold=**"4" **minThreshold=**"-1" **period=**"15" **attribute=** "FreeMemory" **expression=** "PercentMemoryFree*100" **frequency=**"15" **maxThreshold=**"-1" **minThreshold=**"1" **period=**"60"
name= Portal-Domain						

FIG. 22

376

374

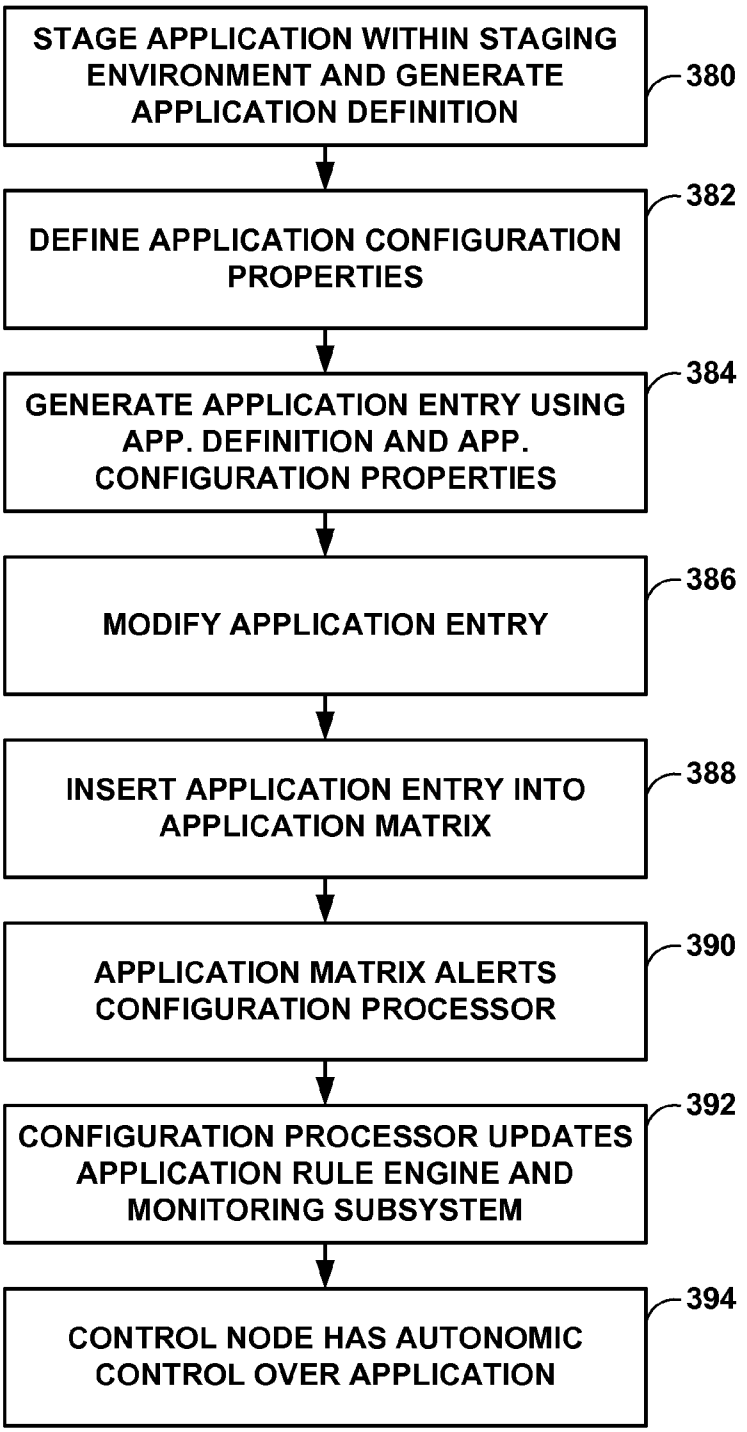
STAGE APPLICATION WITHIN STAGING ENVIRONMENT AND GENERATE APPLICATION DEFINITION
380
DEFINE APPLICATION CONFIGURATION PROPERTIES
382
GENERATE APPLICATION ENTRY USING APP. DEFINITION AND APP. CONFIGURATION PROPERTIES
384
MODIFY APPLICATION ENTRY
386
INSERT APPLICATION ENTRY INTO APPLICATION MATRIX
388
APPLICATION MATRIX ALERTS CONFIGURATION PROCESSOR
390
CONFIGURATION PROCESSOR UPDATES APPLICATION RULE ENGINE AND MONITORING SUBSYSTEM
392
CONTROL NODE HAS AUTONOMIC CONTROL OVER APPLICATION
394

FIG. 23

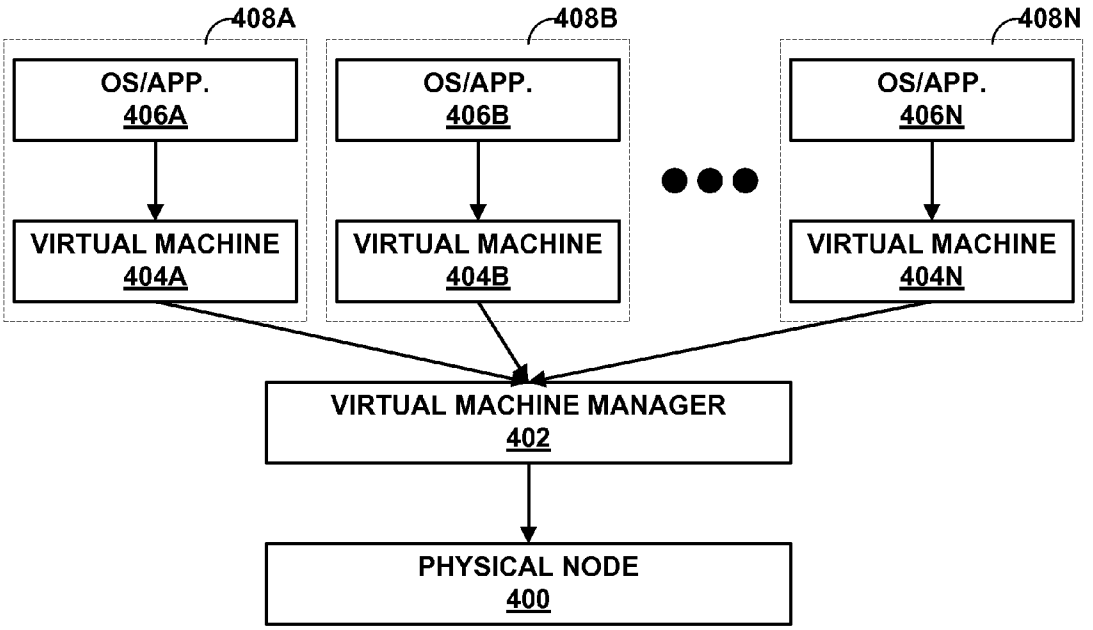
408A
408B
408N
OS/APP.
406A
OS/APP.
406B
OS/APP.
406N
VIRTUAL MACHINE
404A
VIRTUAL MACHINE
404B
VIRTUAL MACHINE
404N
VIRTUAL MACHINE MANAGER
402
PHYSICAL NODE
400

FIG. 24

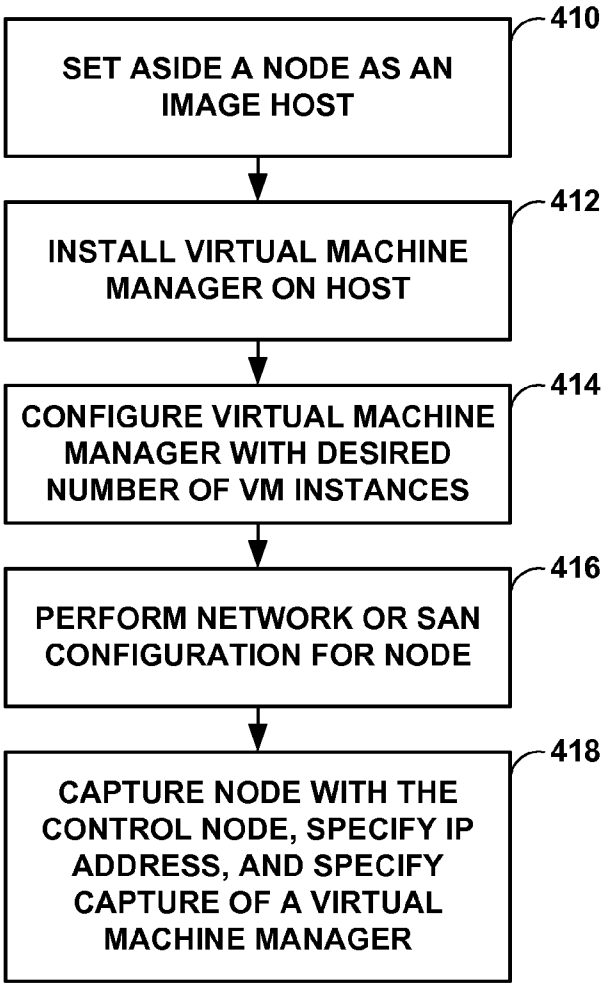
410
SET ASIDE A NODE AS AN IMAGE HOST
412
INSTALL VIRTUAL MACHINE MANAGER ON HOST
414
CONFIGURE VIRTUAL MACHINE MANAGER WITH DESIRED NUMBER OF VM INSTANCES
416
PERFORM NETWORK OR SAN CONFIGURATION FOR NODE
418
CAPTURE NODE WITH THE CONTROL NODE, SPECIFY IP ADDRESS, AND SPECIFY CAPTURE OF A VIRTUAL MACHINE MANAGER

FIG. 25

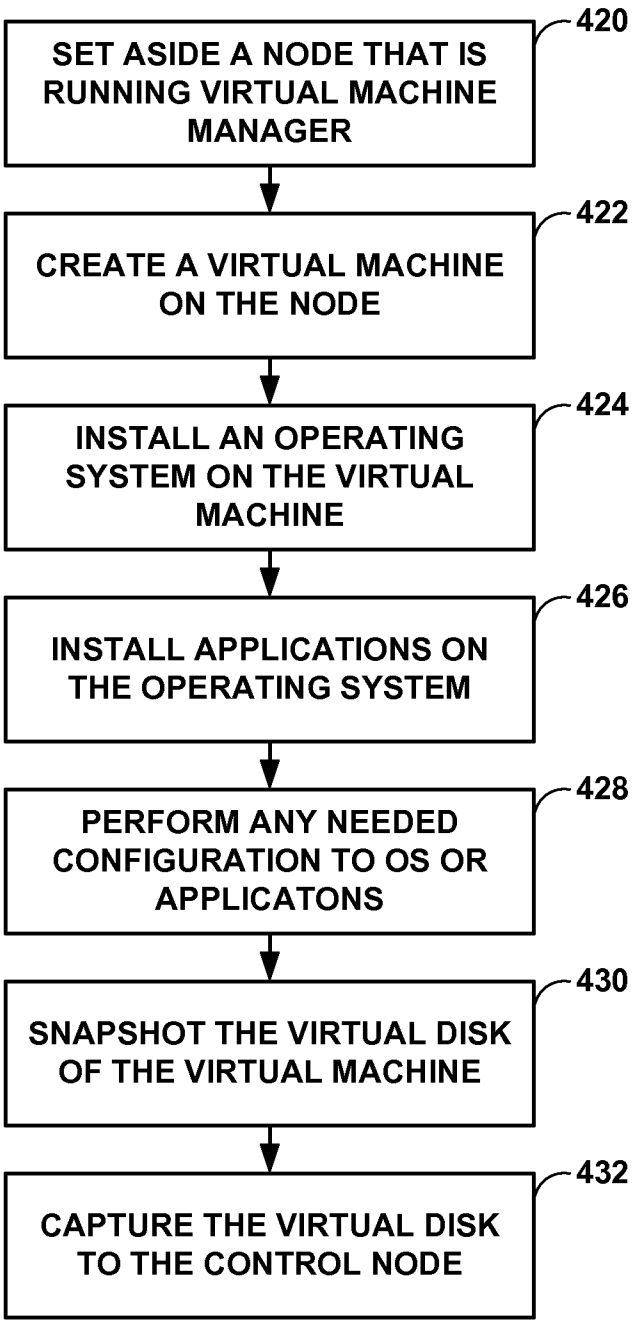
SET ASIDE A NODE THAT IS RUNNING VIRTUAL MACHINE MANAGER
420
CREATE A VIRTUAL MACHINE ON THE NODE
422
INSTALL AN OPERATING SYSTEM ON THE VIRTUAL MACHINE
424
INSTALL APPLICATIONS ON THE OPERATING SYSTEM
426
PERFORM ANY NEEDED CONFIGURATION TO OS OR APPLICATONS
428
SNAPSHOT THE VIRTUAL DISK OF THE VIRTUAL MACHINE
430
CAPTURE THE VIRTUAL DISK TO THE CONTROL NODE
432

FIG. 26

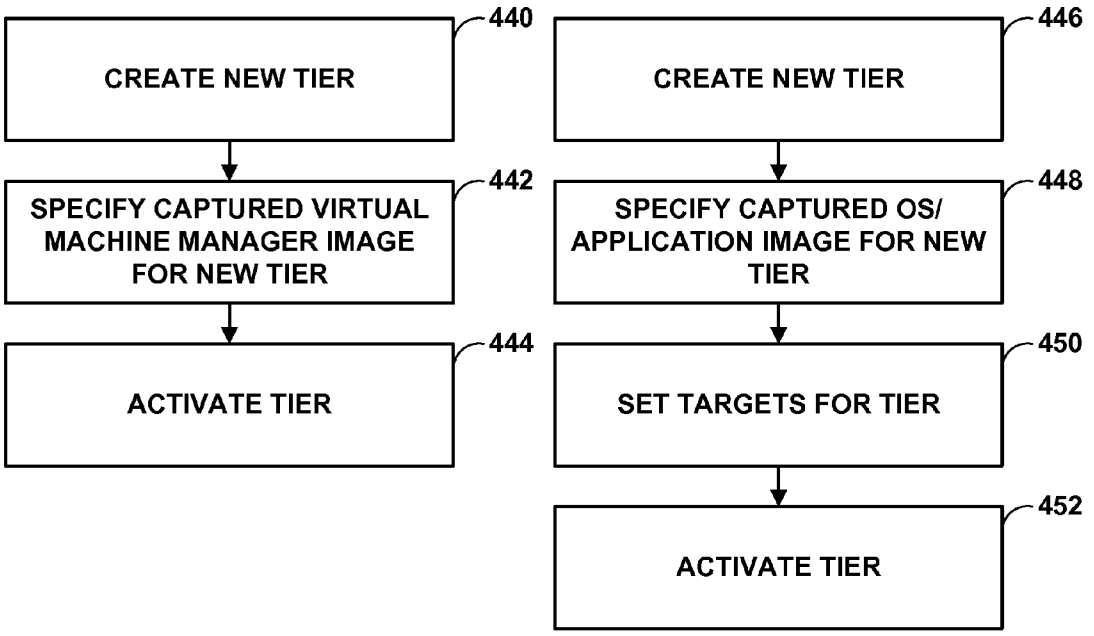

FIG. 27A

FIG. 27B

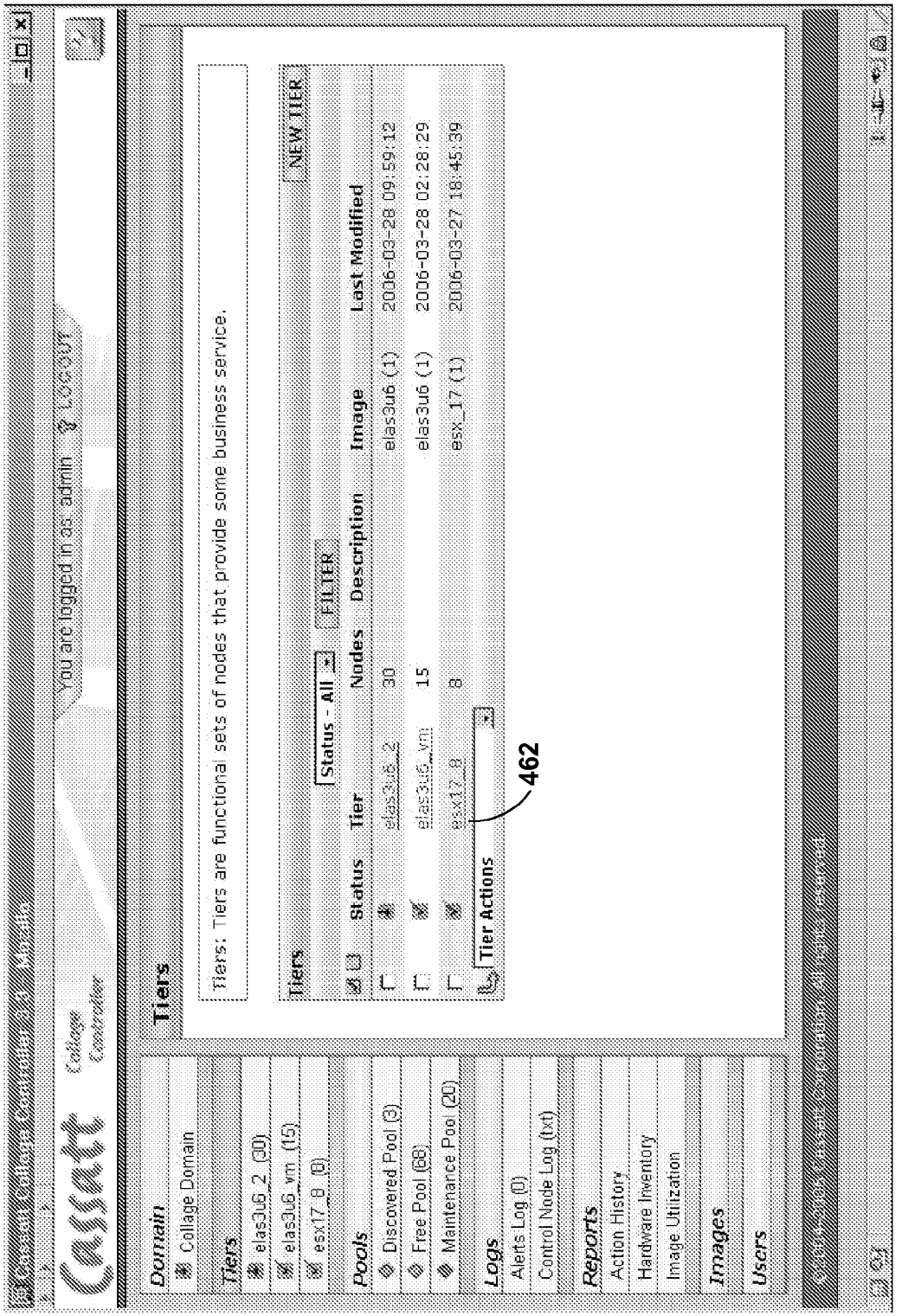
460
462
Tiers
Tiers: Tiers are functional sets of nodes that provide some business service.
NEW TIER
Status - All
FILTER
Tier Actions
Domain
Collage Domain
Tiers
Pools
Logs
Reports
Images
Users

FIG. 28

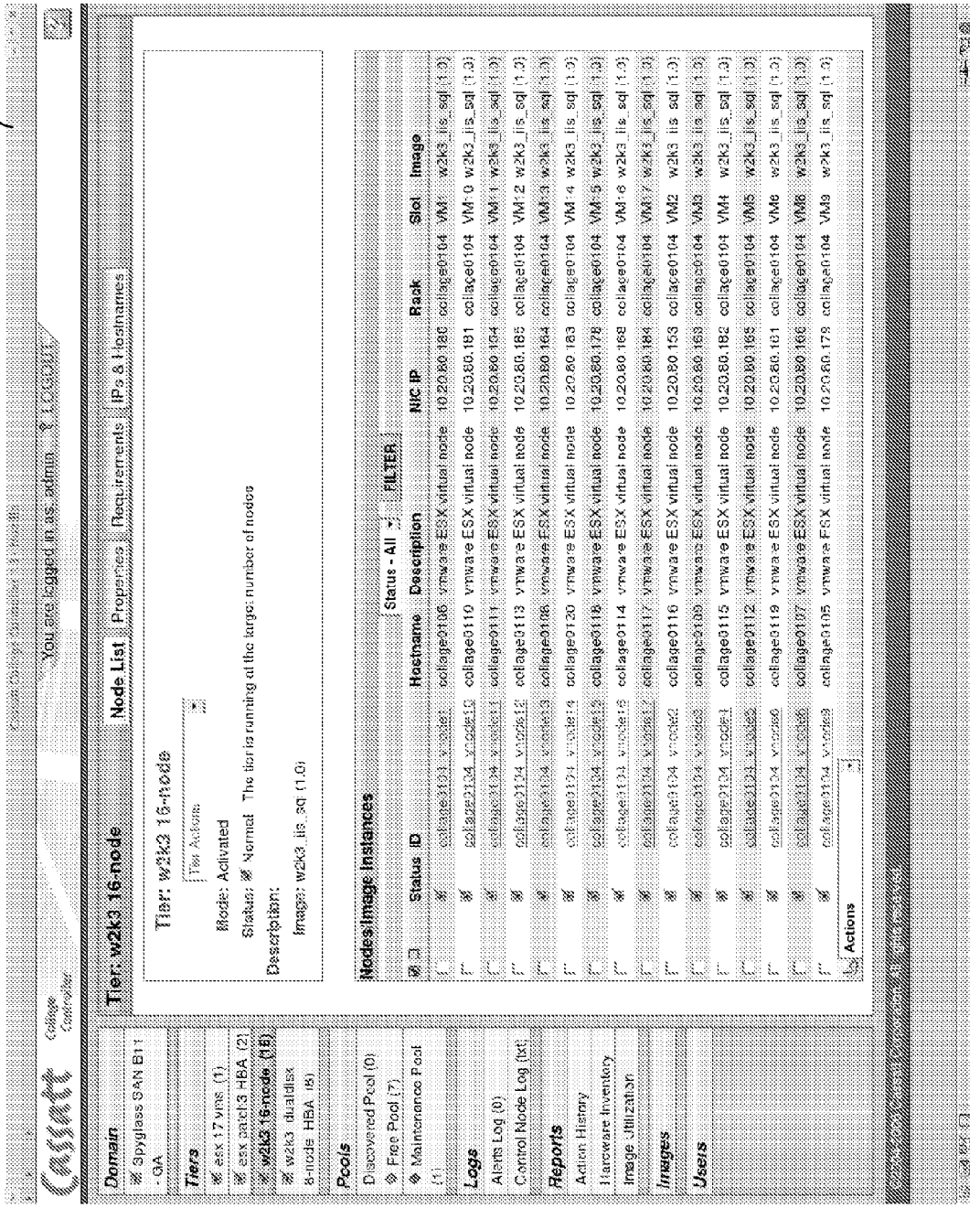
470
Cinarti
You are logged in as: admin
Domain
Spyglass SAN B11 - QA
Tiers
esx 17 vms (1)
esx patch3 HBA (2)
w2k3 16-node (16)
w2k3 dualdisk 8-node HBA (8)
Pools
Discovered Pool (0)
Free Pool (7)
Maintenance Pool (1)
Logs
Alerts Log (0)
Control Node Log (txt)
Reports
Action History
Hardware Inventory
Image Utilization
Images
Users
Tier: w2k3 16-node
Node List
Properties
Requirements
IPs & Hostnames
Tier: w2k3 16-node
Tier Actions
Mode: Activated
Status: Normal The tier is running at the target number of nodes
Description:
Image: w2k3_iis_sql (1.0)
Nodes/Image Instances
Status - All
FILTER
Status ID
Hostname
Description
NIC IP
Rack
Slot
Image
Actions

FIG. 29

DISTRIBUTED COMPUTING SYSTEM HAVING AUTONOMIC DEPLOYMENT OF VIRTUAL MACHINE DISK IMAGES

This application claims the benefit of U.S. provisional Application Ser. No. 60/787,280, filed Mar. 30, 2006, the entire content of which is incorporated herein by reference.

TECHNICAL FIELD

The invention relates to computing environments and, more specifically, to distributed computing systems.

BACKGROUND

Distributed computing systems are increasingly being utilized to support business as well as technical applications. Typically, distributed computing systems are constructed from a collection of computing nodes that combine to provide a set of processing services to implement the distributed computing applications. Each of the computing nodes in the distributed computing system is typically a separate, independent computing device interconnected with each of the other computing nodes via a communications medium, e.g., a network.

One challenge with distributed computing systems is the organization, deployment and administration of such a system within an enterprise environment. For example, it is often difficult to manage the allocation and deployment of enterprise computing functions within the distributed computing system. An enterprise, for example, often includes several business groups, and each group may have competing and variable computing requirements.

SUMMARY

In general, the invention is directed to a distributed computing system that conforms to a multi-level, hierarchical organizational model. One or more control nodes provide for the efficient and automated allocation and management of computing functions and resources within the distributed computing system in accordance with the organization model.

As described herein, the model includes four distinct levels: fabric, domains, tiers and nodes that provide for the logical abstraction and containment of the physical components as well as system and service application software of the enterprise. A user, such as a system administrator, interacts with the control nodes to logically define the hierarchical organization of the distributed computing system. The control nodes are responsible for all levels of management in accordance with the model, including fabric management, domain creation, tier creation and node allocation and deployment.

In one embodiment, a distributed computing system comprises a plurality of application nodes interconnected via a communications network and a control node. The control node comprises a set of one or more applications to be executed on the application nodes, an application matrix that includes parameters for controlling the deployment of the applications within the distributed computing system, and an automation unit having one or more rule engines that provide autonomic control of the application nodes and the applications in accordance with a set of one or more rules and the application matrix.

In another embodiment, a method comprises generating an application matrix that specifies data for controlling the deployment of a set of applications within a distributed computing system, and performing operations to provide autonomic control over the deployment of the applications within the distributed computing system in accordance with parameters of the application matrix.

In another embodiment, a computer-readable medium comprises instructions. The instructions cause the processor to generate an application matrix that specifies data for controlling the deployment of a set of applications within a distributed computing system, and perform operations to provide autonomic control over the deployment of the applications within the distributed computing system in accordance with parameters of the application matrix.

In another embodiment, a distributed computing system comprises a plurality of application nodes interconnected via a communications network. In addition, the distributed computing system includes a software image repository storing: (i) one or more image instances of a virtual machine manager that is executable on the application nodes, wherein when executed on the applications nodes, the image instances of the virtual machine manager provide one or more virtual machines, and (ii) one or more image instances of one or more software applications that are executable on the virtual machines. The distributed computing system also includes a control node that comprises an automation infrastructure to provide autonomic deployment of the image instances of the virtual machine manager on the application nodes and to provide autonomic deployment of the image instances of the software applications on the virtual machines.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a block diagram illustrating a distributed computing system constructed from a collection of computing nodes.

FIG. **2** is a schematic diagram illustrating an example of a model of an enterprise that logically defines an enterprise fabric.

FIG. **3** is a flow diagram that provides a high-level overview of the operation of a control node when configuring the distributed computing system.

FIG. **4** is a flow diagram illustrating exemplary operation of the control node when assigning computing nodes to node slots of tiers.

FIG. **5** is a flow diagram illustrating exemplary operation of a control node when adding an additional computing node to a tier to meet additional processing demands.

FIG. **6** is a flow diagram illustrating exemplary operation of a control node harvesting excess node capacity from one of the tiers and returning the harvested computing node to the free pool.

FIG. **7** is a screen illustration of an exemplary user interface for defining tiers in a particular domain.

FIG. **8** is a screen illustration of an exemplary user interface for defining properties of the tiers.

FIG. **9** is a screen illustration of an exemplary user interface for viewing and identify properties of a computing node.

FIG. **10** is a screen illustration of an exemplary user interface for viewing software images.

FIG. **11** is a screen illustration of an exemplary user interface for viewing a hardware inventory report.

FIG. **12** is a screen illustration of an exemplary user interface for viewing discovered nodes that are located in the free pool.

FIG. **13** is a screen illustration of an exemplary user interface for viewing users of a distributed computing system.

FIG. **14** is a screen illustration of an exemplary user interface for viewing alerts for the distributed computing system.

FIG. **15** is a block diagram illustrating one embodiment of control node that includes a monitoring subsystem, a service level automation infrastructure (SLAI), and a business logic tier (BLT).

FIG. **16** is a block diagram illustrating one embodiment of the monitoring subsystem.

FIG. **17** is a block diagram illustrating one embodiment of the SLAI in further detail.

FIG. **18** is a block diagram of an example working memory associated with rule engines of the SLAI.

FIG. **19** is a block diagram illustrating an example embodiment for the BLT of the control node.

FIG. **20** is a block diagram illustrating one embodiment of a rule engine in further detail.

FIG. **21** is a block diagram illustrating another example embodiment of the control node.

FIG. **22** is a flowchart illustrating an exemplary mode of initiating a control node utilizing an application matrix.

FIG. **23** is a block diagram illustrating an exemplary application matrix.

FIG. **24** is a block diagram illustrating an exemplary configuration of a physical node to which a virtual machine manager and one or more virtual machines are deployed.

FIG. **25** is a flowchart illustrating an exemplary procedure for creating and capturing an image of a virtual machine manager for autonomic deployment within the distributed computing system.

FIG. **26** is a flowchart illustrating an exemplary procedure for creating and capturing a virtual disk image file for autonomic deployment within the distributed computing system.

FIG. **27**A is a flowchart illustrating an exemplary procedure for deploying a virtual machine manager to a node within the distributed computing system.

FIG. **27**B is a flowchart illustrating an exemplary procedure for deploying an operating system and application image to a node that is executing a virtual machine manager within the distributed computing system.

FIG. **28** is a screen image illustrating an exemplary tier control interface for the embodiment described in FIGS. **24** through **27**.

FIG. **29** is a screen image illustrating an exemplary node control interface for the embodiment described in FIGS. **24** through **27**.

DETAILED DESCRIPTION

FIG. **1** is a block diagram illustrating a distributed computing system **10** constructed from a collection of computing nodes. Distributed computing system **10** may be viewed as a collection of computing nodes operating in cooperation with each other to provide distributed processing.

In the illustrated example, the collection of computing nodes forming distributed computing system **10** are logically grouped within a discovered pool **11**, a free pool **13**, an allocated tiers **15** and a maintenance pool **17**. In addition, distributed computing system **10** includes at least one control node **12**.

Within distributed computing system **10**, a computing node refers to the physical computing device. The number of computing nodes needed within distributed computing system **10** is dependent on the processing requirements. For example, distributed computing system **10** may include 8 to 512 computing nodes or more. Each computing node includes one or more programmable processors for executing software instructions stored on one or more computer-readable media.

Discovered pool **11** includes a set of discovered nodes that have been automatically "discovered" within distributed computing system **10** by control node **12**. For example, control node **12** may monitor dynamic host communication protocol (DHCP) leases to discover the connection of a node to network **18**. Once detected, control node **12** automatically inventories the attributes for the discovered node and reassigns the discovered node to free pool **13**. The node attributes identified during the inventory process may include a CPU count, a CPU speed, an amount of memory (e.g., RAM), local disk characteristics or other computing resources. Control node **12** may also receive input identifying node attributes not detectable via the automatic inventory, such as whether the node includes I/O, such as HBA. Further details with respect to the automated discovery and inventory processes are described in U.S. patent application Ser. No. 11/070,851, entitled "AUTOMATED DISCOVERY AND INVENTORY OF NODES WITHIN AN AUTONOMIC DISTRIBUTED COMPUTING SYSTEM," filed Mar. 2, 2005, the entire content of which is hereby incorporated by reference.

Free pool **13** includes a set of unallocated nodes that are available for use within distributed computing system **10**. Control node **12** may dynamically reallocate an unallocated node from free pool **13** to allocated tiers **15** as an application node **14**. For example, control node **12** may use unallocated nodes from free pool **13** to replace a failed application node **14** or to add an application node to allocated tiers **15** to increase processing capacity of distributed computing system **10**.

In general, allocated tiers **15** include one or more tiers of application nodes **14** that are currently providing a computing environment for execution of user software applications. In addition, although not illustrated separately, application nodes **14** may include one or more input/output (I/O) nodes. Application nodes **14** typically have more substantial I/O capabilities than control node **12**, and are typically configured with more computing resources (e.g., processors and memory). Maintenance pool **17** includes a set of nodes that either could not be inventoried or that failed and have been taken out of service from allocated tiers **15**.

Control node **12** provides the system support functions for managing distributed computing system **10**. More specifically, control node **12** manages the roles of each computing node within distributed computing system **10** and the execution of software applications within the distributed computing system. In general, distributed computing system **10** includes at least one control node **12**, but may utilize additional control nodes to assist with the management functions.

Other control nodes **12** (not shown in FIG. **1**) are optional and may be associated with a different subset of the computing nodes within distributed computing system **10**. Moreover, control node **12** may be replicated to provide primary and backup administration functions, thereby allowing for graceful handling a failover in the event control node **12** fails.

Network **18** provides a communications interconnect for control node **12** and application nodes **14**, as well as discovered nodes, unallocated nodes and failed nodes. Communications network **18** permits internode communications among the computing nodes as the nodes perform interrelated operations and functions. Communications network **18** may comprise, for example, direct connections between one or more of the computing nodes, one or more customer networks

maintained by an enterprise, local area networks (LANs), wide area networks (WANs) or a combination thereof. Communications network **18** may include a number of switches, routers, firewalls, load balancers, and the like.

In one embodiment, each of the computing nodes within distributed computing system **10** executes a common general-purpose operating system. One example of a general-purpose operating system is the Windows™ operating system provided by Microsoft Corporation. In some embodiments, the general-purpose operating system such as the Linux kernel may be used.

In the example of FIG. **1**, control node **12** is responsible for software image management. The term "software image" refers to a complete set of software loaded on an individual computing node to provide an execution environment for one or more applications. The software image including the operating system and all boot code, middleware files, and may include application files. As described below embodiments of the invention provide application-level autonomic control over the deployment, execution and monitoring of applications onto software images associated with application nodes **14**.

System administrator **20** may interact with control node **12** and identify the particular types of software images to be associated with application nodes **14**. Alternatively, administration software executing on control node **12** may automatically identify the appropriate software images to be deployed to application nodes **14** based on the input received from system administrator **20**. For example, control node **12** may determine the type of software image to load onto an application node **14** based on the functions assigned to the node by system administrator **20**. Application nodes **14** may be divided into a number of groups based on their assigned functionality. As one example, application nodes **14** may be divided into a first group to provide web server functions, a second group to provide business application functions and a third group to provide database functions. The application nodes **14** of each group may be associated with different software images.

Control node **12** provides for the efficient allocation and management of the various software images within distributed computing system **10**. In some embodiments, control node **12** generates a "golden image" for each type of software image that may be deployed on one or more of application nodes **14**. As described herein, the term "golden image" refers to a reference copy of a complete software stack for providing an execution environment for applications.

System administrator **20** may create a golden image by installing an operating system, middleware and software applications on a computing node and then making a complete copy of the installed software. In this manner, a golden image may be viewed as a "master copy" of the software image for a particular computing function. Control node **12** maintains a software image repository **26** that stores the golden images associated with distributed computing system **10**.

Control node **12** may create a copy of a golden image, referred to as an "image instance," for each possible image instance that may be deployed within distributed computing system **10** for a similar computing function. In other words, control node **12** pre-generates a set of K image instances for a golden image, where K represents the maximum number of image instances for which distributed computing system **10** is configured for the particular type of computing function. For a given computing function, control node **12** may create the complete set of image instance even if not all of the image instances will be initially deployed. Control node **12** creates different sets of image instances for different computing functions, and each set may have a different number of image instances depending on the maximum number of image instances that may be deployed for each set. Control node **12** stores the image instances within software image repository **26**. Each image instance represents a collection of bits that may be deployed on an application node.

Further details of software image management are described in co-pending U.S. patent application Ser. No. 11/046,133, entitled "MANAGEMENT OF SOFTWARE IMAGES FOR COMPUTING NODES OF A DISTRIBUTED COMPUTING SYSTEM," filed Jan. 28, 2005 and co-pending U.S. patent application Ser. No. 11/046,152, entitled "UPDATING SOFTWARE IMAGES ASSOCIATED WITH A DISTRIBUTED COMPUTING SYSTEM," filed Jan. 28, 2005, each of which is incorporated herein by reference in its entirety.

In general, distributed computing system **10** conforms to a multi-level, hierarchical organizational model that includes four distinct levels: fabric, domains, tiers and nodes. Control node **12** is responsible for all levels of management, including fabric management, domain creation, tier creation and node allocation and deployment.

As used herein, the "fabric" level generally refers to the logical constructs that allow for definition, deployment, partitioning and management of distinct enterprise applications. In other words, fabric refers to the integrated set of hardware, system software and application software that can be "knitted" together to form a complete enterprise system. In general, the fabric level consists of two elements: fabric components or fabric payload. Control node **12** provides fabric management and fabric services as described herein.

In contrast, a "domain" is a logical abstraction for containment and management within the fabric. The domain provides a logical unit of fabric allocation that enables the fabric to be partitioned amongst multiple uses, e.g. different business services.

Domains are comprised of tiers, such as a 4-tier application model (web server, application server, business logic, persistence layer) or a single tier monolithic application. Fabric domains contain the free pool of devices available for assignment to tiers.

A tier is a logically associated group of fabric components within a domain that share a set of attributes: usage, availability model or business service mission. Tiers are used to define structure within a domain e.g. N-tier application, and each tier represents a different computing function. A user, such as administrator **20**, typically defines the tier structure within a domain. The hierarchical architecture may provide a high degree of flexibility in mapping customer applications to logical models which run within the fabric environment. The tier is one construct in this modeling process and is the logical container of application resources.

The lowest level, the node level, includes the physical components of the fabric. This includes computing nodes that, as described above, provide operating environments for system applications and enterprise software applications. In addition, the node level may include network devices (e.g., Ethernet switches, load balancers and firewalls) used in creating the infrastructure of network **18**. The node level may further include network storage nodes that are network connected to the fabric.

System administrator **20** accesses administration software executing on control node **12** to logically define the hierarchical organization of distributed computing system **10**. For example, system administrator **20** may provide organizational data **21** to develop a model for the enterprise and

logically define the enterprise fabric. System administrator **20** may, for instance, develop a model for the enterprise that includes a number of domains, tiers, and node slots hierarchically arranged within a single enterprise fabric.

More specifically, system administrator **20** defines one or more domains that each correspond to a single enterprise application or service, such as a customer relation management (CRM) service. System administrator **20** further defines one or more tiers within each domain that represent the functional subcomponents of applications and services provided by the domain. As an example, system administrator **20** may define a storefront domain within the enterprise fabric that includes a web tier, an application tier and a database tier. In this manner, distributed computing system **10** may be configured to automatically provide web server functions, business application functions and database functions.

For each of the tiers, control node **12** creates a number of "node slots" equal to the maximum number of application nodes **14** that may be deployed. In general, each node slot represents a data set that describes specific information for a corresponding node, such as software resources for a physical node that is assigned to the node slot. The node slots may, for instance, identify a particular software image instance associated with an application node **14** as well as a network address associated with that particular image instance.

In this manner, each of the tiers include one or more node slots that reference particular software image instances to boot on the application nodes **14** to which each software image instance is assigned. The application nodes **14** to which control node **12** assigns the image instances temporarily inherit the network address assigned to the image instance for as long as the image instance is deployed on that particular application node. If for some reason the image instance is moved to a different application node **14**, control node **12**A moves the network address to that new application node.

System administrator **20** may further define specific node requirements for each tier of the fabric. For example, the node requirements specified by system administrator **20** may include a central processing unit (CPU) count, a CPU speed, an amount of memory (e.g., RAM), local disk characteristics and other hardware characteristics that may be detected on the individual computing nodes. System administrator **20** may also specify user-defined hardware attributes of the computing nodes, such as whether I/O (like HBA) is required. The user-defined hardware attributes are typically not capable of detection during an automatic inventory. In this manner, system administrator **20** creates a list of attributes that the tier requires of its candidate computing nodes. In addition, particular node requirements may be defined for software image instances.

In addition to the node requirements described above, system administrator **20** may further define policies that are used when re-provisioning computing nodes within the fabric. System administrator **20** may define policies regarding tier characteristics, such as a minimum number of nodes a tier requires, an indication of whether or not a failed node is dynamically replaced by a node from free pool **13**, a priority for each tier relative to other tiers, an indication of whether or not a tier allows nodes to be re-provisioned to other tiers to satisfy processing requirements by other tiers of a higher priority or other policies. Control node **12** uses the policy information input by system administrator **20** to re-provision computing nodes to meet tier processing capacity demands.

After receiving input from system administrator **20** defining the architecture and policy of the enterprise fabric, control node **12** identifies unallocated nodes within free pool **13** that satisfy required node attributes. Control node **12** automatically assigns unallocated nodes from free pool **13** to respective tier node slots of a tier. As will be described in detail herein, in one embodiment, control node **12** may assign computing nodes to the tiers in a "best fit" fashion. Particularly, control node **12** assigns computing nodes to the tier whose node attributes most closely match the node requirements of the tier as defined by administrator **20**. The assignment of the computing nodes may occur on a tier-by-tier basis beginning with a tier with the highest priority and ending with a tier with the lowest priority. Alternatively, or in addition, assignment of computing nodes may be based on dependencies defined between tiers.

As will be described in detail below, control node **12** may automatically add unallocated nodes from free pool **13** to a tier when more processing capacity is needed within the tier, remove nodes from a tier to the free pool when the tier has excess capacity, transfer nodes from tier to tier to meet processing demands, or replace failed nodes with nodes from the free pool. Thus, computing resources, i.e., computing nodes, may be automatically shared between tiers and domains within the fabric based on user-defined policies to dynamically address high-processing demands, failures and other events.

Distributed computing system **10** may provide one or more advantages. For example, distributed computing system **10** may deliver application services in a manner that is independent of the computational infrastructure which generates the application services. For example, the computation infrastructure that provides an application service to a user of distributed computing system **10** may be irrelevant to the user, so long as distributed computing system provides the application service. Distributed computing system **10** may deliver application services in a manner that is independent of the computational infrastructure by utilizing an infrastructure management facility (IMF) that may guarantee application service delivery using "service level automation."

This concept is itself based upon two concepts: The Service Delivery Model and Service Level Automation.

1. Service Delivery Model: The concept of computing as a service is based upon the ability of the consumer to be guaranteed availability of the quantity and quality of an application service required at the time and location necessary, independent of the type of service provided (e.g. audio, video, application programs, etc). This may be achieved if the application services are provided in a manner that is independent of the location and condition of the physical and logical infrastructure which generates the application service, limited only by total capability and capacity available. This disclosure may refer to this concept as the "Service Delivery Model."

Physical and logical infrastructure facilities that provide an application service may comprise a "computing infrastructure." A "computing infrastructure" may include computing, storage and communication hardware and related software infrastructure; the application software and application containers; and other enabling facilities and services that are part of the environment necessary to generate and deliver application services.

2. Service Level Automation: In order to implement the service delivery model, the IMF may provide service level automation. The IMF may implement the service delivery model for single and/or multiple application service flows. For example, the IMF may automatically and dynamically adjust application service levels of these application service flows based on a policy automation facility. The policy automation facility may automate delivery of application service based upon dynamically extensible policies. These dynami-

cally extensible policies may include but are not limited to: customer, location, priority, duration, date and time of day, service type, business demands and conditions, quantity and quality of the application service. The policy automation facility may also enable independent control of the application service by a service provider and by a consumer. Furthermore, the policy automation facility may allow the consumer provide the application service or a service based on the application service to another consumer. In addition, the IMF may measure both efficiency and cost as reflected in the behavior of the product. For example, the IMF may provide the ability to make decisions that account for the best uses of the resources on a dynamic basis in order to choose between functionally equivalent alternatives that make the best usage of the economics of the infrastructure at the time. This disclosure may refer to this concept as "Service Level Automation" (SLA).

Service-level automation may enable the separation of some or all aspects of the implementation of the computing infrastructure from the delivery of application services. Separating the implementation of the computing infrastructure from the delivery of application services may allow a consumer of the application services to decrease risk and cost while increasing business agility. Implementations of service-level automation may be based upon a new abstraction which operates independent of existing software categories (e.g. applications, middleware, data base, operating systems and system management) which for the purposes of this disclosure shall be referred to as "Metaware."

The IMF may comprise Metaware that regulates the delivery of application services through service-level automation. The IMF may use service-level automation to regulate the delivery of application services in a manner that is independent of the computing infrastructure that provides the application services. Because application services are the result of applications running within distributed computing system **10**, the IMF may automate application service levels and may make independent of all aspects of the computing infrastructure within the limits of the capability and capacity available for delivery to the consumer. Service-level automation may provide extensible, dynamic policy-driven control of service delivery for both service providers and service consumers. The IMF may include the following six functional design capabilities:

1. Application Service Independence: The basic concept which enables the IMF to deliver application services may be the ability of the IMF to dynamically manage service-level automation in a manner that is independent of the computing infrastructure. A key element of this is that application services themselves are independent and unmodified. The IMF may be able to accomplish this by abstracting the physical and logical computing infrastructure away from the quantity and quality of application services generated by the computing infrastructure.

2. Scale Independence: The incremental overhead of the IMF required by any server included in distributed computing system **10** may be independent of the number of nodes in distributed computing system **10**.

3. Container Capacity Metering: Distributed computing system **10** may achieve application service independence by dynamically metering higher-level software facilities of the computing infrastructure. The higher-level software facilities may generate the application services, service flow and flux. This disclosure may refer to these facilities as "container services." Examples of container services may include, but are not limited to, virtual machine managers, operating systems, and web application servers. Furthermore, some container services may contain other container services that the IMF manages. The system may conceptualize the application service as being independent of the type of computing infrastructure (e.g., middleware and hardware nodes) that generate these services.

4. Policy Automation: The IMF may deliver the required service-level automation through its extensible policy management facility. The policy management facility may dynamically adjust application service levels in order to implement user-defined policy. The ability to adjust application service levels may be limited only by the capacity and capability of the available computing infrastructure. The policy management facility may be capable of providing guaranteed service levels for single and/or multiple application service flows which the IMF automatically and dynamically adjust based on user-defined and extensible policies in response to changes in the environment. Examples of policies may include, but are not limited to: customer, location, service type, cost and/or pricing, quantity and quality of service, priority, duration, date and time of day, business demands and conditions, and other policies. The policy management facility may also allow the service provider to manage delivery and meter the capacity that the service provider delivers to individual customers. The policy management facility may allow the service provider to manage delivery and meter capacity independent of the ability of the customer to set and manage their own policies of how their capacity is utilized. This may be effectively done by leveraging application service independence.

5. Dynamic Provisioning: The IMF described herein may support the ability to dynamically provision at boot and run time all software in order to support installation, capacity management, service levels and other policies, and software upgrades. Offering a computing infrastructure architecture that is application service independent may create flexibility in deployment of a single instance of a service.

6. Data Capture Capability: The IMF described herein may acquire the data necessary to enable the service provider to implement metering and auditing facilities necessary to control, audit, bill and account for services provided in complete detail. The customer may also use the ability to capture this data as a means to educate the IMF about the performance characteristics of combinations of resources in order to allow the IMF to improve the quality of its scheduling decisions over time. Improvement of the quality of scheduling decisions may enhance the ability of the IMF to provide the requisite services with high efficiency.

The described system may allow customers to conveniently acquire the guaranteed quantity and quality of application services required at competitive market-driven rates with the ability to directly control the SLA capability of the IMF in order to maximize their operations efficiency and effectiveness without having to tradeoff operation risk, cost and business agility. Potential advantages may include, but are not limited to:

1. Efficiency and Effectiveness: The customer may not need to manage the technology, and can focus on the automation of the application service to improve their efficiency and effectiveness without having to tradeoff operation risk, cost and business agility which the IMF may enable through the service-level automation capability of the IMF.

2. Capabilities & Convenience: By leveraging the Internet as a generic, global delivery facility and separating the computing infrastructure from the application service delivery, the IMF may simplify the consumer's life in several ways:

i. Complexity: The IMF may eliminate the complexity of purchasing, installing, configuring, managing and administering the computing infrastructure.

ii. Access: The IMF may provide ubiquitous access to a full range of computing services wherever and whenever desired from any client device capable of accessing the Internet.

iii. Service Provider Independence: Consumers may be free to change providers by simply transferring their software images to a new service provider.

iv. Service Management: Service management may enable a consumer to provide services to customers of the consumer. For example, a corporation may be able to regulate and bill their individual business units for the capacity consumed.

3. Cost: By logically abstracting the application services from the computing infrastructure, the IMF may enable a competitive service provider industry that includes:

i. Capacity Utilization: A service provider using the IMF may be able to charge customers for capacity actually utilized by the customers. Presently, customers typically pay for the maximum capacity they would need at peak load.

ii. Choice of Suppliers: As the basic computing infrastructure facilities may be generic, the customer may have a choice of suppliers without the level of lock-in current vendors may enjoy. This may be enabled through the image and policy management implementation of the IMF. The image and policy management implementation of the IMF may allow portability across service providers through by enabling the customer to simply transfer the files to the new provider and initiating it with the IMF Metaware. The ability to easily migrate from a first service provider to a second service provider may drive the pricing competition. In this way, the ability of the IMF to provide application services independent of the computing infrastructure may enable customers to choose a service provider more effectively.

iii. Capital Expense Leverage: The customer may not need to own the capital equipment or software. Rather the service provider may be motivated to use the most cost effective components and amortize costs of these components across a customer base of the service provider. As a result, the cost to the consumer may be lower.

iv. Operations Expense Leverage: As the IMF automates most of the information technology operations functions, these costs may drop dramatically.

The IMF may enable the implementation of a service delivery model based on service-level automation by service providers:

1. A service provider may use the IMF to implement a service delivery model for application services independent of the computing infrastructure or of the service types provided. This capability may enable the service provider to deliver service-level automation on a global basis utilizing generic computing infrastructure for all types of digital services. Such digital service may include traditional applications and service flow processing, digital audio and digital video services independently to any consumer type (e.g. individual, organization or corporation) as long as the consumer has access to sufficient capacity of broadband communications for the services levels require, and other types of digital services. This capability of the IMF may also allow a consumer of an application service to, in turn, be a service provider as well.

2. The IMF described herein may enable a service provider to meter application services that distributed computing system **10** delivers. For example, the service provider may meter application services based on the capacity of computing infrastructure consumed by customer. The service provider may meter application services in order to control, audit, bill and account for the application services provided to individual consumers of the application services. This capability may represent a uniform model of service-level automation that is independent of the capacity of computing infrastructure for some or all types of application services. As a result, a pricing model of a service provider may reflect the goal of utility computing by enabling the service provider to bill based upon a combination of application service delivery parameters. These application service delivery parameters may include, but not limited to: customer, type of service, duration, date and/or time of day, location, point of delivery, quantity and quality of service and excess or reserved capacity, and other application service delivery parameters.

3. The IMF may also enable the service provider to leverage the economics of the service delivery model in several ways:

i. Utilization: By managing the computing infrastructure with the IMF, a service provider may be able to maintain much higher average utilization levels of the computing infrastructure. The maintenance of higher average utilization levels may dramatically reduce the amount of hardware purchased, software licensed and operations expenses.

ii. Global Service Demand Levels: Demand for an application service by an organization may vary by local time of day. By leveraging the global reach of the Internet, a service provider may be able to effectively manage the utilization of the computing infrastructure necessary to meet demand for the application service on a global "follow the sun" basis.

iii. Service Digitization: As more services become digital, service providers may deliver these services using a generic computing infrastructure architecture.

iv. Value-Added Services: A service provider may be free to provide value-added services beyond basic application services. A few examples of value-added services may include: a bundle of personal computer services that includes applications, storage, security, administration and related services; software as a service; compliance verification and certification, and other types of value-added services.

v. Hardware Commoditization: Hardware commoditization may enable a service provider to implement a computing infrastructure using generic low cost servers, storage facilities, and network switches. These hardware elements are undergoing dramatic commoditization which may allows for much lower capital expenses then in the past. This commoditization may continue for many years to come making capital expenses a much smaller part of the fixed costs for the service provider.

vi. Automation of Operations: One of the primary economic values of the IMF is that IMF may automate most of the runtime operations costs of the computing infrastructure. Operations expenses may constitute the majority of the costs of today. Because the IMF automates the runtime operations, the IMF may reduce runtime operations costs. Thus by leveraging the ability of the IMF to dramatically reduce the capital and operations expenses, the service provider may be able to implement an service delivery model that may justify the consumers switching cost.

vii. Software Commoditization: Software pricing is being commoditized based upon several factors which may continue to accelerate. These factors may include:

1. Service-Oriented Architecture: Software systems that utilize a service-oriented architecture may accelerate innovation, allow for incremental independent innovation, eliminate down stream lock in by software vendors, and may make it possible to use commodity servers to run applications that previously required large expensive servers. Service-oriented architecture may also reduce complex applications to their most fundamental independently divisible functional services which will be the basis for the complete commoditization of software further leveraging the open source movement.
2. Open Source Software: The open source software paradigm may serve as an accelerator for the commoditization of many types of software by both compromising the pricing power of software and serving as a reusable model of software services which may further compromise the value of horizontal software services.
3. Good Enough: Application services are becoming more and more generic, thus accelerating their commoditization further in combination with service-oriented architectures and Open Source.

FIG. **2** is a schematic diagram illustrating an example embodiment of organizational data **21** that defines a model logically representing an enterprise fabric in accordance with the invention. In the example illustrated in FIG. **2**, control node **12** (FIG. **1**) maintains organizational data **21** to define a simple e-commerce fabric **32**.

In this example, e-commerce fabric **32** includes a storefront domain **34**A and a financial planning domain **34**B. Storefront domain **34**A corresponds to the enterprise storefront domain and allows customers to find and purchase products over a network, such as the Internet. Financial planning domain **34**B allows one or more employees to perform financial planning tasks for the enterprise.

Tier level **31**C includes one or more tiers within each domain that represent the functional subcomponents of applications and services provided by the domain. For example, storefront domain **34**A includes a web server tier (labeled "web tier") **36**A, a business application tier (labeled "app tier") **36**B, and a database tier (labeled "DB tier") **36**C. Web server tier **36**A, business application tier **36**B and database tier **36**C interact with one another to present a customer with an online storefront application and services. For example, the customer may interact with web server tier **36**A via a web browser. When the customer searches for a product, web server tier **36**A may interacts with business application tier **36**B, which may in turn access a database tier **36**C. Similarly, financial planning domain **34**B includes a financial planning tier **36**D that provides subcomponents of applications and services of the financial planning domain **34**B. Thus, in this example, a domain may include a single tier.

Tier level **31**D includes one or more logical node slots **38**A-**38**H ("node slots **38**") within each of the tiers. Each of node slots **38** include node specific information, such as software resources for an application node **14** that is assigned to a respective one of the node slots **38**. Node slots **38** may, for instance, identify particular software image instances within image repository **26** and map the identified software image instances to respective application nodes **14**. As an example, node slots **38**A and **38**B belonging to web server tier **36**A may reference particular software image instances used to boot two application nodes **14** to provide web server functions. Similarly, the other node slots **38** may reference software image instances to provide business application functions, database functions, or financial application functions depending upon the tier to which the node slots are logically associated.

Although in the example of FIG. **2**, there are two node slots **38** corresponding to each tier, the tiers may include any number of node slots depending on the processing capacity needed on the tier. Furthermore, not all of node slots **38** may be currently assigned to an application node **14**. For example, node slot **28**B may be associated with an inactive software image instance and, when needed, may be assigned to an application node **14** for deployment of the software image instance.

In this example, organizational data **21** associates free node pool **13** with the highest-level of the model, i.e., e-commerce fabric **32**. As described above, control node **12** may automatically assign unallocated nodes from free node pool **13** to at least a portion of tier node slots **38** of tiers **36** as needed using the "best fit" algorithm described above or another algorithm. Additionally, control node **12** may also add nodes from free pool **13** to a tier when more processing capacity is needed within the tier, remove nodes from a tier to free pool **13** when a tier has excess capacity, transfer nodes from tier to tier to meet processing demands, and replace failed nodes with nodes from the free tier.

Although not illustrated, the model for the enterprise fabric may include multiple free node pools. For example, the model may associate free node pools with individual domains at the domain level or with individual tier levels. In this manner, administrator **20** may define policies for the model such that unallocated computing nodes of free node pools associated with domains or tiers may only be used within the domain or tier to which they are assigned. In this manner, a portion of the computing nodes may be shared between domains of the entire fabric while other computing nodes may be restricted to particular domains or tiers.

FIG. **3** is a flow diagram that provides a high-level overview of the operation of control node **12** when configuring distributed computing system **10**. Initially, control node **12** receives input from a system administrator defining the hierarchical organization of distributed computing system **10** (**50**). In one example, control node **12** receives input that defines a model that specifies a number of hierarchically arranged nodes as described in detail in FIG. **2**. Particularly, the defined architecture of distributed computing system **10** includes an overall fabric having a number of hierarchically arranged domains, tiers and node slots.

During this process, control node **12** may receive input specifying node requirements of each of the tiers of the hierarchical model (**52**). As described above, administrator **20** may specify a list of attributes, e.g., a central processing unit (CPU) count, a CPU speed, an amount of memory (e.g., RAM), or local disk characteristics, that the tiers require of their candidate computing nodes. In addition, control node **12** may further receive user-defined custom attributes, such as requiring the node to have I/O, such as HBA connectivity. The node requirements or attributes defined by system administrator **20** may each include a name used to identify the characteristic, a data type (e.g., integer, long, float or string), and a weight to define the importance of the requirement.

Control node **12** identifies the attributes for all candidate computing nodes within free pool **13** or a lower priority tier (**54**). As described above, control node **12** may have already discovered the computing nodes and inventoried the candidate computing nodes to identify hardware characteristics of all candidate computing nodes. Additionally, control node **12**

may receive input from system administrator **20** identifying specialized capabilities of one or more computing nodes that are not detectable by the inventory process.

Control node **12** dynamically assigns computing nodes to the node slots of each tier based on the node requirements specified for the tiers and the identified node attributes (**56**). Population of the node slots of the tier may be performed on a tier-by-tier basis beginning with the tier with the highest priority, i.e., the tier with the highest weight assigned to it. As will be described in detail, in one embodiment, control node **12** may populate the node slots of the tiers with the computing nodes that have attributes that most closely match the node requirements of the particular tiers. Thus, the computing nodes may be assigned using a "best fit" algorithm.

FIG. **4** is a flow diagram illustrating exemplary operation of control node **12** when assigning computing nodes to node slots of tiers. Initially, control node **12** selects a tier to enable (**60**). As described above, control node **12** may select the tier based on a weight or priority assigned to the tier by administrator **20**. Control node **12** may, for example, initially select the tier with the highest priority and successively enable the tiers based on priority.

Next, control node **12** retrieves the node requirements associated with the selected tier (**62**). Control node **12** may, for example, maintain a database having entries for each node slot, where the entries identify the node requirements for each of the tiers. Control node **12** retrieves the node requirements for the selected tier from the database.

In addition, control node **12** accesses the database and retrieves the computing node attributes of one of the unallocated computing nodes of free pool **13**. Control node **12** compares the node requirements of the tier to the node attributes of the selected computing node (**64**).

Based on the comparison, control node **12** determines whether the node attributes of the computing node meets the minimum node requirements of the tier (**66**). If the node attributes of the selected computing node do not meet the minimum node requirements of the tier, then the computing node is removed from the list of candidate nodes for this particular tier (**68**). Control node **12** repeats the process by retrieving the node attributes of another of the computing nodes of the free pool and compares the node requirements of the tier to the node attributes of the computing node.

If the node attributes of the selected computing node meet the minimum node requirements of the tier (YES of **66**), control node **12** determines whether the node attributes are an exact match to the node requirements of the tier (**70**). If the node attributes of the selected computing node and the node requirements of the tier are a perfect match (YES of **70**), the computing node is immediately assigned from the free pool to a node slot of the tier and the image instance for the slot is associated with the computing node for deployment (**72**).

Control node **12** then determines whether the node count for the tier is met (**74**). Control node **12** may, for example, determine whether the tier is assigned the minimum number of nodes necessary to provide adequate processing capabilities. In another example, control node **12** may determine whether the tier is assigned the ideal number of nodes defined by system administrator **20**. When the node count for the tier is met, control node **12** selects the next tier to enable, e.g., the tier with the next largest priority, and repeats the process until all defined tiers are enabled, i.e., populated with application nodes (**60**).

If the node attributes of the selected computing node and the node requirements of the tier are not a perfect match control node **12** calculates and records a "processing energy" of the node (**76**). As used herein, the term "processing energy" refers to a numerical representation of the difference between the node attributes of a selected node and the node requirements of the tier. A positive processing energy indicates the node attributes more than satisfy the node requirements of the tier. The magnitude of the processing energy represents the degree to which the node requirements exceed the tier requirements.

After computing and recording the processing energy of the nodes, control node **12** determines whether there are more candidate nodes in free pool **13** (**78**). If there are additional candidate nodes, control node **12** repeats the process by retrieving the computing node attributes of another one of the computing nodes of the free pool of computing nodes and comparing the node requirements of the tier to the node attributes of the computing node (**64**).

When all of the candidate computing nodes in the free pool have been examined, control node **12** selects the candidate computing node having the minimum positive processing energy and assigns the selected computing node to a node slot of the tier (**80**). Control node **12** determines whether the minimum node count for the tier is met (**82**). If the minimum node count for the tier has not been met, control node **12** assigns the computing node with the next lowest calculated processing energy to the tier (**80**). Control node **12** repeats this process until the node count is met. At this point, control node **12** selects the next tier to enable, e.g., the tier with the next largest priority (**60**).

In the event there are an insufficient number of computing nodes in free pool **13**, or an insufficient number of computing nodes that meet the tier requirements, control node **12** notifies system administrator **20**. System administrator **20** may add more nodes to free pool **13**, add more capable nodes to the free pool, reduce the node requirements of the tier so more of the unallocated nodes meet the requirements, or reduce the configured minimum node counts for the tiers.

FIG. **5** is a flow diagram illustrating exemplary operation of control node **12** when adding an additional computing node to a tier to meet increased processing demands. Initially, control node **12** or system administrator **20** identifies a need for additional processing capacity on one of the tiers (**90**). Control node **12** may, for example, identify a high processing load on the tier or receive input from a system administrator identifying the need for additional processing capacity on the tier.

Control node **12** then determines whether there are any computing nodes in the free pool of nodes that meet the minimum node requirements of the tier (**92**). When there are one or more nodes that meet the minimum node requirements of the tier, control node **12** selects the node from the free pool based the node requirements of the tier, as described above, (**94**) and assigns the node to the tier (**95**). As described in detail with respect to FIG. **4**, control node **12** may determine whether there are any nodes that have node attributes that are an exact match to the node requirements of the tier. If an exact match is found, the corresponding computing node is assigned to a node slot of the tier. If no exact match is found, control node **12** computes the processing energy for each node and assigns the computing node with the minimum processing energy to the tier. Control node **12** remotely powers on the assigned node and remotely boots the node with the image instance associated with the node slot. Additionally, the booted computing node inherits the network address associated with the node slot.

If there are no adequate computing nodes in the free pool, i.e., no nodes at all or no nodes that match the minimal node requirements of the tier, control node **12** identifies the tiers with a lower priority than the tier needing more processing capacity (**96**).

Control node **12** determines which of the nodes of the lower priority tiers meet the minimum requirements of the tier in need of processing capacity (**98**). Control node **12** may, for example, compare the attributes of each of the nodes assigned to node slots of the lower priority tiers to the node requirements of the tier in need of processing capacity. Lower priority tiers that have the minimum number of computing nodes may be removed from possible tiers from which to harvest an application node. If, however, all the lower priority tiers have the minimum number of computing nodes defined for the respective tier, the lowest priority tier is selected from which to harvest the one or more nodes.

Control node **12** calculates the processing energy of each of the nodes of the lower priority tiers that meet the minimum requirements (**100**). The energies of the nodes are calculated using the differences between the node attributes and the node requirements of the tier needing additional capacity. Control node **12** selects the computing node with the lowest processing energy that meets the minimum requirements, and assigns the selected computing node to the tier in need of processing capacity (**102**, **95**).

FIG. **6** is a flow diagram illustrating exemplary operation of control node **12** when harvesting excess node capacity from one of the tiers and returning the harvested computing node to free pool **13**. Initially, control node **12** identifies a tier having excess node capacity (**110**). Control node **12** may, for example, periodically check the node capacity of the tiers to identify any tiers having excess node capacity. Performing a periodic check and removal of excess nodes increases the likelihood that a capable computing node will be in free pool **13** in the event one of the tiers needs additional node capacity.

When harvesting a node, control node **12** calculates the processing energy of all the nodes in the tier as described above with reference to FIG. **4** (**112**). Control node **12** identifies the node within the tier with the highest processing energy and returns the identified node to the free pool of nodes (**114**, **116**). As described above, the node with the highest processing energy corresponds to the node whose node attributes are the most in excess of the node requirements of the tier.

Returning the node to the free pool may involve remotely powering off the computing node and updating the database to associate the harvested node with free pool **13**. In addition, control node **12** updates the database to disassociate the returned node with the node slot to which it was assigned. At this point, the node no longer uses the network address associated with the image instance mapped to the node slot. Control node **12** may, therefore, assign a temporary network address to the node while the node is assigned to free pool **13**.

FIG. **7** is a screen illustration of an exemplary user interface **120** presented by control node **12** with which administrator **20** interacts to define tiers for a particular domain. In the example illustrated in FIG. **7**, system administrator **20** has selected the "Collage Domain." User interface **120** presents the tiers that are currently in the selected domain. In the example illustrated, the Collage Domain includes three tiers, "test tier **1**," "test tier **2**," and "test tier **3**." As shown in FIG. **7**, in this example, each of the tiers includes two nodes. In addition, user interface **120** lists the type of software image currently deployed to application nodes for each of the tiers. In the example illustrated, image "applone (1.0.0)" is deployed to the nodes of test tier **1** and image "appltwo (1.0.0)" is deployed to the nodes of test tier **2**. System administrator **20** may add one or more tiers to the domain by clicking on new tier button **122**.

FIG. **8** is a screen illustration of an exemplary user interface **130** for defining properties of the tiers. In particular, user interface **130** allows system administrator **20** to input a name for the tier, a description of the tier, and an image associated with the tier. The image associated with the tier refers to a golden image from which image instances are generated and deployed to the nodes assigned to the tier.

When configuring a tier, system administrator **20** may elect to activate email alerts. For example, system administrator **20** may activate the email alerts feature in order to receive email alerts providing system administrator **20** with critical and/or non-critical tier information, such as a notification that a tier has been upgraded, a node of the tier has failed or the like. Furthermore, system administrator **20** may input various policies, such node failure rules. For example, system administrator **20** may identify whether control node **12** should reboot a node in case of failure or whether the failed node should automatically be moved to maintenance pool **17**. Similarly, system administrator **20** may identify whether nodes assigned to the tier may be harvested by other tiers.

User interface **130** may also allow system administrator **20** to input node requirements of a tier. In order to input node requirements of a tier, system administrator **20** may click on the "Requirements" tab **132**, causing user interface **130** to present an input area to particular node requirements of the tier.

FIG. **9** is a screen illustration of an exemplary user interface **140** for viewing and identifying properties of a computing node. User interface **140** allows system administrator **20** to define a name, description, and location (including a rack and slot) of a computing node. In addition user interface **140** may specify user-defined properties of a node, such as whether the computing node has I/O HBA capabilities.

User interface **140** also displays properties that control node **12** has identified during the computing node inventory process. In this example, user interface **140** presents system administrator **20** with the a CPU node count, a CPU speed, the amount of RAM, the disk size and other characteristics that are identifiable during the automated node inventory. User interface **140** additionally presents interface information to system administrator **20**. Specifically, user interface **140** provides system administrator **20** with a list of components and their associated IP and MAC addresses.

User interface **140** also allows system administrator **20** to define other custom requirements. For example, system administrator **20** may define one or more attributes and add those attributes to the list of node attributes presented to system administrator **20**.

FIG. **10** is a screen illustration of an exemplary user interface **150** for viewing software images. User interface **150** presents to a system administrator or another user a list of images maintained by control node **12** within image repository **26**. The image list further includes the status of each image (i.e., either active or inactive), the version of the image, the operating system on which the image should be run, the operating system version on which the image should be run and a brief description of the image.

System administrator **20** or another user may select an image by clicking on the box in front of the image identifier/name and perform one or more actions on the image. Actions that system administrator **20** may perform on an image include deleting the image, updating the image, and the like. System administrator **20** may select one of the image actions via dropdown menu **152**. In some embodiments, user interface **150** may further display other details about the images such as the node to which the images are assigned (if the node status is "active"), the network address associated with the images and the like.

FIG. **11** is a screen illustration of an exemplary user interface **160** for viewing a hardware inventory report. User interface **160** presents to system administrator **20** or another user a list of the nodes that are currently assigned to a domain. System administrator **20** may elect to view the nodes for the entire domain, for a single tier within the domain or for a single rack within a tier.

For each node, user interface **160** presents a node ID, a status of the node, the tier to which the node belongs, a hostname associated with the node, a NIC IP address, a rack location, a slot location, the number of CPU's of the node, the amount of RAM on the node, the number of disks on the node, whether the node has I/O HBA, and the number of NICs of the node.

System administrator **20** or other user may select a node by clicking on the box in front of the node identifier/name and perform one or more actions on the node. Actions that system administrator **20** may perform on the node include deleting the node, updating the node attributes or other properties of the node, and the like. System administrator **20** may select one of the node actions via dropdown menu **162**.

FIG. **12** is a screen illustration of an exemplary user interface **170** for viewing discovered nodes that are located in discovered pool **11**. For each node, user interface **170** presents a node ID, a state of the node, a NIC IP address, a rack location, a slot location, the number of CPU's of the node, the amount of RAM on the node, the number of disks on the node, whether the node has I/O HBA, and the number of NICs of the node.

FIG. **13** is a screen illustration of an exemplary user interface **180** for viewing users of distributed computing system **10**. User interface **180** presents a list of users as well as the role assigned to each of the users and the status of each of the users. Thus, system administrator **20** may define different roles to each of the users. For example, a user may be either an operator (i.e., general user) or an administrator. System administrator **20** may add a new user to the list of users by clicking on the "New User" button **182**.

FIG. **14** is a screen illustration of an exemplary user interface **190** for viewing alerts for distributed computing system **10**. For each of the alerts, user interface **190** identifies the severity of the alert, whether the alert has been acknowledged, an object associated with the alert, an event associated with the alert, a state of the alert, a user associated with the alert and a date associated with the alert.

System administrator **20** or other user may select an alert by clicking on the box in front of the logged alert and perform one or more actions on the logged alert. Actions that system administrator **20** may perform include deleting the alert, changing the status of the alert, or the like. System administrator **20** may specify the log actions via dropdown menu **192**.

FIG. **15** is a block diagram illustrating one embodiment of control node **12** in further detail. In the illustrated example, control node **12** includes a monitoring subsystem **202**, a service level automation infrastructure (SLAI) **204**, and a business logic tier (BLT) **206**.

Monitoring subsystem **202** provides real-time monitoring of the distributed computing system **10**. In particular, monitoring subsystem **202** dynamically collects status data **203** from the hardware and software operating within distributed computing system **10**, and feeds the status data in the form of monitor inputs **208** to SLAI **204**. Monitoring inputs **208** may be viewed as representing the actual state of the fabric defined for the organizational model implemented by distributed computing system **10**. Monitoring subsystem **202** may utilize well defined interfaces, e.g., the Simple Network Management Protocol (SNMP) and the Java Management Extensions (JMX), to collect and export real-time monitoring information to SLAI **204**.

SLAI **204** may be viewed as an automation subsystem that provides support for autonomic computing and acts as a central nervous system for the controlled fabric. In general, SLAI **204** receives monitoring inputs **208** from monitoring subsystem **202**, analyzes the inputs and outputs appropriate action requests **212** to BLT **206**. In one embodiment, SLAI **204** is a cybernetic system that controls the defined fabric via feedback loops. More specifically, administrator **20** may interact with BLT **206** to define an expected state **210** for the fabric. BLT **206** communicates expected state **210** to SLAI **204**. SLAI **204** receives the monitoring inputs from monitoring subsystem **202** and applies rules to determine the most effective way of reducing the differences between the expected and actual states for the fabric.

For example, SLAI **204** may apply a rule to determine that a node within a high priority tier has failed and that the node should be replaced by harvesting a node from a lower priority tier. In this example, SLAI **204** outputs an action request **212** to invoke BLT **206** to move a node from one tier to the other.

In general, BLT **206** implements high-level business operations on fabrics, domains and tiers. SLAI **204** invokes BLT **206** to bring the actual state of the fabric into accordance with the expected state. In particular, BLT **206** outputs fabric actions **207** to perform the physical fabric changes. In addition, BLT **206** outputs an initial expected state **210** to SLAI **204** and initial monitoring information **214** to SLAI **204** and monitoring subsystem **202**, respectively. In addition, BLT **206** outputs notifications **211** to SLAI **204** and monitoring subsystem **202** to indicate the state and monitoring changes to distributed computing system **10**. As one example, BLT **206** may provide control operations that can be used to replace failed nodes. For example, BLT **206** may output an action request indicating that a node having address 10.10.10.10 has been removed from tier ABC and a node having address 10.10.10.11 has been added to tier XYZ. In response, monitoring subsystem **202** stops attempting to collect status data **203** from node 10.10.10.10 and starts monitoring for status data from node 10.10.10.11. In addition, SLAI **204** updates an internal model to automatically associate monitoring inputs from node 10.10.10.11 with tier XYZ.

FIG. **16** is a block diagram illustrating one embodiment of monitoring subsystem **202**. In general, monitoring subsystem **202** dynamically detects and monitors a variety of hardware and software components within the fabric. For example, monitoring subsystem **202** identifies, in a timely and efficient manner, any computing nodes that have failed, i.e., any node that does not respond to a request to a known service. More generally, monitoring subsystem **202** provides a concise, consistent and constantly updating view of the components of the fabric.

As described further below, monitoring subsystem **202** employs a modular architecture that allows new detection and monitoring collectors **224** to be "plugged-in" for existing and new protocols and for existing and new hardware and software. As illustrated in FIG. **16**, monitoring subsystem **202** provides a plug-in architecture that allows different information collectors **224** to be installed. In general, collectors **224** are responsible for protocol-specific collection of monitoring information. The plug-in architecture allows for new protocols to be added by simply adhering to a collector plug-in signature. In this example, monitoring subsystem **202** includes collectors **224**A and **224**B for collecting information from operating systems and applications executing on nodes within tier A and tier B, respectively.

In one embodiment, collectors **224** are loaded at startup of control node **12** and are configured with information retrieved from BLT **206**. Monitoring engine **222** receives collection requests from SLAI **204**, sorts and prioritizes the requests, and invokes the appropriate one of collectors **224** based on the protocol specified in the collection requests. The invoked collector is responsible for collecting the required status data and returning the status data to monitoring engine **222**. If the collector is unable to collect the requested status data, the collector returns an error code.

In one embodiment, collectors **224** are Java code compiled into a jar file and loaded with a class loader at run time. Each of collectors **224** has an associated configuration file written in a data description language, such as the extensible markup language (XML). In addition, a user may interact with BLT **206** to add run-time configuration to dynamically configure collectors **224** for specific computing environments. Each of collectors **224** expose an application programming interface (API) to monitoring engine **222** for communication and data exchange.

A user, such as a system administrator, specifies the protocol or protocols to be used for monitoring a software image when the image is created. In addition, the users may specify the protocols to be used for monitoring the nodes and each service executing on the nodes. Example protocols supported by the collectors **224** include Secure Shell (SSH), Simple Network Management Protocol (SNMP), Internet Control Message Protocol (ICMP) ping, Java Management Extensions (JMX) and the Hypertext Transfer Protocol (HTTP).

Some protocols require special privileges, e.g., root privileges, to perform the required data collection. In this case, the corresponding collectors **224** communicate with a separate process that executes as the root. Moreover, some protocols may require deployment and/or configuration of data providers within the fabric. Software agents may, for example, be installed and configured on nodes and configured on other hardware. If needed, custom in-fabric components may be deployed.

In this example, the modular architecture of monitoring subsystem **202** also supports one or more plug-in interfaces **220** for data collection from a wide range of third-party monitoring systems **228**. Third-party monitoring systems **228** monitor portions of the fabric and may be vendor-specific.

FIG. **17** is a block diagram illustrating one embodiment of SLAI **204** in further detail. In the illustrated embodiment, SLAI **204** is composed of three subsystems: a sensor subsystem **240**, an analysis subsystem **244** and an effector subsystem **248**.

In general, sensor subsystem **240** receives actual state data from monitoring subsystem **202** in the form of monitoring inputs **208** and supplies ongoing, dynamic input data to analysis subsystem **244**. For example, sensor subsystem **240** is notified of physical changes to distributed computing system **10** by monitoring subsystem **202**. Sensor subsystem **240** uses the state data received from monitoring subsystem **202** to maintain ongoing, calculated values that can be sent to analysis subsystem **244** in accordance with scheduler **242**.

In one embodiment, sensor subsystem **240** performs time-based hierarchical data aggregation of the actual state data in accordance with the defined organization model. Sensor subsystem **240** maintains organizational data in a tree-like structure that reflects the current configuration of the hierarchical organization model. Sensor subsystem **240** uses the organizational data to perform the real-time data aggregation and map tiers and domains to specific nodes. Sensor subsystem **240** maintains the organizational data based on notifications **211** received from BLT **206**.

Sensor subsystem **240** sends inputs to analysis subsystem **244** to communicate the aggregated data on a periodic or event-driven basis. Analysis subsystem **244** may register an interest in a particular aggregated data value with sensor subsystem **240** and request updates at a specified frequency. In response, sensor subsystem **240** interacts with monitoring subsystem **202** and scheduler **242** to generate the aggregated data required by analysis subsystem **244**.

Sensor subsystem **240** performs arbitrary data aggregations via instances of plug-in classes (referred to as "triggers") that define the aggregations. Each trigger is registered under a compound name based on the entity being monitored and the type of data being gathered. For example, a trigger may be defined to aggregate and compute an average computing load for a tier every five minutes. Analysis subsystem **244** requests the aggregated data based on the registered names. In some embodiments, analysis subsystem **244** may define calculations directly and pass them to sensor subsystem **240** dynamically.

Analysis subsystem **244** is composed of a plurality of forward chaining rule engines **246**A-**246**N. In general, rule engines **246** match patterns in a combination of configuration data and monitoring data, which is presented by extraction agent **251** in the form of events. Events contain the aggregated data values that are sent to rule engines **246** in accordance with scheduler **242**.

Sensor subsystem **240** may interact with analysis subsystem **244** via trigger listeners **247** that receives updates from a trigger within sensor subsystem **240** when specified events occur. An event may be based on system state (e.g., a node transitioning to an up or down state) or may be time based.

Analysis subsystem **244** allows rule sets to be loaded in source form and compiled at load time into discrimination networks. Each rule set specifies trigger-delivered attributes. Upon loading the rule sets, analysis subsystem **244** establishes trigger listeners **247** to receive sensor notifications and update respective working memories of rule engines **246**. As illustrated in FIG. **17**, each of rule engines **246** may serve a different tier defined within the fabric. Alternatively, multiple rule engines **246** may serve a single tier or a single rule engine may serve multiple tiers.

Rule engines **246** process the events and invoke action requests via calls to effector subsystem **248**. In addition, rule engines **246** provide a call-back interface so that effector subsystem **248** can inform a rule engine when an action has completed. Rule engines **246** prevent a particular rule from re-firing as long as any action invoked by the rule has not finished. In general, rules contain notification calls and service invocations though either may be disabled by configuration of effector subsystem **248**. BLT **206** supplies initial system configuration descriptions to seed each of rule engines **246**.

In general, rule engines **246** analyze the events and discover discrepancies between an expected state of the fabric and an actual state. Each of rule engines **246** may be viewed as software that performs logical reasoning using knowledge encoded in high-level condition-action rules. Each of rule engines **246** applies automated reasoning that works forward from preconditions to goals defined by system administrator **20**. For example, rule engines **246** may apply modus ponens inferences rules.

Rule engines **246** output requests to effector subsystem **248** which produce actions requests **212** for BLT **206** to resolve the discrepancies. Effector subsystem **248** performs all operations on behalf of analysis subsystem **244**. For example, event generator **250**, task invocation module **252**

and logger **254** of effector subsystem **248** perform event generation, BLT action invocation and rule logging, respectively. More specifically, task invocation module **252** invokes asynchronous operations within BLT **206**. In response, BLT **206** creates a new thread of control for each task which is tracked by a unique task identifier (task id). Rules engine **246** uses the task id to determine when a task completes and, if needed, to re-fire any rules that were pended until completion of the task. These tasks may take arbitrary amounts of time, and rules engine **246** tracks the progress of individual task via change notifications **211** produced by BLT **206**.

Event generator **250** creates persistent event records of the state of processing of SLAI **204** and stores the event records within a database. Clients uses these event records to track progress and determine the current state of the SLAI **204**.

Logger **254** generates detailed trace information about system activities for use in rule development and debugging. The logging level can be raised or lowered as needed without changing operation of SLAI **204**.

FIG. **18** is a block diagram of an example working memory **270** associated with rule engines **246**. In this example, working memory **270** includes a read-only first data region **272** that stores the expected state received from BLT **206**. Data region **272** is read-only in the sense that it cannot be modified in response to a trigger from sensor subsystem **240** or by rule engines **246** without notification from BLT **206**.

In addition, working memory **270** includes a second data region **274** that is modifiable (i.e., read/write) and may be updated by monitoring subsystem **202** or used internally by rule engines **246**. In general, data region **274** stores aggregated data representing the actual state of the fabric and can be updated by sensor subsystem **240** or by rule engines **246**. The actual state may consist of a set of property annotations that can be attached to objects received from BLT **206** or to objects locally defined within a rule engine, such as local object **276**.

FIG. **19** is a block diagram illustrating an example embodiment for BLT **206**. In this example, BLT **206** includes a set of one or more web service definition language (WSDL) interfaces **300**, a report generator **302**, a fabric administration interface service **304**, a fabric view service **306**, a user administration service **308**, a task interface **311**, a task manager **312** and an event subsystem **315**.

As described, BLT **206** provides the facilities necessary to create and administer the organizational model (e.g., fabric, domains, tiers and nodes) implemented by distributed computing system **10**. In general, BLT **206** abstracts access to the persisted configuration state of the fabric, and controls the interactions with interfaces to fabric hardware services. As such, BLT **206** provides fabric management capabilities, such as the ability to create a tier and replace a failed node. WSDL interfaces **300** provide web service interfaces to the functionality of BLT **206** that may be invoked by web service clients **313**. Many of WSDL interfaces **300** offered by BLT **206** allow administrator **20** to define goals, such as specifying a goal of the expected state of the fabric. As further described below, rule engines **246** within SLAI **204**, in turn, invoke task manger **312** to initiate one or more BLT tasks to achieve the specified goal. In general, web service clients **313** may be presentation layer applications, command line applications, or other clients.

BLT **206** abstracts all interaction with physical hardware for web service clients **313**. BLT **206** is an enabling component for autonomic management behavior, but does not respond to real-time events that either prevent a goal from being achieved or produce a set of deviations between the expected state and the actual state of the system. In contrast, BLT **206** originates goals for autonomic reactions to changing configuration and state. SLAI **204** analyzes and acts upon these goals along with real-time state changes. BLT **206** sets the goals to which SLAI **204** strives to achieve, and provides functionality used by the SLAI in order to achieve the goals.

In general, BLT **206** does not dictate the steps taken in pursuit of a goal since these are likely to change based on the current state of distributed computing system **10** and changes to configurable policy. SLAI **204** makes these decisions based on the configured rule sets for the fabric and by evaluating monitoring data received from monitoring subsystem **202**.

Fabric administration service **304** implements a set of methods for managing all aspects of the fabric. Example methods include methods for adding, viewing, updating and removing domains, tiers, nodes, notifications, assets, applications, software images, connectors, and monitors. Other example methods include controlling power at a node, and cloning, capturing, importing, exporting or upgrading software images. Rule engines **246** of SLAI **204** may, for example, invoke these methods by issuing action requests **212**.

Task manager **312** receives action requests **212** via task interface **311**. In general, task interface **311** provides an interface for receiving action requests **212** from SLAI **204** or other internal subsystem. In response, task manager **312** manages asynchronous and long running actions that are invoked by SLAI **204** to satisfy a goal or perform an action requested by a client.

Task manager **312** generates task data **310** that represents identification and status for each task. Task manager **312** returns a task identifier to the calling web service clients **313** or the internal subsystem, e.g., SLAI **204**, that initiated the task. Rule engines **246** and web service clients **313** use the task identifiers to track progress and retrieve output, results, and errors associated with achieving the goal.

In one embodiment, there are no WSDL interfaces **300** for initiating specific tasks. Rather, administrator **20** interacts with BLT **206** though goal interfaces presented by WSDL interfaces **300** to define the goals for the fabric. In contrast, the term task is used to refer to internal system constructs that require no user interaction. Tasks are distinct, low-level units of work that affect the state of the fabric. SLAI **204** may combine tasks to achieve or maintain a goal state.

For example, administrator **20** can request configuration changes by either adding new goals to an object or by modifying the attributes on existing goals. Scheduled goals apply a configuration at a designated time. For example, the goals for a particular tier may specify the minimum, maximum, and target node counts for that tier. As a result, the tier can increase or decrease current node capacity by scheduling goals with different configuration values.

This may be useful, for example, in scheduling a software image upgrade. As another example, entire domains may transition online and offline per a defined grid schedule. Administrator **20** may mix and match goals on a component to achieve configurations specific to the application and environment. For example, a tier that does not support autonomic node replacement would not be configured with a harvesting goal.

In some embodiments, goals are either "in force" or "out of force." SLAI **204** only works to achieve and maintain those goals that are currently in force. SLAI **204** may applies a concept of "gravity" as the goals transition from in force to out of force. For example, SLAI **204** may transition a tier offline when an online goal is marked out of force. Some goal types may have prerequisite goals. For example, an image upgrade goal may require as a prerequisite that a tier be

transitioned to offline before the image upgrade can be performed. In other embodiments, goals are always in force until modified.

SLAI **204** may automatically formulate dependencies between goals or may allow a user to specify the dependencies. For example, a user may request that a newly created tier come online. As a result of this goal, SLAI **204** may automatically direct task manager **312** to generate a task of harvesting a target number of nodes to enable the tier. Generally, all goals remain in-force by SLAI **204** until modified by BLT **206**. In one embodiment, each goal remains in-force in one of three states: Satisfied, Warning, or Critical depending on how successful SLAI **204** was in achieving the goal at the time the event record was generated and stored.

In this manner, SLAI **204** controls the life cycle of a goal (i.e., the creation, scheduling, update, deletion of the goal), and provides a common implementation of these and other services such as timeout, event writing, goal conflicts, management of intra-goal dependencies, and tracking tasks to achieving the goals.

Progress toward a goal is tracked though event subsystem **315**. In particular, event subsystem **315** tracks the progress of each in force goal based on the goal identifiers. Tasks executed to achieve a particular goal produce events to communicate result or errors. The events provide a convenient time-based view of all actions and behaviors.

Examples of goal types that may be defined by administrator **20** include software image management goals, node allocation goals, harvest goals, tier capacity goals, asset requirement goals, tier online/offline goals, and data gathering goals.

In one embodiment, BLT **206** presents a task interface to SLAI **204** for the creation and management of specific tasks in order to achieve the currently in force goals. In particular, rule engines **246** invoke the task interface based on evaluation of the defined rule sets in view of the expected state and actual state for the fabric. Example task interfaces include interfaces to: reserve node resources; query resources for a node slot; associate or disassociate an image with a node in a tier node slot; allocate, de-allocate, startup or shutdown a node; move a node to a tier; apply, remove or cycle power of a node; create a golden image; create or delete an image instance; and delete an activity, node or tier.

Report generator **302** provides an extensible mechanism for generating reports **314**. Typical reports include image utilization reports that contain information with respect to the number of nodes running each software image, inventory reports detailing both the logical and physical aspects of the fabric, and system event reports showing all events that have occurred within the fabric. Report generator **302** gathers, localizes, formats and displays data into report form for presentation to the user. Report generator **302** may include one or more data gathering modules (not shown) that gather events in accordance with a schedule and update an events table to record the events. The data gathering modules may write the events in XML format.

FIG. **20** is a block diagram illustrating one embodiment of a rule engine **246** (FIG. **17**). In the illustrated embodiment, rule engine **246** includes a rule compiler **344** and an execution engine **346**. Each of rules **342** represents a unit of code that conforms to a rule language and expresses a set of triggering conditions and a set of implied actions. When the conditions are met, the actions are eligible to occur. The following is one example of a configuration rule:

```
rule checkTierLoad {
    Tier t where status != "overloaded";
    LoadParameter p where app == t.app && maxload < t.load;
} -> {
    modify t {
        status: "overloaded";
    };
}
```

When translated, this example rule marks a tier as overloaded if an application is implemented by the tier and the maximum specified load for the application has been exceeded. Another example rule for outputting a notification that a tier is overloaded and automatically invoking a task within BLT **206** to add a node is:

```
rule tierOverloadNotify {
    Tier t where status == "overloaded";
} -> {
    notify "Tier: " + t + "is overloaded.";
    BLT.addNode(f);
}
```

Rule compiler **344** compiles each of rules **344** and translates match conditions of the rules into a discrimination network that avoids redundant tests during rule execution. Execution engine **346** handles rule administration, object insertion and retrieval, rule invocation and execution of rule actions. In general, execution engine **346** first matches a current set of rules **342** against a current state of working memory **348** and local objects **350**. Execution engine **346** then collects all rules that match as well as the matched objects and selects a particular rule instantiation to fire. Next, execution engine **346** fires (executes) the instantiated rule and propagates any changes to working memory **348**. Execution engine **346** repeats the process until no more matching rule instantiations can be found.

Firing of a rule typically produces a very small number of changes to working memory **348**. This allows sophisticated rule engines to scale by retaining match state between cycles. Only the rules and rule instantiations affected by changes are updated, thereby avoiding the bulk of the matching process. One exemplary algorithm that may be used by execution engine **346** to handle the matching process includes the RETE algorithm that creates a decision tree that combines the patterns in all the rules and is intended to improve the speed of forward-chained rule system by limiting the effort required to re-compute a conflict set after a rule is fired. One example of a RETE algorithm is described in Forgy, C. L.: 1982, 'RETE: a fast algorithm for the many pattern/many object pattern match problem', Artificial Intelligence 19, 1737, hereby incorporated by reference. Other alternatives include the TREAT algorithms, and LEAPS algorithm, as described by Miranker, D. P.: 'TREAT: A New and Efficient Match Algorithm for AI Production Systems'. ISBN 0934613710 Daniel P. Miranker, David A. Brant, Bernie Lofaso, David Gadbois: On the Performance of Lazy Matching in Production Systems. AAAI 1990: 685692, each of which is hereby incorporated by reference.

FIG. **21** is a block diagram illustrating an alternative embodiment of control unit **12** (FIG. **15**). In this embodiment, control unit **12** operates substantially as described above, but includes an application matrix **350**, an application governor **352**, a configuration processor **354**, and an application service level automation infrastructure ("application SLAI") **358**. As

described below, application matrix **350**, application governor **352**, configuration processor **354**, and application SLAI **358** provide a framework that allows control unit **12** to autonomically control the deployment, execution and monitoring of applications across application nodes **14** of distributed computing system **10**.

Application matrix **350** contains all the information needed by control unit **12** to interact with one or more applications or application servers and provide autonomic control over a set of applications. Specifically, application matrix **350** provides a logical definition for deploying and controlling the set of applications to one or more tiers within distributed computing system **10**. In one embodiment, application matrix **350** is an electronic document that conforms to a data description language, e.g., the extensible markup language (XML). Application SLAI **358** includes an application rules engine **355** dedicated to processing application-level rules, i.e., forward-chaining rules to provide autonomic control over the applications defined within application matrix **350**. Like rules engine **246**, application rules engine **355** contains a rule compiler, an execution engine, and a working memory. In order to give effect to changes in application matrix **350**, application SLAI **358** automatically updates application rules engine **355** and monitoring subsystem **202**. In particular, application matrix **350** sends an alert whenever application matrix **350** changes. In response to this alert, application SLAI **358** captures application-specific attributes from application matrix **350**. Specifically, application SLAI **358** captures configuration attributes and rule attributes contained in application matrix **350**. Application SLAI **358** transfers any new rule attributes to the working memory of application rules engine **355** to provide autonomic control over the deployment, monitoring and the execution of the applications defined within application matrix **350**. In addition, application SLAI **358** updates monitoring subsystem **202** to collect information required to control the applications In this manner, administrator **20** may continue to add new application definitions and configurations to application matrix **350** after distributed control node **12** has started.

As described in further detail below, configuration processor **354** is a software module that generates an application matrix entry based on an application definition and application configuration properties of a "staged" application. A staged application is an application that has been deployed in a staging environment and customized for subsequent deployment within distributed computing system **10**. After creating the application matrix entry, administrator **20** may insert the application matrix entry into application matrix **350**.

Configuration processor **354** is "pluggable." That is, administrator **20** can "plug in" different implementations of configuration processor **354** as needed. For example, administrator **20** may need to "plug in" a different implementation of configuration processor **354** to handle applications that do not use an application server.

Application governor **352** is a software engine that performs application-level actions based on requests received from application rules engine **355**. In this manner, BLT **206** effects fabric-level actions (e.g., deployment and monitoring of nodes and images) based on request from fabric-level rules engines **246** (FIG. **17**), while matrix governor **352** performs application-level actions (e.g., deployment and monitoring of applications) based on requests from application rules engine **355**.

Application governor **352** uses application matrix **350** as a source of parameters when carrying out the application-level operations requested by application rules engine **355**. For example, application rules engine **355** may detect that a node to which the application is not deployed is ready for use by the application. As a result, application rules engine **355** directs application governor **352** to handle the details of deploying the application to the node. In turn, application governor **352** accesses application matrix **350** to retrieve application-specific parameters necessary to deploy the application. Storing application-specific parameters in application matrix **350** allows the application-specific parameters to change without having to recompile the rules within working memory of application rules engine **355**.

Application governor **352** performs a similar procedure to undeploy an application. That is, application rules engine **355** may detect that a second application needs to use a node more than a first application that is currently deployed to the node. In this situation, application rules engine **355** sends an instruction to application governor **352** to undeploy the first application and deploy the second application. To carry out this instruction, application governor **352** accesses application matrix **350** to discover configuration parameters of both applications. Application governor **352** then uses the discovered configuration parameters to communicate with the applications.

Like configuration processor **354**, application governor **352** is also "pluggable." That is, administrator **20** can easily install or remove implementations of application governor **352** depending on the circumstances. Because application governor **352**, and configuration processor **354** represent interchangeable, plug-in modules, the other parts of control unit **12** and system **10**, including application rules engine **355**, can remain generic and application neutral while providing autonomic control over distributed computing system **10**.

FIG. **22** provides a conceptual view of an exemplary application matrix **350**. Although application matrix **350** is typically represented in an encoded, electronic document (e.g., an XML document), FIG. **22** provides a conceptual view for ease of illustration.

In this example, application matrix **350** contains seven columns and two rows. Each row represents a different application entry for deployment within distributed computing system **10**. In FIG. **22**, only the first entry is shown in detail.

Each of the columns represents a different category of elements that make up an application's logical definition. In this example, the columns include:

(1) an application column **360** that includes elements generally related to the deployment of the application,

(2) an application nodes column **362** that contains elements related to the tier node slots to which the application may be assigned,

(3) a services column **364** that contains elements related to the executable services launched when the application is deployed,

(4) a node monitor values column **366** that contains elements related to attributes of the nodes that are to be monitored after the application is deployed to that node,

(5) a service monitored attributes column **368** that contains elements related to attributes of the services that are to be monitored after the application is deployed,

(6) a service levels column **370** that contains elements related to attributes for use when constructing rules to monitor execution of the services, and

(7) a deployment constraints column **372** that contains elements related to attributes for use when constructing rules to control deployment of the application.

Different types of applications may have different elements in each column, and different numbers of columns.

In the example of FIG. **22**, application matrix **350** contains two applications **360** "DataDomain" **374** and "PortalDomain" **376**. DataDomain application **374** has eleven attributes that define how control node **12** accesses and launches the application. For instance, the "adminIP" and "adminPort" attributes instruct governor **352** as to which the server and port hosts the administrative part of the logically defined application. Other attributes like "maxNodes" and "minNodes" instruct application rules engine **355** to run the application no less than minNodes and no more than maxNodes. Applications other than application **374** may have different numbers or types of attributes. In XML format, the attributes of application **374** may appear as follows:

```
<WebServerDomain
    name="DataDomain"
    adminIP="172.31.64.201"
    adminPort="1100"
    adminTier="Web Admin"
    clusterName="PathCluster"
    expectedStartupDelay="120"
    loadDelay="120"
    maxNodes="2"
    minNodes="1"
    nodeManagerPort="5811"
    nodeTier="Web App"
>
```

In addition to these attributes, application **374** contains a series of elements (columns **362-372**). In general, application nodes **362** contain a list of all of the available tier-node slots to which control node **12** may deploy application **374**. In this example, two tier-node slots are specified. In XML, managed servers **362** appears as:

```
<ManagedServers IP="172.31.64.201" name="managedServer_0"
state="STOPPED" />
<ManagedServers IP="172.31.64.201" name="managedServer_1"
state="STOPPED" />
```

Each services **364** element identifies a service that control node **12** launches when deploying application **374** on a given application node. A service element comprises a service name and a path to a file containing the executable service. Governor **352** uses the path to locate and launch the service. For example, the following XML code indicates that governor **352** must access the file at "/lib/worklistApp/worklistApp.ear".

```
<services name="Worklist User Interface"
path="/lib/worklistApp/worklistApp.ear" />
```

Node Monitored Values **366** elements represent characteristics for use in constructing rules for monitoring nodes to which the applications are deployed. Similarly, Service Monitored Values **368** elements represent characteristics for use in constructing rules for monitoring services that are launched once the application is deployed. In this example, a "nodeMonitoredValues" element defines characteristics of a particular node that are to be monitored. For instance, the amount of free memory in a node is one example of a characteristic listed as a "nodeMonitoredValues" element. On the other hand, a "serviceMonitoredValues" element is specific attribute of a service that is to be monitored. For example, the number of pending operating system-level requests for the service, the number of idle threads, etc., could be service monitored values. In a XML rendition of application matrix **350**, node monitored values and service monitored values could appear as follows:

```
<nodeMonitoredValues name="Load5Average" />
<nodeMonitoredValues name="PercentMemoryFree" />
<serviceMonitoredValues name="PendingRequests" />
<serviceMonitoredValues name="ExecuteThreadIdleCount" />
<serviceMonitoredValues name="ExecuteThreadTotalCount" />
```

Deployment constraint elements **372** specify characteristics of a node under which application rules engine **355** should (or should not) deploy a service to the node. In this example, a deployment constraint element has five attributes: "attribute", "expression", "frequency", "maxThreshold", "minThreshold", and "period." The "attribute" attribute names the deployment constraint. The "expression" attribute specifies an arithmetic expression manipulating a monitored value. For example, the expression could be "PercentMemoryFree*100", meaning monitor the value of the "PercentMemoryFree" node monitored value multiplied by 100. The "expression" attribute may specify one or more node monitored values. The "frequency" attribute informs application rules engine **355** how frequently to check the monitored value. The "maxThreshold" attribute tells application rules engine **355** to invoke a rule when the value of the expression exceeds the value specified by the "maxThreshold" attribute. Similarly, the "minThreshold" attribute tells application rules engine **355** to invoke the rule when the value of the expression drops below the value specified by the "minThreshold" attribute. Finally, the "period" attribute informs application rules engine **355** of the period over which to collect monitored value. For example, a deployment constraint element may specify that application rules engine **355** should monitor the PercentMemoryFree attribute of a node every 15 seconds for 60 seconds. If the value of PercentMemoryFree*100 should drop below 1.0 (i.e. 1% of memory free) for 60 seconds, then application rules engine **355** should not deploy the application to that node. In XML, this rule would be represented as:

```
<deploymentConstraints attribute="FreeMemory"
expression="PercentMemoryFree*100" frequency="15" maxThreshold="-
1.0" minThreshold="1.0" period="60" />
```

Service level elements **370** have the same five attributes as deployment constraints elements: "attribute", "expression", "frequency", "maxThreshold", "minThreshold", and "period". However, the "expression" attribute deals with service monitored attributes rather than node monitored attributes. For example, a service level element may specify that application rules engine **355** check the "pendingRequest" service-monitored attribute every 15 seconds for 30 seconds. Then, if there are more than 20 pending requests for more than 30 seconds, application rules engine **355** should take the action of starting a new application. On the other hand, if there are fewer than 5 pending requests for 30 seconds, application rules engine **355** enables the action to remove the application to free up space on a node. Such a service level element could be represented as:

```
<serviceLevels attribute="PendingRequests"
expression="PendingRequests" frequency="15" maxThreshold="20.0"
minThreshold="5.0" period="30" />
```

Put together, an XML representation of an application matrix logically defining a single application for deployment within autonomically controlled distributed computing system **10** may appear as follows:

```
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<appMatrixRegister>
<WebServerDomain adminIP="172.31.64.201" adminPort="1100"
adminTier="Web
Admin" clusterName="PathCluster" expectedStartupDelay="120"
loadDelay="120" maxNodes="2" minNodes="1" name="DataDomain"
nodeManagerPort="5811" nodeTier="Web App">
    <ManagedServers IP="172.31.64.201" name="managedServer_0"
    state="STOPPED" />
    <ManagedServers IP="172.31.64.201" name="managedServer_1"
    state="STOPPED" />
    <applications name="AI Design-time"
    path="/lib/ai-designtime.ear" />
    <applications name="System EJBs" path="/lib/ejbs.ear" />
    <applications name="Worklist Worker User Interface"
    path="/lib/worklist/worklist.ear" />
    <applications name="DBMS_ADK" path="/lib/DBMS_ADK.ear"
    />
    <applications name="UserApp"
    path="/user_projects/domains/userApp.ear"
    />
    <nodeMonitoredValues name="Load5Average" />
    <nodeMonitoredValues name="PercentMemoryFree" />
    <serviceMonitoredValues name="PendingRequests" />
    <serviceMonitoredValues name="ExecuteThreadIdleCount" />
    <serviceMonitoredValues name="ExecuteThreadTotalCount" />
    <deploymentConstraints attribute="LoadAverage"
    expression="Load5Average" frequency="15"
    maxThreshold="4.0"
    minThreshold="-1.0" period="15" />
    <deploymentConstraints attribute="FreeMemory"
    expression="PercentMemoryFree*100" frequency="15"
    maxThreshold="-1.0"
    minThreshold="1.0" period="60" />
    <serviceLevels attribute="BusyThreadPercentage"
    expression="(ExecuteThreadTotalCount-
    ExecuteThreadIdleCount) *100/ExecuteThreadTotalCount"
    frequency="15"
    maxThreshold="20.0" minThreshold="5.0" period="30" />
    <serviceLevels attribute="PendingRequests"
    expression="PendingRequests" frequency="15"
    maxThreshold="20.0"
    minThreshold="5.0" period="30" />
</WebserverDomain>
</appMatrixRegister>
```

FIG. **23** is a flowchart illustrating an exemplary series of general steps that are performed to add an application to application matrix **350** in accordance with the principles of this invention. Administrator **20** first stages the application within a staging environment including deploying the application on a desired image, creating a domain, specifying any services and external system connectivity (e.g., connections to databases, queues) (**380**).

During this process, administrator **20** directs the application to generate an application definition file that represents an application-specific configuration based on the environment specified by the administrator. The application definition file contains information specific to an installation instance of the application. For example, the application definition file typically specifies the locations (paths) for all software components of the application as staged within the staging environment, a list of files to execute, connectivity information for the application, and other information that may be recorded by the configured application.

After staging the application, administrator **20** defines a set of application configuration properties that specify desired behavior of the application within distributed computing system **10** (**382**). Examples of such application configuration properties include a minimum number of nodes, minimum resource requirements for a node, deployment timing information, network addresses of tier node slots that are able to execute the application and other properties.

Next, administrator **20** directs configuration processor **354** to generate an application entry for the application using the application definition and the application configuration properties (**384**). The application entry contains configuration attributes used by application governor **352** to interact with the application. In addition, the application entry contains rule attributes used by application rules engine **355** that define how control node **12** monitors the deployment and execution of the application within distributed computing environment **10**.

After configuration processor **354** creates the application entry, administrator **20** may modify the application entry (**386**). In particular, administrator **20** may update start scripts or shell scripts for the application due to path changes between the staging environment and distributed computing system **10**.

Once administrator **20** has finished modifying the application entry, administrator **20** inserts the application entry into application matrix **350** (**388**). Because application matrix **350** detects that it has changed, application matrix **350** sends an alert to application SLAI **358** (**390**).

In response to the alert, application SLAI **358** may update application rules engine **355** and monitoring subsystem **202** (**392**). In particular, application SLAI **358** automatically scans application matrix **350**. If application SLAI **358** detects new rule attributes, application SLAI **358** creates local objects reflecting the new rule attributes in the working memory of application rules engine **355**. In addition, if application SLAI **358** detects new monitored values, application SLAI **358** updates monitoring subsystem **202** to add new monitoring collectors **224** (FIG. **16**).

After application SLAI **358** updates application rules engine **355** and monitoring subsystem **202**, control node **12** has autonomic control over the deployment of applications to tiers based on the configuration of application matrix **350** (**394**). For example, control node **12** deploys images, deploys applications, monitors the state of nodes and the execution of the applications, and applies tier-level rules as well as application-specific rules. Application SLAI **358** continues to listen for alerts from application matrix **350**.

FIGS. **24** through **29** illustrate exemplary embodiments of distributed computing system **10** that provides autonomic control and deployment of virtual machines and virtual disk image files. For example, FIG. **24** is a block diagram illustrating an exemplary configuration of a physical node **400**. Node **400** may be any node within distributed computing system **10** (FIG. **1**). For instance, node **400** may be any one of application nodes **14**.

As illustrated in FIG. **24**, a virtual machine manager **402** is executing on node **400**. As used herein, a virtual machine manager is a software program that is capable of managing one or more virtual machines. For example, virtual machine manager **402** may be an instance of VMWare ESX software produced by VMWare, Inc. of Palo Alto, Calif.

When deployed on physical node **200**, virtual machine manager **402** hosts virtual machines **404**A through **404**N (collectively, virtual machines **404**). The term virtual

machine is used herein to refer to software that creates an environment that emulates a computer platform. For example, virtual machines **40** provide environments on which guest operating systems (OS) execute as through the operating systems were operating directly on a physical computing platform. In this manner, multiple operating systems and software applications **406**A through **406**N (collectively, operating systems and applications **406**) may execute on virtual machines **404**A through **404**N, respectively, and the virtual machines **404** may execute on a single physical node **400** or multiple physical nodes. For example, if virtual machine **404**A emulates an x86 machine, an instance of the Microsoft Windows operating system (e.g., OS **406**A) may execute on virtual machine **404**A as through the instance of Windows were running on a physical x86 machine. Other software applications may be installed and configured on the guest operating system running on virtual machine **404**. For example, an instance of Microsoft Internet Information Server may execute on an instance of Microsoft Windows that is executing on a virtual machine that emulates an x86 machine. In this manner, virtual machine manager **402** and virtual machines **404** provide a level of independence from the particular hardware environment provided by physical node **400**.

Virtual machine manager **402** utilizes operating system data and application data for execution of each of virtual machines **404**. The operating system data and application data, as well as instance-specific configuration data for the underlying virtual machines **404**, is stored as respective virtual disk image files **408**. From the perspective of the guest operating system, each of virtual disk image files **408** appears as a bootable hard disk of the host computer. In other words, the virtual disk image file provides a bootable software image of the operating system and applications, and includes all necessary configuration data and file structures. As illustrated in FIG. **24**, virtual machine disk image file **408**A provides a bootable software image for operating system/application information **406**A that is capable of being executed on virtual machine **404**A. For instance, if virtual machine manager **402** is an instance of VMWare ESX, virtual machine disk image files **408** may be specially captured .vmdk files.

A two-phase capture process may be used to provide autonomic control and deployment of the virtual machine disk image files **408** as well as virtual machine manager **402** to physical nodes within distributed computing system **10**. In particular, control node **12** may first capture an image of virtual machine manager **402** installed on physical node **400** prior to installation and configuration of any guest operating system and applications **406**. Control node **12** may utilize this captured image of virtual machine manager **402** as a "golden image" from which instance images can be created for this type virtual machine. The instance images may be stored within application matrix **350** for autonomic deployment as other software images (FIG. **21**).

After the first capture is complete, an administrator may install one or more virtual machines **404** to virtual machine manager **402**. After the user installs and configures guest operating systems and any necessary applications **406** on the virtual machines **404**, control node **12** may capture software images for storage as virtual disk image files **408**. Specifically, control node **12** may utilize the captured images as a golden images for the particular operating systems, applications and specific configuration of the virtual machine. The golden image may then be used to produce image instances, i.e., virtual disk images in this case, that are bootable on the virtual machines. The image instances may likewise be stored in application matrix **350** for autonomic deployment.

After generation of image instances for virtual machine manager **402** and virtual disk image files **408**, control node **12** may deploy the image instance of virtual machine manager **402** to one or more nodes in free pool **13**. Once control node **12** deploys the image instance of virtual machine manager **402** to a node, the node appears to be one or more new, unallocated nodes. For instance, if the image instance of virtual machine manager **402** is configured to support five virtual machines, control node **12** represents the newly deployed image instance as though five new, unallocated nodes have been added to free pool **13**. Subsequently, control node **12** may deploy an image instance of virtual disk image files **408** to one of the new unallocated nodes.

In one embodiment, during deployment, administrator **20** may specify whether data in virtual disk image files is to be treated as persistent or non-persistent. If administrator **20** specifies that the virtual disk image files are persistent, changes made to a virtual disk image file persist when node is restarted. To ensure the persistence of the data, administrator **20** may configure virtual machine manager **402** to store virtual disk image files in a storage area network (SAN). Otherwise, if administrator **20** specifies that virtual disk image files are non-persistent, the original virtual disk image file is reloaded from control node **12**. Non-persistence may be valuable to minimize risks (e.g., potential corruption due to viruses) associated with prolonged use of an operating system. Further, corrupt or invalid data in the virtual disk image file may be corrected by use of non-persistent image instances for the virtual disk image files.

In this way, distributed computing system **10** may autonomically utilize application nodes, e.g, node **400**, to flexibly support a wide variety of operating systems and applications, and provide virtualized execution environment for those operating systems and applications. For instance, node **400** may autonomically configured to support a Macintosh Operating System designed for a PowerPC processor, and a Microsoft Windows Operating System designed for an x86 processor based on the particular goals of the autonomic system. Thus, control node **12** may not need to distinguish between hardware processor architectures when deploying operating systems and applications. However, this system may also allow administrator **20** to specify that control node **12** operate an image instance directly on a node without the intervening virtual machine and virtual machine manager. Furthermore, by executing multiple operating systems on a single node, distributed computing system **10** may be able to use and deploy the resources of each node more efficiently.

FIG. **25** is a flowchart illustrating an exemplary procedure for creating and capturing a golden image for a particular virtual machine manager **402** (FIG. **24**). Initially, administrator **20** sets aside a node (e.g., node **400**) as an image host (**410**). Administrator **20** may then install a particular type of virtual machine manager **402** on node **400** (**412**). After administrator **20** installs virtual machine manager **402** on node **400**, administrator **20** may configure the virtual machine manager to support a desired number of virtual machine instances (**414**). For example, administrator **20** could configure virtual machine manager **402** to support one or more virtual machines. Administrator **20** may then perform other network or Storage Area Network (SAN) configuration on virtual machine manager **402** (**416**). After administrator **20** performs all of the necessary configuration, administrator **20** instructs control node **12** to capture the image of virtual machine manager **402** with the configurations (**418**). Control node **12** may store the captured image as a golden image in application matrix **350** for use in subsequent autonomic deployment of image instances.

FIG. **26** is a flowchart illustrating an exemplary procedure for creating and capturing a virtual disk image file, i.e., a golden image of a guest operating system and applications for execution on a virtual machine. Initially, administrator **20** sets aside a node (e.g., node **400**) that is running a virtual machine manager (e.g., virtual machine manager **402**) (**420**). Administrator **20** may then configure the virtual machine manager to create a virtual machine (e.g., virtual machine **404**) on node **400** (**422**). After creating the virtual machine, administrator **20** installs the particular operating system on virtual machine **404** (**424**). Administrator **20** may then install one or more applications on the operating system (**426**). After installation, administrator **20** may configure the operating system and applications as needed (**428**). In some embodiments, virtual machine manager **402** stores definition data for the particular virtual machine, operating system, and applications in a virtual disk image file. Once configuration is complete, administrator **20** takes a "snapshot" of the data in the virtual disk image file (**430**). Administrator **20** may then capture this "snapshot" to control node **12** as a golden image (**432**). Control node **12** may store the "snapshot" in application matrix **350** as a golden image for use in autonomic deployment of one or more image instances to virtual machines hosting the particular operating system and applications.

FIG. **27**A is a flowchart illustrating an exemplary procedure for autonomic deploying a virtual machine manager to a node. Initially, administrator **20** may instruct control node **12** to create a new tier (**440**). Subsequently, administrator **20** specifies one or more captured virtual machine manager image instances for assignment to the slots of the new tier (**442**). Administrator **20** may also specify whether the image instances of the tier run in persistent or non-persistent mode. Administrator **20** may then activate the new tier (**444**). After these physical nodes boot with the virtual machine manager image instance, each of the nodes creates a set of virtual machines as specified by the image instances. Control node **12** may then discover each of these virtual machines and place them in free pool **13** as if they were independent nodes. In this manner, each of the virtual machines appear to be physical nodes available for use as application nodes **14** when needed. However, control node **12** maintains tags or other metadata that distinguish between virtual machines and actual physical nodes. Finally, based on the current state and goals of distributed computing system **10**, control node **12** may allocate one or more of the virtual machines to the slots within the tier, similar to the process by which nodes are deployed from the free pool **13** to a tier as needed.

FIG. **27**B is a flowchart illustrating an exemplary procedure for deploying an operating system and application image instance to a node that is executing a virtual machine manager. To start the procedure, administrator **20** may instruct control node **12** to create a new tier, including defining the number of slots for the tier, or select an existing tier (**446**). Administrator **20** may then specify a captured operating system and application image for the tier (**448**). In addition, administrator **20** may set minimum, maximum, and target values for the image instances to be deployed to the slots new tier (**450**). Administrator **20** may then activate the tier (**452**). After administrator **20** activates the tier, based on the current state and goals of distributed computing system **10**, control node **12** autonomically selects a virtual machine from free pool **13**, associates the virtual machine with a slot in the tier, identifies the virtual disk image file (image instance) associated with the particular slot, copies the virtual disk image file to the local hard disk of the physical node on which the virtual node resides or the an associated SAN, and finally boots the virtual machine from the virtual disk image file.

FIG. **28** is a screen image illustrating an exemplary tier control interface **460** for the embodiment described in FIGS. **24** through **27** above. In this example, control interface **460** displays a set of three tiers "elas3u6_2", "elas3u6_vm", and "esx17_8". As illustrated in FIG. **28**, tier "esx17_8", labeled **462**, contains eight physical nodes. The image "esx_17" is operating on each node in tier **462**. If the "esx_17" image is a virtual machine manager image that operates seventeen virtual machines, the eight nodes of tier **462** operate as 136 virtual machines.

FIG. **29** is a screen image illustrating an exemplary node control interface **470** for the embodiment described in FIGS. **24** through **27** above. As illustrated in FIG. **29**, a single physical node "collage0104" hosts seventeen virtual machines "collage0104_vnode1" through "collage0104_vnode17". Each of these virtual machines is loaded with the "w2k3_iis_sql (1.0)" image. For instance, the "w2k3_iis_sql (1.0)" image may be an image containing instances of Microsoft Windows 2003 Internet Information Server and Microsoft SQL Server.

Various embodiments of the invention have been described. These and other embodiments are within the scope of the following claims.

The invention claimed is:

1. A distributed computing system comprising:

a software image repository comprising non-transitory, computer-readable media operable to store: (i) a plurality of image instances of a virtual machine manager that is executable on a plurality of application nodes, wherein when executed on the applications nodes, the image instances of the virtual machine manager provide a plurality of virtual machines, each of the plurality of virtual machine operable to provide an environment that emulates a computer platform, and (ii) a plurality of image instances of a plurality of software applications that are executable on the plurality of virtual machines; and

a control node that comprises an automation infrastructure to provide autonomic deployment of the plurality of image instances of the virtual machine manager on the application nodes by causing the plurality of image instances of the virtual machine manager to be copied from the software image repository to the application nodes and to provide autonomic deployment of the plurality of image instances of the software applications on the virtual machines by causing the plurality of image instances of the software applications to be copied from the software image repository to the application nodes.

2. The distributed computing system of claim **1**, wherein the image instances of the plurality of software applications comprise virtual disk image files.

3. The distributed computing system of claim **1**, wherein a first image instance of the plurality of image instances of the plurality of software applications comprises an operating system.

4. The distributed computing system of claim **1**, wherein a first image instance of the plurality of image instances of the plurality of software applications comprises a server application.

5. The distributed computing system of claim **1**, wherein a first one of the virtual machines provides an environment that emulates an x86 platform.

6. The distributed computing system of claim **1**, wherein the automation infrastructure captures a first image instance of the image instances of the virtual machine manager from a first application node of the plurality of application nodes.

7. The distributed computing system of claim 6, wherein the first application node executes the virtual machine manager.

8. The distributed computing system of claim 1, wherein the control node maintains the plurality of image instances of the virtual machine manager and the plurality of image instances of the plurality of software applications as persistent or non-persistent based on a configuration.

9. The distributed computing system of claim 1, wherein the control node further comprises one or more rule engines that provide autonomic deployment of the software applications to the virtual machines in accordance with a set of one or more rules.

10. The distributed computing system of claim 9, wherein the one or more rule engines are forward-chaining rule engines.

11. The distributed computing system of claim 9, wherein the automation infrastructure automatically updates the one or more rules engines to autonomically control the deployment of the software applications to the application nodes in accordance with a current state of an application matrix.

12. The distributed computing system of claim 1, wherein the control node further comprises an application matrix that includes parameters for controlling the deployment, undeployment, and execution of the software applications to the virtual machines within the distributed computing system.

13. The distributed computing system of claim 12, further comprising an application governor that accesses the application matrix to communicate instructions from the automation infrastructure to the software applications.

14. The distributed computing system of claim 9, wherein the automation infrastructure automatically updates the one or more rules engines to monitor the execution of the software applications when deployed to the application nodes in accordance with a current state of the application matrix.

15. The distributed computing system of claim 1, wherein the automation subsystem includes a rule compiler that compiles rules into one or more discrimination networks.

16. The distributed computing system of claim 1, wherein the control node further comprises:

a monitoring subsystem that collects status data from the application nodes and communicates the status data to the automation subsystem, wherein the status data represents an actual state for the application nodes; and

a business logic tier that provides expected state data to the automation subsystem, wherein the expected state data represents an expected state for the application nodes,

wherein one or more rule engines analyze the status data from the monitoring subsystem and apply a set of rules to produce action requests to the business logic tier to control the application nodes to reduce any difference between the actual state and the expected state.

17. The distributed computing system of claim 1, wherein the application nodes are organized into tiers, and wherein status data is collected based on the tiers.

18. The distributed computing system of claim 1, further comprising:

a database storing data that defines a model for a hierarchical organization of the distributed computing system, wherein the model specifies a fabric having one or more domains, and wherein each domain has at least one tier that includes at least one of the application nodes,

wherein one or more rule engines automatically produce action requests to control the deployment of the software applications in accordance with the hierarchical organization of the distributed computing system defined by the model.

19. A method comprising:

storing a plurality of image instances of a virtual machine manager that is executable on a plurality of application nodes in a distributed computing system, wherein the image instances of the virtual machine manager provide a plurality of virtual machines, each virtual machine operable to provide an environment that emulates a computer platform;

storing a plurality of image instances of a plurality of software applications that are executable on the plurality of virtual machines;

executing a rules engine to perform operations to autonomically deploy the image instances of the virtual machine manager on the application nodes by causing the image instances of the virtual machine manager to be copied to the application nodes; and

executing the rules engine to perform operations to autonomically deploy the image instances of the software applications on the virtual machines by causing the image instances of the software applications to be copied to the application nodes.

20. The method of claim 19, wherein storing the image instances of the plurality of software applications comprises storing virtual disk image files.

21. The method of claim 19, wherein a first image instance of the plurality of image instances of the plurality of software applications comprises an operating system.

22. The method of claim 19,

further comprising generating an application matrix that specifies data for controlling the deployment of the software applications within the distributed computing system; and

wherein performing operations to provide autonomic control comprises providing autonomic control over the deployment, undeployment, and execution of the software applications on the virtual machines within the distributed computing system in accordance with parameters of the application matrix.

23. The method of claim 19, wherein performing operations to autonomically deploy the image instances of the software applications on the virtual machines comprises:

receiving status data for the distributed computing system, wherein the status data represents an actual state of the application nodes;

processing the status data with rules in a set of rule engines to determine operations for reducing any difference between an expected state and the actual state of the application nodes; and

performing the operations to provide autonomic control over the deployment of the software applications on the virtual machines within the distributed computing system in accordance with the rules.

24. The method of claim 19, further comprising accessing parameters of an application matrix and determining one or more rules for use in autonomically controlling the deployment of the software applications on the virtual machines.

25. The method of claim 24, further comprising processing the one or more rules with a plurality of forward-chaining rule engines that compile the one or more rules into one or more discrimination networks.

26. A non-transitory, computer-readable medium comprising instructions stored thereon, that when executed by a programmable processor:

store a plurality of image instances of a virtual machine manager that is executable on a plurality of application nodes in a distributed computing system, wherein the image instances of the virtual machine manager provide

a plurality of virtual machines, each virtual machine operable to provide an environment that emulates a computer platform;

store a plurality of image instances of a plurality of software applications that are executable on the plurality of virtual machines;

perform operations to autonomically deploy the image instances of the virtual machine manager on the application nodes by causing the image instances of the virtual machine manager to be copied to the application nodes; and

perform operations to autonomically deploy the image instances of the software applications on the virtual machines by causing the image instances of the software applications to be copied to the application nodes.

* * * * *