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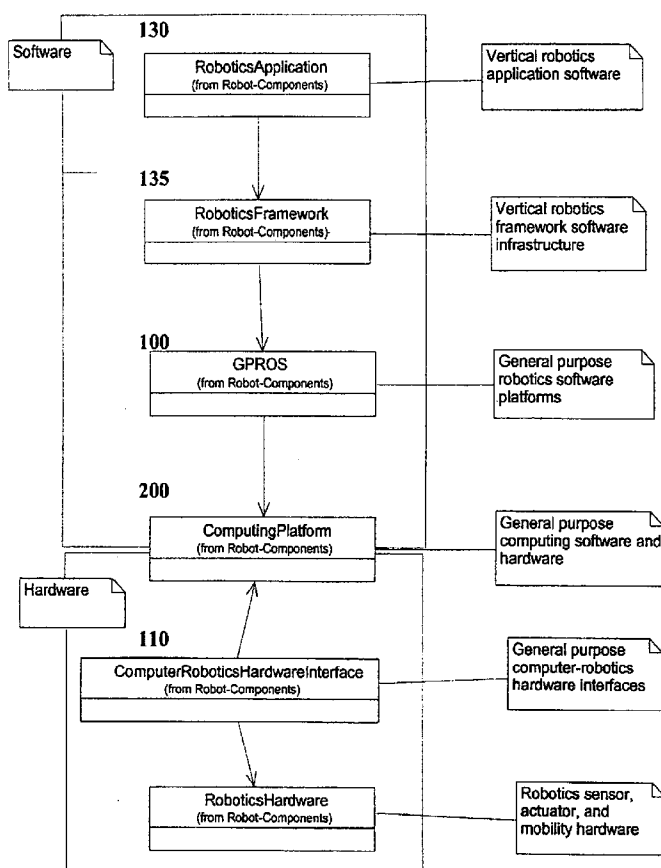
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(54) Title: A GENERAL PURPOSE ROBOTICS OPERATING SYSTEM



(57) Abstract: The present invention provides a general purpose operating system that shows particular usefulness in the robotics and automation fields. The operating system provides individual services and the combination and interconnections of such services using built-in service extensions, built-in completely configurable generic services, and a way to plug in additional service extensions to yield a comprehensive and cohesive framework for developing, configuring, assembling, constructing, deploying, and managing robotics and/or automation applications.



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A GENERAL PURPOSE ROBOTICS OPERATING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application relies on the disclosure of, and claims the benefit of the filing date of, U.S. patent application number 11/361,974, filed 27 February 2006, the entire disclosure of which is hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

[001] The present invention generally relates to operating systems for computers and devices comprising computers. More specifically, the invention relates to a general purpose software platform and toolkit that can be used in various settings, such as in robotics and automation, to rapidly and affordably create solutions and functional products of all kinds, shapes, and sizes.

Description of the Related Art

[002] There are many applications, domains, and resulting structures for robots. Examples range from and include unmanned autonomous robotic vehicles in a military domain, surveillance and security robots in a commercial domain, robotic manipulator arms in an industrial domain, medicinal transport robots in a professional service domain, vacuum cleaning robots in a home, legged entertainment robots for personal use, among many others. The resulting structures for these robots assume all sorts of shapes and sizes. The mechanisms, electronics, sensors, actuators, and their interconnections all also vary across robots. Furthermore, the software that embodies the behavior of a robot also varies across robotics applications.

[003] Existing approaches to providing robotics solutions have been highly specialized to a particular application, domain, and selected structure. As a result, typical robotics product architectures are inherently monolithic, lack inter-operability, lack use of mainstream open standards, and end up being costly. For example, if a new robotics application for a particular environment and domain is desired, the combination of underlying mechanisms, electronics, sensors, and actuators are

selected and configured and all of the software for interacting with such hardware as well as the software for embodying the desired application behavior is either created from scratch and/or laboriously repurposed from an existing specialized robotics application, domain, and/or structure to the new robotics application, domain, and/or structure. Unlike applications in other industries where component-based software development is more common, in existing robotics applications, such drawbacks exist for each new robotics application that is to be developed, both across organizations and within the same organization. Even if a new sensor, means of actuation, or new behavior is added to an existing robotics application, a laborious process of integrating new software into a monolithic architecture ensues.

[004] For example, U.S. Patent No. 6,889,118, issued to Evolution Robotics, describes a method of providing hardware abstraction for robot control software. More specifically, the patent discloses that the inventors were motivated to develop a hardware-independent abstraction layer for robotics. The invention detects a hardware configuration for the robot, provides a plurality of resource drivers for the robot, receives a request from the robot control software to use a type of resource, automatically selects a resource from the available resources that corresponds to the type of resource requested by the robot control software, and exchanges a second information with a low-level device driver corresponding to the resource.

[005] In addition, U.S. Patent No. 6,636,781, issued to University of Southern California, describes a method of discovering a communication connection to autonomous agents communicatively coupled together in a reconfigurable network topology. Each robot module comprises one or more actuators to cause movement of the robot module and a communication interface to send and receive messages to and from the other robot modules.

[006] Further, U.S. Patent No. 6,175,206, issued to Kawasaki, describes a robot information processing apparatus comprising: 1) a server processing unit that includes detecting means for detecting the positions of a plurality of axes of a robot body, which serves as an object to be driven, and for outputting detection data; and 2)

first communication means for transmitting the detection data outputted from the detecting means.

[007] Also, U.S. Patent No. 6,405,099, issued to SMC Kabushiki Kaisha, describes an automatic control system comprising a server offered by a service provider that stores control applets to control a particular control object device and a control device comprising a control object device and a computer device to control said control object device. The control object device comprises an actuator. Control applets stored in the server can be JAVA applets stated in the JAVA language.

[008] Yet another example of a vertical solution for robotics is U.S. Patent No. 6,658,325, issued to Stephen Zweig. This patent describes a mobile robot with an onboard web server, telecommunications means to link the onboard web server with the internet, and onboard telecommunications means to establish additional short-range bi-directional digital radio links with a plurality of non-internet connected external computer controlled devices.

[009] U.S. Patent No. 6,513,058, issued to Roy-G-Biv, describes a system for allowing an application program to communicate with any one of a group of supported hardware devices.

[010] U.S. Patent No. 6,078,747, issued to James Jewitt, describes a computer-implemented method of interfacing between a plurality of application programs and a physical device.

[011] U.S. Patent No. 6,266,577, issued to GTE Internetworking, describes a robot network having a plurality of robots, wherein each of the plurality of robots performs an assigned task according to a control logic.

[012] U.S. Patent No. 5,124,918, issued to Case Western Reserve, describes an autonomous robotic locomotion control system.

[013] U.S. patent application publication number 2005/0182518, assigned to Evolution Robotics, describes a method of visual and simultaneous localization and mapping, using visual features to recognize landmarks in an environment.

[014] Japanese patent JP-02182688A2, issued to Kobe Steel, describes a method of making robots cooperate with each other by preliminarily providing each robot with a unit motion program for executing a concrete unit motion independent of the robots.

[015] Japanese patent JP-2003145462 A2, assigned to Kawasaki Heavy, describes a robot cooperative control system which can prevent any deviation of the operation of each robot while maintaining a plurality of control devices in a constantly synchronous manner with each other.

[016] PCT Publication WO 2005103848, assigned to Frontline Robotics, describes a control system for a mobile autonomous system, wherein a robot leader can command and control a platoon of robotic agent nodes.

[017] Although there have been numerous specific solutions for various specific needs in the automation and robotics fields, there still exists a need for a broad solution to programming and implementing software and hardware in these fields. Furthermore, in order for there to be proliferation of robotics and automation across the broader market landscape, time and cost to deploy and integrate end-user robotics and automation solutions must be dramatically lowered. Two primary points of integration within an end-user robotics and automation solution exist. One primary integration point is between a vertical end-user robotics or automation application and an underlying robotics or automation platform. The other primary integration point is between a robotics or automation software platform and underlying plug-and-play mobility, sensor, and actuator hardware. The monolithic robotics and automation architectures to date blur the boundaries of these two integration points and accentuate the need for a general purpose robotics and/or automation software platform bridging the gap and complexities between robotics and automation application software and hardware.

SUMMARY OF THE INVENTION

[018] The present invention addresses needs in the art by providing a general purpose robotics and automation operating system. The system of the invention enables designers of robotics and automation solutions to easily integrate those

solutions into a working product by providing a standardized, full service platform upon which the various and widely divergent robotics and automation applications may sit.

[019] In general, the current invention provides generic and general purposes software services for use by any robotics and automation application. The invention provides generic software services that may be commonly used by any software application, extends these services with services that may be commonly used by any robotics and automation application, and combines these services to provide a general purpose software platform for use in any robotics and automation application. This method provides a way to more rapidly develop, configure, assemble, deploy, and extend robotics and automation applications over existing technologies.

[020] The invention defines a method that provides and enables complete configurability of application services in a manner which allows the pluggability of any underlying source of configuration data (*e.g.*, configuration data in XML files, databases, on remote servers, etc). The invention also defines a method by which configuration data may be loaded, transparent to the application, from one or more configuration data sources in both a static fashion (*i.e.*, at application startup) or dynamically (*i.e.*, as the application is running). The invention combines these generic application configuration services with a robotics and/or automation platform to provide this ability to robotics and automation applications.

[021] The invention also defines an approach for automatic assembly and construction of applications based on configuration data. The invention additionally defines an approach for automatic deployment of applications in a distributed fashion and provides a means for managing the lifecycle (*e.g.*, start, stop, and shutdown) of applications either within a process or via a distributed fashion based on configuration data. By providing a completely configurable means for such services, the invention provides a methodology which lends itself to automating the process of application configuration, assembly, construction, deployment, and management. The invention combines these generic application services with a robotics and automation platform

to provide this ability to robotics and automation applications in a manner which is needed but not addressed by currently available technologies.

[022] Such an approach also reduces development time for robotics and automation application developers. By using the present invention, developers can focus on writing any custom robotics or automation business logic and leave the rest of the implementation process to the operating system of the invention (referred to herein at times as "GPROS") as a robotics and automation engine and toolkit for rapid application development. Because the invention provides a completely configurable robotics and automation engine, the invention lends itself to automating the process of robotics and automation configuration, assembly, construction, deployment, and development by use of tools.

[023] In addition to a core set of common services built into the GPROS, the invention also provides a method for complete pluggability of third party, proprietary, open source, open standard, custom, or otherwise extensions (*i.e.*, "plug and play" ability). That is, means for plugging in any underlying configuration data source medium (*e.g.*, XML files, database data), any application object to be loaded, any underlying distributed communications medium (*e.g.*, Web services, CORBA), any external peripheral source (*e.g.*, a display, a printer), any external communications interface type (*e.g.*, serial port, USB port), any application thread control mechanism (*e.g.*, synchronous thread, asynchronous thread), any type of data or message format (*e.g.*, NMEA format, proprietary message format), any type of logging mechanism (*e.g.*, log to database, third-party logger), any type of system timer, any type of test package, any type of sensor (*e.g.*, GPS sensor), any type of actuator (*e.g.*, a DC motor), any type of motor or PWM control approach, any type of mechanical or gear configuration (*e.g.*, DC motor gears, differential gears), any type of mobility platform configuration (*e.g.*, wheeled mobility, legged mobility), any type of reference or GPS sensor, any type of range sensor, any type or LADAR or RADAR sensor, any type of feedback control approach (*e.g.*, quadrature encoding), any type of analog or digital I/O approach, any type of application conduct or behavioral logic, any type or robot planning logic, any type of rules engine approach (*e.g.*, a third-party rule engine), any

type of neural network approach (e.g., a third-party neural network), any type of obstacle classification, any type of obstacle detection approach, any type of obstacle resolution approach, any type of sensor fusion approach, etc. The GPROS hence provides a completely extensible platform enabling plug-and-play of extensions from third party, proprietary, open source, open standard, custom, or other sources. As stated, the GPROS also provides a set of built-in generic and specific services approaches for all of the above.

[024] The technology provided by the present invention thus allows for greater ease of communication, both static and dynamic, between components within the same robotics application, between robot and other robotic agents equipped with the same open platform (operating system upon which the software exists), as well as between human and robotic agents. Of the many features of the invention, one advantageous feature of this invention is its particular approach to complete configurability, componetization, and encapsulation of those services that are commonly useful to any type of robotics and automation application using the combination of a variety of proprietary services, allowing a robotics and automation application to be defined, assembled, deployed, and managed in a completely configurable and pluggable fashion. It is also dynamically reconfigurable and lends itself to use of tools for automating a robotics and automation application development and deployment process itself. Configuration data can be read or sent over a variety of network connections, and the code itself can be read or sent over a network, such that the initial code requires no additional customization. If multiple robots on a network include the present invention, new configuration and code (and hence, behavior) can all be dynamically, and optionally simultaneously, loaded into any robot on the network. Moreover, such an invention lends itself to use of tools for the automated configuration, assembly, and deployment of robotics applications and hence dramatically reducing the time it takes to develop and deploy robotics applications.

[025] The GPROS provides services common to any robotics and automation application. A set of robotics and automation specific services that may be commonly

leveraged by any robotics and automation application are provided by GPROS. A set of general software application services that may be commonly leveraged by software application are also provided by GPROS. These general software application services are extended and used by the robotics and automation application specific services in a combined fashion within GPROS.

[026] A VRAF extension of GPROS provides services common to a specific vertical robotics and automation application domain. A set of robotics and automation services specific to a particular vertical application domain (*e.g.*, UGVs, UAVs) that may be commonly leveraged by any robotics and automation application in a vertical application domain are provided by a VRAF. The GPROS services are extended and used by VRAF services in a combined fashion.

[027] The GPROS is not limited to software or firmware that runs onboard a robot. It may encapsulate common robotics software services that also runs inside of a centralized robot system planning tool or inside of a robot monitoring and control device.

[028] Thus, the current invention makes use of open standards to facilitate the creation of a general purpose software platform for use in both robotic- and non-robot-specific applications. The present invention can provide applications that can be created for broad use in robotics without low-level customization for any particular proprietary robot. This technology allows for greater ease of communication, both static and dynamic, between human and robotic agents, as well as between robot and other robotic agents equipped with the same open platform (operating system upon which the software exists). As noted above, some development of hardware transparency for robotics control exists and has been included in earlier inventions. However, among other things, one uniqueness of the present invention is in its particular approach to complete configurability using the combination of a variety of proprietary services, allowing a robot application to be defined in a completely configurable fashion. In yet another example of the advantages provided by the present invention is its dynamic reconfigurability (in the present invention, this dynamic reconfiguration capability is described and labeled as "envoy").

Configuration data can be read or sent over a variety of network connections, and the code itself can be read or sent over a network, such that the initial code requires no additional customization. Embodiments of the invention advantageously isolate the robotic software from the robotic hardware, such that the abstraction of the robot can be performed without full knowledge of the actual robot configuration. If multiple bots on a network include the present invention, new configuration and code (and hence, behavior) can all be dynamically, and optionally simultaneously, loaded into any bot on the network.

[029] The present invention provides a method and apparatus for a general purpose robotics operating system (GPROS). Thus, it provides a general purpose operating system, which has, in embodiments, applicability to robotics. This platform makes use of open standards to facilitate the creation of non-robot-specific and robot-specific applications such that the applications can be created for broad use, such as in robotics, without low-level customization for any particular proprietary robot.

[030] As mentioned above, the technology provided by the present invention allows for greater ease of communication, both static and dynamic, between human and robotic agents, as well as between robot and other robotic agents equipped with the same open platform. Units comprising the GPROS of the present invention are equipped with a combination of neural network/rules engine technologies that allows one or more equipped robots in a simultaneous or individual mode to adapt rapidly to new environments and tasks and to communicate such learned information to other units running the GPROS. Open-source and standard or proprietary technologies, such as, but not limited to Java, C+, C++, C#, .NET, and Ruby, can be the basis through which the robot-specific mechanics, sensors, and actuators are generalized so that inter-GPROS communication can occur regardless of the robot-specific technology underneath. Java and other programming languages have APIs enabling use of the eXtensible Markup Language (XML) as a data representation format and has built-in support for standard distributed communication technologies such as TCP/IP, HTTP, CORBA, SOAP, and Web services. Given the flexibility of the GPROS platform, robots can be produced in different profile standards, depending on

the needs of the end-user. As such, a GPROS unit could be essentially any size (as small as a beetle or as large as an elephant).

[031] According to the invention, such technologies are integrated and used to create a generic platform for low cost mobile autonomous robotic applications, as well as other applications. Such an open generic platform in effect standardizes and commoditizes the operational infrastructure for mobile autonomous robots and thus lowers the cost points for hardware vendors to supply underlying mechanics, sensors, and actuators to be driven by such a platform. It also dramatically lowers the cost points for specific vertical robotic applications to be deployed atop such a platform. The cost savings, for example, include lower the costs associated with control of proprietary robotic applications with proprietary software by using the generic features associated with the present invention.

[032] GPROS technology makes use of neural networks and rules engine technology to advance the current potential for autonomous mobile robotic applications, especially in terms of localization and mapping. Rather than traditional algorithm-based techniques, which are limited and far removed from natural human thinking, rules engine technology can use proximity and location data, sensor data, navigation rules defined offline by humans, and newly defined navigation rules defined online by humans to determine what movement planning actions should be undertaken. Furthermore, rules learned or conditions acquired by other robots may also be broadcast to cooperating robots in the vicinity to enhance the movement and navigational plan for the robot.

[033] As mentioned above, the GPROS is not limited to software or firmware that runs onboard a robot. It is to be understood that, although the detailed description of the invention focuses on a preferred embodiment, as the invention relates to robots, the invention is not so limited. Rather, it includes all applications of the general purpose platform provided by the invention. For example, it may encapsulate common robotics software services that also runs inside of a centralized robot system planning tool or inside of a robot monitoring and control device.

[034] In view of the features noted above, in a first aspect, the invention provides computer software. The software of the invention is a general purpose operating system that can be implemented in computers and networks of computers used in any field, but which finds particular usefulness in the robotics and automation fields. The software, also referred to herein as GPROS, provides an operating system or platform comprising services common for all applications designed to run in a computer-driven environment. In preferred embodiments, it provides a platform comprising services common for all applications in a robotics or automation environment, and provides for integration of any and all services extensions for robotics and automation. The software allows programmers to develop software solutions for particular needs, in any language, and implement those solutions into a functional product through integration of the solution with the software of the present invention. Integration is enabled by the present software, providing ease of use and highly effective and efficient adaptability for all solutions engineered for all needs. The present software, unlike robotics software solutions currently provided in the art, is not monolithic and designed to address a single need or solve a single problem by providing an ability to integrate a single service or service extension. Rather, it is capable of accommodating any and all service extensions to create a fully integrated and adaptable software solution to relatively simple to complex needs. Its ability to provide a plethora of services and to accommodate numerous different service extensions, modules, etc. makes it a powerful tool, which has immediate and apparent applicability to the robotics and automation fields. For example, it provides a robust platform for implementation of software solutions, and for effecting software-hardware implementations, in the automation field, such as a sensor package. As another example, the invention was used to rapidly develop a robotic Unmanned Ground Vehicle (UGV) application, which was tested at the October 2005 DARPA Grand Challenge (an historic event offering a prize to the team that could build an autonomous vehicle to race over 125 miles through the Mojave desert avoiding obstacles along the way). The DARPA Grand Challenge was established to address drawbacks in the prior art and to push the envelope of technology for autonomous

robotic vehicles since no such feat had ever before been achievable and had previously been considered impossible prior to October 2005. The invention's embodiment in such a project demonstrated its utility and novelty for rapidly and affordably building highly complex robotics applications and in addressing drawbacks of the prior art.

[035] The software of the invention is completely configurable, and can be adapted both statically and dynamically. This feature provides numerous advantages, particularly in autonomous robotics applications and in applications where numerous individual and independent units are integrated into an overall functional group, such as might be desirable or necessary when implementing a robot solution for military purposes (*e.g.*, a fleet of airborne drones for reconnaissance, a ground-based search and destroy unit). Furthermore, unlike software currently available, the software of the present invention enables automatic assembly and development of robotics and automation applications, and provides the ability to automatically manage the life cycle of one or more applications in a robotics or automation environment. The ability to plug in a wide variety of third-party services (*e.g.*, loggers, rule engines, communication mechanisms) provides an advantage not available from current technologies in the robotics and automation fields.

[036] Due to its power and adaptability, the software of the present invention can be a tool for programmers. Indeed, one key feature of the present software is its usefulness to programmers in developing software and/or software-hardware combination solutions to problems, particularly problems in the robotics and automation fields. By providing a standardized platform for communications between software applications and the hardware those applications are designed to control, the present software provides a convenient, stable, adaptable, and reliable basis for programmers in all fields with all types of backgrounds, needs, and skill levels to develop solutions.

[037] The software of the invention, in embodiments, provides a combination of services that are common to any or all general applications, and to any or all robotics or automation applications. It can provide these independently of each other or as a

combination. Of course, the general software (GPROS), as a stand-alone platform, may be combined with applications that are specific for other fields (other than robotics and automation) to provide powerful solutions in those fields. Exemplary services that can be included in the software of the invention are discussed below. The software of the present invention may include some or all of those services, as well as other services that are not mentioned. As a general matter, the software of the invention is launched to read data from one or more configuration data sources stored in any sort of underlying configuration storage medium. The configuration services are used in conjunction with an object registration service to automatically create, configure, assemble, deploy, launch, and manage any application objects defined in the configuration. For the integrated robotics and automation application of such general services, generic robotics and automation objects inherent to the invention are loaded and provide a general purpose platform for robotics and automation applications. Either built-in, generically configurable, or add-on extensions for encapsulating sensor, actuator, and behavioral conduct are loaded, assembled, linked-in, and managed by the robotics and automation platform. During online operations, data is read from sensors synchronously or asynchronously, behavioral conduct is executed, and actuators are able to be commanded or controlled to actuate. Various configurations and extensions to the sensor, actuator, and conduct services are either built-in or pluggable to enable integration of a cohesive and comprehensive robotics and automation application. All such services may be incorporated either locally within a process or in a distributed and remote fashion using any sort of pluggable underlying communications medium. In such a way, a robotics and automation application hosted atop of such a platform is automatically configured, assembled, deployed, and managed.

[038] In another aspect, the invention provides a method of using the computer software. In general, the method comprises running the software on a computer to achieve a desired goal. For example, it can comprise running the software to autonomously control a robot. It also can comprise running the software to automate a repetitive action or to control a piece of hardware, such as a sensor. Of course, the

method can comprise running the software on multiple computers or micro-controllers that are linked in a network. In such a situation, some of the software can be resident on one computer or micro-controller while other of the software is resident on one or more different computers or micro-controllers. Thus, the method of the invention can be a method of controlling two or more pieces of hardware, such as two or more robots. Due to the power of the software of the invention, the method can comprise autonomously controlling two or more pieces of hardware, where two or more of the pieces of hardware are performing different functions at any one time. For example, the method can permit multiple robots to function as a unit, in which one robot performs one task while, at the same time, another robot performs another task (*e.g.*, one robot performs surveillance of a road in front of a building while another robot performs surveillance of the interior of the building).

[039] In embodiments, the method also comprises installing some or all of the software onto a storage medium or piece of hardware. For example, it can comprise loading the software, completely or partially, into the RAM of a computer, or installing the software, either completely or partially, onto a permanent storage device of a computer, such as on a hard drive of the computer. In addition, the method can comprise other steps that are commonly executed by users or computers when running software, such as moving information from storage media to memory, creating and deleting temporary files, and the like.

[040] Various optional additional method steps are discussed below in the context of the figures. According to the present invention, one, some, or all of the functions described below can be performed as part of the method of the invention, to provide the various actions described for each. It is well within the skill level of those of skill in the art to select among the various functions to achieve an end-product and a method that achieves a particular goal.

[041] The methods for using the invention include use of the GPROS to configure and build a robotics application that senses data from the environment, formulates some plan of behavior analysis and action, and actuates some actuators in response. The invention may be used inside of a robotics platform, inside of a

platform to locally or remotely control a robot, or inside of a more centralized system that controls one or more robots either locally or remotely. The invention may also be used in automation applications where local or distributed sensing is all that is needed or perhaps sensing coupled with some behavioral conduct to, for example, display the fused result of multiple sensor sources. Robotics and automation applications that also require actuation with or without use of sensors and with or without use of behavioral conduct are also methods of using the invention. The invention may also be used for not only building a robotics or automation application but in building simulations of a robotics or automation applications. The invention may also be used to build a vertical robotics and automation framework atop of the invention which provides additional common services specific to a vertical application domain enabling the combination of such services to be used in an end user robotics and automation application. The invention may also be used to provide extensions for general purpose or specific robotics and automation applications which provides additional robotics and automation services enabling the combination of such services to be used in an end user robotics and automation application. The invention may also be used to provide extensions for general purpose or specific applications which provides services enabling the combination of such services to be used in an application.

[042] In embodiments, the method is a method of programming. In these embodiments, the software of the invention can be run alone or in conjunction with additional software applications, services extensions, modules, etc. (*i.e.*, plug-ins), which may be created separately by a programmer. The additional plug-ins can be any software in any language, and may specify a single function or action, or may specify multiple functions or actions. For example, it may be software for running one or more optical sensors automatically. Alternatively, for example, it may be software for running one or more optical sensors automatically and for running one or more steering motors automatically. Where the method comprises running one or more plug-ins, the method can be used to determine if the plug-in software functions as desired. Thus, the method may be a method of debugging a software application.

[043] In a further aspect, the invention provides a system. As used herein, a system is a combination of the computer software and use of the software to achieve a particular goal. Thus, according to the present invention, a system can be a general purpose operating system for automation and/or robotics, and a method of using it to autonomously control a device, such as a robot.

[044] In general, the invention provides a general purpose operating system, such as a general purpose robotics operating system (GPROS). The system typically comprises: a set of application services that provides access to configuration data using a generic abstraction, such that the access is independent of any underlying hardware platform (*i.e.*, software according to the invention); and implementation of the software to achieve a desired goal. In the context of the system of the invention, the hardware platform mentioned is one that allows for any combination of communication or operational conduct for any communication or operational task. The goal can be any goal envisioned by a user. In exemplary embodiments, the goal is an automated action of a robot or other piece of hardware in the automation environment.

[045] Within the framework provided above for the software and system, many different optional embodiments can be envisioned. Numerous such embodiments are listed in the following paragraphs; however, it is to be understood that many more embodiments are encompassed by the present software and systems, and the following list is not intended as an exhaustive listing of all possible embodiments. Various non-limiting embodiments, which can be implemented in conjunction with the software and system of the invention alone or in combination with one or more other embodiments, include: a service that utilizes the generic abstraction to allow configuration data to be stored across different sources (also referred to herein as a config service); a service that includes the generic abstraction to create objects in a dedicated, shared, or pooled fashion (also referred to herein as a registry service); a service that utilizes the generic abstraction to link one or several peripherals to one or several interfaces (also referred to herein as a comm service); a service that includes a generic abstraction to create, manage, and terminate synchronous, asynchronous, and

real time application threads (also referred to herein as an ap service); a service that utilizes a generic abstraction to allow client code to communicate with a remote server via a client-side envoy (also referred to herein as an envoy service); and a service that utilizes a generic abstraction to allow for interacting with and managing peripherals external to any hardware system (also referred to herein as a peripheral service).

[046] Additional non-limiting embodiments include: a GPROS comprising a set of robotic application services that provides access to configuration data by using a generic abstraction, wherein the access is independent of any underlying robotics platform, and wherein the robotics platform allows for any combination of communication or operational conduct for any communication or operational task; a service that utilizes a generic abstraction for sensors (also referred to herein as sensors service); a service that provides base abstractions for range-type sensing (also referred to herein as range service); a service that provides base abstractions for laser radar (LADAR) (also referred to herein as ladar service); a service that provides base abstractions for dealing with LADAR-type range sensing using the SICK LMS product (also referred to herein as ladar sick service); a service that provides base abstractions for radar-type range sensing (also referred to herein as radar service); and a service that provides base abstractions for dealing with radar-type range sensing using the vorad vbox radar product (also referred to herein as radar vorad service). Other non-limiting embodiments include: a service that provides base abstractions for sensing reference points including position and orientation (also referred to herein as reference service); a service that provides base abstractions for dealing with geographic reference positioning and orientation (also referred to herein as reference geo service); a service that provides abstractions that deal with parsing and interpreting GPS-type information in the NMEA format (also referred to herein as reference nmea service); a service that utilizes a generic abstraction for operations for control of mechanical hardware (also referred to herein as mechanism, gear service); a service that utilizes a generic abstraction for actuators (also referred to herein as actuator service); a service that provides abstractions for motors in a system (also referred to herein as motor service); and a service that utilizes timer capabilities to

provide a set of abstractions for actuating motors using pulse-width-modulated (PWM) method (also referred to herein as timer, pwm service). Further non-limiting exemplary embodiments include: a service that utilizes a generic abstraction for modeling robotic conduct (also referred to herein as conduct service); a service that utilizes a generic abstraction for mobilizing robotic conduct (also referred to herein as mobility service); a service that utilizes a wheeled platform; a service that utilizes a legged platform; a service that utilizes a tracked platform; a service that utilizes flight operations, including helicopter operations; and a service that utilizes a generic abstraction for navigation. In various non-limiting embodiments, abstractions are provided for encapsulating a route and course over which a robot travels, planning navigation of a robot, and encapsulating route planning based on map data (also referred to herein as navigation service). In yet further non-limiting embodiments, the invention provides a service that utilizes generic abstractions to determine and standardize behavior of a group of robots, and optionally also utilizes generic abstractions for behavioral initialization and termination for said robots (also referred to herein as robot god service); a service that utilizes rules engines or neural networks for encapsulating rules of behavior (also referred to herein as rules, neural service).

[047] Other additional non-limiting embodiments provide a GPROS comprising: a set of application services that provides access to configuration data using a generic abstraction, such that the access is independent of any underlying robotics platform, and wherein the robotics platform allows for any combination of communication or operational conduct for any communication or operational task; a service that utilizes the generic abstraction to allow configuration data to be stored across different sources (also referred to herein as config service); a service that utilizes said generic abstraction to create objects in a dedicated, shared, or pooled fashion (also referred to herein as registry service); a service that utilizes the generic abstraction to link one or several peripherals to one or several interfaces (also referred to herein as comm service); a service that utilizes a generic abstraction to create and terminate synchronous, asynchronous, and real time application threads (also referred to herein as ap service); a service that utilizes a generic abstraction to allow client code to

communicate with a remote server via a client-side envoy (also referred to herein as envoy service); and a service that utilizes a generic abstraction to allow for interacting with and managing peripherals external to any hardware system (also referred to herein as peripheral service).

[048] In yet another aspect, the invention provides a device comprising the software of the invention. In general, the device is any piece or combination of pieces of computer hardware that can comprise the software of the invention. Thus, the device may be a circuit board comprising the instruction set of the software of the invention. Likewise, the device may be a central processing unit (CPU) comprising the software of the invention, or a motherboard comprising the software, either on the board itself or as part of the board due to connection of the board with another piece of hardware (*e.g.*, a CPU or peripheral board). Furthermore, the device may be random access memory (RAM) or another type of hardware for ephemeral storage of some or all of the software of the invention. In some embodiments, the device comprises two or more components, which together contain the software of the invention (*e.g.*, two or more banks of RAM; a CPU and a co-processor, etc.). Many such computer components are known in the art, and the device of the present invention may be fabricated in the form of any of those. The device may be a single, separate unit, such as a CPU or circuit board that can be packaged and sold for use in larger automation or robotics devices, or it may be a component of a larger unit, such as an automated or robotic device. The device may also be one that has one or more moving parts, such as would be seen in autonomously controlled units that can move in one way or another to achieve a physical task.

[049] In embodiments, the device is capable of executing the software of the present invention to achieve a desired goal. In other embodiments, the device is capable of comprising the software, but can execute the instructions of the software only when the device is functionally connected to one or more other devices or one or more pieces of hardware, such as other components of a computer, a micro-controller, a robot, an automated device, or an autonomously controlled device.

[050] Accordingly, in one aspect, the present invention provides an article of manufacture comprising the software of the invention. For example, in embodiments, the article of manufacture is a storage medium comprising the software of the invention. The article of manufacture can be any of the various articles known in the computer art as useful for storing, either permanently or ephemerally, computer programs or software. It can be a removable storage medium, such as a disk (*e.g.*, CD, floppy disk, memory stick, flash memory disk, flash memory disk) or a non-removable storage medium (*e.g.*, hard drive, tape). It can also be a medium accessed directly, remotely accessed, or downloaded from another computer (*e.g.* the Web, client-server, peer-to-peer). In general, the storage medium can be any known storage medium, such as those based on optical storage of data and those based on magnetic storage of data.

[051] In another aspect, the invention provides an autonomously controlled device. By autonomously controlled, it is meant that the device is capable of controlling one or more actions of itself, either a single time or repeatedly, without or with limited human intervention. That is, an autonomously controlled device comprises, either intrinsically or in conjunction with another device, sufficient computer software and mechanical elements to carry out one or more actions, without or with limited intervention of a human controller. In embodiments, the autonomously controlled device is provided as a completed unit that is programmed and fabricated to function without further modification of software or hardware (except to replace worn or broken parts). In other embodiments, the autonomously controlled device is provided with software and hardware that is sufficient to achieve a pre-defined goal, but that is also designed to be updated with new software or hardware to adapt to changing conditions or goals. For example, a device that is designed not to be updated can be an automated device for sensing movement in a defined area and generating an alert or other detectable signal, or causing some other action, in response to detection of movement in the area. Because the area does not change over time and the pre-selected alert or other action is adequate to achieve the goal of surveillance and detection, there is no need to update the device. In contrast,

an exemplary device that is designed to be updated can be an autonomous unit that is capable of movement over various terrain, such as an unmanned ground vehicle (UGV), or through the air, such as an unmanned air vehicle (UAV). Such vehicles can be reprogrammed or have their software updated, either as a periodic re-load or as a continuous or semi-continuous updating, or "learning" as new environments are encountered or as new units are added as part of a larger force that is intended to act in a coordinated fashion to achieve a goal, such as search or reconnaissance.

[052] One type of autonomously controlled device is a robot. As mentioned above, numerous types of robots are now known or proposed. Any such robot is included within the scope of this invention, including, but not limited to, stationary robots and mobile robots. Among the stationary robots, exemplary ones are those that function without movement to achieve a task (*e.g.*, by detection of movement or sound), and among the mobile robots are those that function, at least in part, with movement to achieve a task (*e.g.*, automated devices for building other machines or devices, such as automobiles, UGV, and UAV). Exemplary robots thus include those for household applications, such as vacuums and security devices; those for industrial applications, such as those used in making motorized vehicles, and those for stocking, retrieving, and maintaining retail inventories; and those for military applications, such as UGV and UAV. Other examples of robots and autonomous units include entertainment robots and toys, sports playing robots, fire extinguishing robots, robotic lawn mowers, robotic farming equipment, robotic and moving cameras, robotic vehicles in factories, robotic vehicles for planetary exploration, robotic vehicles for hospital supply and mail delivery, unmanned air vehicles, unmanned underwater vehicles, unmanned sea vehicles, unmanned ground vehicles, articulated robotic building structures, bulk measurement scanning applications, automatic identification applications, classification and scanning applications, mine analysis and detection robots, among others.

[053] The autonomously controlled devices of the invention comprise hardware (including both computer hardware and other mechanical components for structure and movement) and software. The software is any software that can contain

instructions for autonomously controlling the device, such as described elsewhere in this document. It can be written in any programming language and implemented in any type of computer hardware/software combination. Connections for hardware components running the software, and for the software itself, can be any connections known in the art as useful for implementing software. For example, connections that allow the software to load, execute, or communicate with devices or other software can be by way of electrical connections (*e.g.*, wiring) or any type of electromagnetic radiation (*e.g.*, sound, light/optical, infrared, microwave, radio wave). Furthermore, the hardware for the structural components of the autonomously controlled devices may be any suitable hardware, fabricated from any suitable material, that is capable of achieving the pre-defined goal of the device. Thus, hardware and mechanical components may be fabricated from any combination of metals (*e.g.*, iron, steel, aluminum, tin), plastics or other polymeric materials, glass, fiberglass, and the like. The hardware and mechanical components may be connected to each other, including parts comprising software, through any suitable connectors, fasteners, etc., such as, but not limited to, bolts, screws, rivets, wires, rods, hook-and-loop fasteners, adhesives, welds, magnetization, and friction fits.

[054] In yet a further aspect, the invention provides a method of controlling an autonomously controlled device. In general, the method comprises providing a set of instructions in the form of computer software that is functionally connected to the device; and executing the software to effect desired action by the device. By "functionally connected" it is meant that the software, when executed either completely or partially, causes one or more piece of the hardware or mechanical components to perform a task. For example, software that is functionally connected to a wheeled vehicle can receive information from a sensor (*e.g.*, optical information indicating an obstacle is in front of the vehicle) and cause a motor within a steering mechanism of the device to engage, resulting in turning of the front wheels of the device to avoid the obstacle detected by the sensor.

[055] Because the invention provides a general purpose platform and rich suite of services for which any type of robotics and automation application may be built,

some of the services and built-in features of the invention may not always be used in every application scenario. Thus, for example, while the ability to configure one or more sensors, one or more behavioral conduct operations, and one or more actuators is provided by the invention, one use of the invention may be to employ the invention for distributed sensing applications wherein no actuators are used even though the invention provides such a capability. Furthermore, various built-in and configuration properties are provided by the invention but not all such built-in features or configuration properties may be utilized in an actual system that incorporates the invention.

[056] In embodiments, the method further comprises modifying the software. For example, it can comprise updating the software to include new services. It likewise can comprise adding drivers or other applications to the software to provide specific functionalities for particular pieces of hardware of the device or for particular pieces of software to integrate. For example, it can comprise installing a software application for controlling a steering mechanism or for controlling a rotatable optical sensor. Modifying the software can also include installing updates to modify the functioning of the software as new or additional independent devices are provided, such as when the device is converted from a single unit to a member of a multi-unit force, as might often occur in military applications.

[057] Providing of the software can occur prior to fabrication of the device, during fabrication of the device, or after fabrication of the device. Likewise, modifying the software can occur before, during, or after fabrication of the device. Thus, modifying the software may be accomplished by physical connection of one or more computers capable of modifying the software to the device, or from a distance, such as by way of transmission of updates via radio signals to the device. Similarly, hardware or mechanical components of the device may be modified, repaired, replaced, added, or removed at any time during fabrication and use of the device. Changes to the software and hardware may be made independently of each other, but are often made at the same time.

[058] According to this method of the invention, the desired action by the device can be any action. Thus, although the action is often physical movement of one or more parts of the device, it need not be so. Rather, the desired action may be physical movement or simply processing of information received from one or more sensors. In such a situation, the action may further comprise communicating the sensor information, or processed information from that sensor information, to one or more computers, which can be located in close proximity or at a distance. Accordingly, the action can comprise receiving sensor information and forwarding that information to another processor for processing and decision-making. The action also may comprise receiving information or instructions from a processor outside of the device, and causing an action to occur based on that information. For example, a robot may include the software of the invention, an optical sensor, and software for specifically controlling the optical sensor. The optical sensor may detect movement in a building and send that information to the software of the invention. The software may then forward that information to a control center hundreds of meters or kilometers away. A computer at the control center, which may be controlling multiple similar units, may send instructions back for the robot to proceed into the building. The software of the invention would receive those instructions and cause the robot to move into the building.

[059] The software of the invention may also be used in simulation or development environments. That is, extensions of the software may be used to integrate the software into other software packages for simulating or developing robotics and automation applications. For example, extensions of the invention may provide software that simulates sensor information and environment reactions to actuators. The invention may be used in such an environment for simulation of robotics and automation applications. As another example, the invention may be used inside of or in conjunction with a development environment used to build robotics and automation applications.

[060] In another aspect, the invention provides a method for using a general purpose robotics operating system (GPROS). In this method, the method comprises:

providing a set of application services for accessing configuration data using a generic abstraction, such that the accessing is independent of any underlying hardware platform that is capable of performing any communication or operational conduct for any communication or operational task. Preferably, the method further comprises executing one or more of the application services. In embodiments, the method further comprises one or more of the following steps (in any order): utilizing the generic abstraction to allow configuration data to be stored across different sources (also referred to herein as the config service); utilizing the generic abstraction to create objects in a dedicated, shared, or pooled fashion (also referred to herein as registry service); utilizing the generic abstraction to link one or several peripherals to one or several interfaces (also referred to herein as comm service); utilizing a generic abstraction to create and terminate synchronous, asynchronous, and real time application threads (also referred to herein as ap service); utilizing a generic abstraction to allow client code to communicate with a remote server via a client-side envoy (also referred to herein as envoy service); utilizing a generic abstraction to allow for interacting with and managing peripherals external to any hardware system (also referred to herein as peripheral service). This aspect is also a method for using a general purpose robotics operating system (GPROS), wherein the method comprises: providing a set of robotics application services to access configuration data using a generic abstraction, such that the accessing is independent of any underlying hardware platform that is capable of performing any communication or operational conduct for any communication or operational task. In embodiments, the method further comprises: utilizing a generic abstraction for sensors (also referred to herein as sensors service); providing base abstractions for range-type sensing (also referred to herein as range service); providing base abstractions for laser radar (LADAR) (also referred to herein as ladar service); providing base abstractions for dealing with LADAR-type range sensing using the SICK LMS product (also referred to herein as ladar sick service); providing base abstractions for radar-type range sensing (also referred to herein as radar service); providing base abstractions for radar-type range sensing using the vorad vbox radar product (also referred to herein as radar vorad

service); providing base abstractions for sensing reference points including position and orientation (also referred to herein as reference service); providing base abstractions for geographic reference positioning and orientation (also referred to herein as reference geo service); providing abstractions that deal with parsing and interpreting GPS-type information in the NMEA format (also referred to herein as reference nmea service); utilizing a generic abstraction for operations to control mechanical hardware (also referred to herein as mechanism, gear service); utilizing a generic abstraction for actuators (also referred to herein as actuator service); providing abstractions for motors in a system (also referred to herein as motor service); utilizing timer capabilities, thereby providing a set of abstractions for actuating motors using pulse-width-modulated (PWM) method (also referred to herein as timer, pwm service); utilizing a generic abstraction to model robotic conduct (also referred to herein as conduct service); utilizing a generic abstraction to mobilize robotic conduct (also referred to herein as mobility service); utilizing a wheeled platform; utilizing a legged platform; utilizing a tracked platform; utilizing flight operations, including helicopter operations; utilizing a generic abstraction for navigation, thereby providing abstractions for encapsulating a route and course over which a robot travels; planning the navigation of a robot; and encapsulating route planning based on map data. The method may also comprise utilizing generic abstractions to determine and standardize the behavior of a group of robots, and initialize and terminate their behaviors; and utilizing rules engines or neural networks to encapsulate rules of behavior (also referred to herein as rules, neural service).

[061] In another aspect, the invention provides a system for using a general purpose robotics operating system (GPROS), where the system comprises: providing a set of application services for accessing configuration data using a generic abstraction, such that the access is independent of any underlying hardware platform that is capable of performing any communication or operational conduct for any communication or operational task. Preferably, the system further comprises executing the set of application services, or a subset thereof, to achieve a pre-defined goal. In embodiments, the system further comprises: utilizing the generic abstraction

to allow configuration data to be stored across different sources (also referred to herein as the config service); including the generic abstraction to create objects in a dedicated, shared, or pooled fashion (also referred to herein as registry service); utilizing the generic abstraction to link one or several peripherals to one or several interfaces (also referred to herein as comm service); including a generic abstraction to create and terminate synchronous, asynchronous, and real time application threads (also referred to herein as ap service); utilizing a generic abstraction to allow client code to communicate with a remote server via a client-side envoy (also referred to herein as envoy service); utilizing a generic abstraction to allow for interacting with and managing peripherals external to any hardware system (also referred to herein as peripheral service). In yet other embodiments, this invention provides a system for using a general purpose robotics operating system (GPROS), where the system comprises: providing a set of application services for accessing configuration data using a generic abstraction, such that the access is independent of any underlying hardware platform that is capable of performing any communication or operational conduct for any communication or operational task. Preferably, the system further comprises executing some or all of the application services. In some embodiments, the method further comprises: utilizing a generic abstraction for sensors (also referred to herein as sensors service); providing base abstractions for dealing with range-type sensing (also referred to herein as range service); providing base abstractions for laser radar (LADAR) (also referred to herein as ladar service); providing base abstractions for LADAR-type range sensing using the SICK LMS product (also referred to herein as ladar sick service); providing base abstractions for radar-type range sensing (also referred to herein as radar service); providing base abstractions for radar-type range sensing using the vorad vbox radar product (also referred to herein as radar vorad service); providing base abstractions for sensing reference points including position and orientation (also referred to herein as reference service); providing base abstractions for geographic reference positioning and orientation (also referred to herein as reference geo service); providing abstractions for parsing and interpreting GPS-type information in the NMEA format (also referred to herein as reference nmea

service); utilizing a generic abstraction for controlling mechanical hardware (also referred to herein as mechanism, gear service); utilizing a generic abstraction for actuators (also referred to herein as actuator service); providing abstractions for motors in a system (also referred to herein as motor service); utilizing timer capabilities, thereby providing a set of abstractions for actuating motors using pulse-width-modulated (PWM) method (also referred to herein as timer, pwm service); utilizing a generic abstraction for modeling robotic conduct (also referred to herein as conduct service); utilizing a generic abstraction for mobilizing robotic conduct (also referred to herein as mobility service); utilizing a wheeled platform; utilizing a legged platform; utilizing a tracked platform; utilizing flight operations, including helicopter operations; utilizing a generic abstraction for navigation, thereby providing abstractions for encapsulating a route and course over which a robot travels; planning the navigation of a robot; encapsulating route planning based on map data; utilizing generic abstractions to determine and standardize the behavior of a group of robots, and initialize and terminate their behaviors; and utilizing rules engines or neural networks for encapsulating rules of behavior (also referred to herein as rules, neural service).

BRIEF DESCRIPTION OF THE DRAWINGS

[062] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate several embodiments of the invention and together with the written description, serve to explain various principles and details of embodiments of the invention.

[063] FIG. 1 is a UML class/concept diagram that illustrates the General Purpose Robotics Operating System (GPROS) Context.

[064] FIG. 2 is a UML class/concept diagram that illustrates a computing platform.

[065] FIG. 3 is a UML class/concept diagram that illustrates the layout of actual robotics hardware.

- [066] FIG. 4 is a UML class/concept diagram that illustrates general robotics applicability.
- [067] FIG. 5 is a UML class/concept diagram that illustrates the ID service.
- [068] FIG. 6 is a UML class/concept diagram that illustrates the ANY service.
- [069] FIG. 7 is a UML class/concept diagram that illustrates the AUTOMATON service.
- [070] FIG. 8 is a UML class/concept diagram that illustrates the LOG service.
- [071] FIG. 9 is a UML class/concept diagram that illustrates the CONFIG service.
- [072] FIG. 10 is a UML class/concept diagram that illustrates the ENVOY service.
- [073] FIG. 11 is a UML class/concept diagram that illustrates the AP service.
- [074] FIG. 12 is a UML class/concept diagram that illustrates the SYSTEM service.
- [075] FIG. 13 is a UML class/concept diagram that illustrates the SIGNALS service.
- [076] FIG. 14 is a UML class/concept diagram that illustrates the SIGNALS.MESSAGE service.
- [077] FIG. 15 is a UML class/concept diagram that illustrates the COMM service.
- [078] FIG. 16 is a UML class/concept diagram that illustrates the PERIPHERALS service.
- [079] FIG. 17 is a UML class/concept diagram that illustrates the TIMER service.
- [080] FIG. 18 is a UML class/concept diagram that illustrates the SCHEDULE service.
- [081] FIG. 19 is a UML class/concept diagram that illustrates the ROBOT.GOD and ROBOT.UNIVERSE services.

- [082] FIG. 20 is a UML class/concept diagram that illustrates the SENSOR service.
- [083] FIG. 21 is a UML class/concept diagram that illustrates the ACTUATORS service.
- [084] FIG. 22 is a UML class/concept diagram that illustrates the MECHANISM service.
- [085] FIG. 23 is a UML class/concept diagram that illustrates the MOTOR service.
- [086] FIG. 24 is a UML class/concept diagram that illustrates the PWM service.
- [087] FIG. 25 is a UML class/concept diagram that illustrates the CONTROLS service.
- [088] FIG. 26-27 are UML class/concept diagrams that illustrates aspects of the MOBILITY service.
- [089] FIG. 28 is a UML class/concept diagram that illustrates the OBSTACLE service.
- [090] FIG. 29 is a UML class/concept diagram that illustrates the NAVIGATION.COURSE service.
- [091] FIG. 30A is a UML class/concept diagram that illustrates the NAVIGATION.PLANNING service. FIG. 30B is a UML class/concept diagram that illustrates the CONDUCT service and sub-services.
- [092] FIGs. 31-44 are UML sequence diagrams that illustrate various general aspects of the invention.
- [093] FIGs. 45-52 are UML sequence diagrams that illustrate further aspects and embodiments of the ENVOY service aspect of the invention, as depicted in FIG. 10.

DETAILED DESCRIPTION OF VARIOUS
EMBODIMENTS OF THE INVENTION

[094] The invention will now be described with reference to various exemplary embodiments. Although the following detailed description will focus on certain embodiments, the invention should not be considered to be limited to those embodiments.

[095] The following detailed description focuses on the figures, which show various features of the invention. It is to be noted that some or all of these features may be included in the various embodiments of the invention. Those of skill in the art may select which features and combinations of features and hardware and mechanical components to include in a particular embodiment based on the particular uses of the software platform and hardware and mechanical components that are desired. In addition, the following detailed description provides and discusses various UML class/concept diagrams and UML sequence diagrams. It is understood by those of skill in the art that there are many tools commonly available that enable one to generate source code from such diagrams, alone or upon inclusion of non-critical details for implementing the actions depicted in the diagrams, and that the diagrams can be used to generate software in any of the various languages typically used in the art, such as, but not limited to, Java and C++. One non-limiting example of a tool that is available to programmers is the Rational Rose program.

Structural Aspects

[096] FIGs 1-4 present the general context of the invention. The General Purpose Robotics Operating System (GPROS) 100 serves to encapsulate operations and functionality common to all robotics applications. The GPROS runs on top of a computing platform (FIG 2) 200 comprising computing hardware 210 (*e.g.*, a standard micro-processing and/or micro-controller environment), a computing operating system or runtime 220 (*e.g.*, Windows, Linux, Java virtual machine, micro-controller runtime), and additional computing software platform components (*e.g.*, serial port driver, proprietary sensor driver). By use of a computing platform 200, access to

robotics hardware 300 is allowed. Robotics hardware (FIG 3) 300 may comprise robotics sensors 310, actuators 320, and mechanical components 330. Robotics hardware 300 may sometimes be directly connected to existing computing platforms 200 (e.g., via serial ports or USB ports) but may also require additional intermediate computer to robotics hardware interfaces 350 as illustrated in FIG 1. Such a hardware interface may include motor drivers, analog I/O ports, digital I/O ports, and/or real-time and deterministic processing support.

[097] GPROS, as depicted in FIG 1, allows for specific robotics applications 130 to be created. For example, an autonomous unmanned ground vehicle (UGV) application for traversing a long distance within a route corridor while avoiding obstacles may be built on the GPROS, leveraging common robotics software services. The same common GPROS robotics software services may also be leveraged by an autonomous unmanned air vehicle (UAV) application. As shown in FIG 1, additional commonality across specific vertical robotics applications are broken up into frameworks built on top of GPROS 100. These vertical robotics application framework (VRAF) 135 instances extend the GPROS 100 for specific vertical applications. Software services common to a specific vertical application domain are encapsulated within a framework. For example, a UGV framework that resides on GPROS 100 provides for generic use across any type of UGV application.

[098] The GPROS 100 is not limited to software or firmware that runs onboard a robot. It may encapsulate common robotics software services that also run inside a centralized robot system planning tool 410 or inside of a robot monitoring and control device 420. A human 430 will often interact with the robot 400 directly, through a system planner, or through a monitoring and control device. The GPROS 100 may run in any such incarnation and environment. FIG 4 depicts these relations and common inheritance hierarchy.

[099] A set of common services exist within GPROS 100 that provide a rich and generic set of services. These services are defined in a generic fashion and are in fact not limited to robotics and automation applications. They in fact have applicability to

a wide variety of applications. They are defined here, however, because they are heavily leveraged by GPROS and form the basis for many of its features.

[100] The GPROS hence provides services common to any robotics and automation application. A set of robotics and automation specific services that may be commonly leveraged by any robotics and automation application are provided by GPROS. A set of general software application services that may be commonly leveraged by software application are also provided by GPROS. These general software application services are extended and used by the robotics and automation application specific services in a combined fashion within GPROS.

[101] A VRAF extension of GPROS provides services common to a specific vertical robotics and automation application domain. A set of robotics and automation services specific to a particular vertical application domain (e.g., UGVs, UAVs) that may be commonly leveraged by any robotics and automation application in a vertical application domain are provided by a VRAF. The GPROS services are extended and used by VRAF services in a combined fashion.

[102] By using the invention's services, robotics and automation applications inherit complete static and dynamic configurability, configurability using any underlying configuration medium, automateable assembly and construction based on configuration information, automateable deployment based on configuration information, configurable and distributable lifecycle management, configurable ability to plug-in any underlying distributed service communications approach, generic means for handling messages and data, generic means for configuring one or more application peripherals to interoperate with one or more external communication interfaces, generic means for encapsulating behavior, generic means for interfacing with and managing electronics hardware interfaces, and other core services. Provision of all of these services in a combined fashion enables robotics application providers (e.g., developers and tools) to focus on specifying the business logic and configuration data specific to a robotics or automation application. The GPROS engine provides the rest and hence a platform atop of which robotics and automation applications can be more rapidly, dynamically, extensibly, and affordably developed, configured,

assembled, deployed, distributed, and managed. These common services are defined in such a way that they are not bound to robotics and automation applications but can be useful for any application development approach.

[103] FIGs 5-19 illustrate general application services. FIG 5 illustrates the ID service. The ID **500** service contains abstractions that encapsulate the identification of information in a system. IDs **500** are used throughout the system to identify attributes, objects, data, behavior, state, and other concepts. An ID **500** can be used as a name to reference some object. IDs **500** are commonly used to look up handles to services and other objects. The ID abstraction encapsulates an identifier of "something". It may identify an object, an attribute, a class, or some other entity. This ID class is a basic class whereby no constraints are imposed on the structure of an ID or on its uniqueness within an ID context. The IDContext **501** abstraction encapsulates a context within which an ID is valid and perhaps unique.

[104] FIG 6 illustrates the Any service. The Any **510** service provides generic abstractions to encapsulate any type of data or behavior in a system. Any sort of data may be attached and retrieved, and behavior may be registered and invoked using the abstractions in this service. The AnyInterface **511** and Any **510** abstractions provide an interface and implementation, respectively, of a generic container of data and behavior. Any type of object data may be attached or retrieved from Any **510** objects including collections of objects. Any sort of behavior may also be registered and invoked on Any **510** objects. The storage of data and behavior in Any **510** objects is decoupled from their interface. The data for an Any **510** may, for example, be stored in memory, in a database, or in a remote server object. A default and concrete AnyInterface **511** implementation, MemoryAny **512**, stores data and behavior in memory.

[105] FIG 7 illustrates the Automaton service. The Automaton service **520** provides base abstractions for encapsulating finite state automata. Information flowing through an Automaton **520**, the state of the Automaton **521**, and the functionality of the Automaton itself **522** are all encapsulated within this service.

[106] FIG 8 illustrates the Log service. The Log service **530** provides a generic interface for logging information in the system. A Log **530** abstraction is used to log information from within applications defined according to different log levels **532** of importance. A Logger **531** interface provides a generic interface from which different types of concrete logging mechanisms may be implemented such as logging to a file, logging to a database, or logging to a remote server. A basic default logger **533** implementation logs to a log file or standard output stream. A generic interface is provided such that third-party logging mechanisms may also be configured into the system without changing application code.

[107] FIG 9 illustrates the Config service, which provides a generic means for configuring applications. The Config service **540** leverages the Any service **510** for providing generic access to data storable across different underlying mediums transparent to the application interface. The Config service **540** extends the Any service **510** by providing specific calls and services that relate to retrieving and storing configuration data. Thus, configuration data may be stored in any type of underlying storage medium (*e.g.*, file, XML, database, remote server, etc). In addition, the Config service **540** permits access to configuration data stored in one or more mediums. Thus some configuration data may be stored in multiple XML files while some data may be stored in a database. The dynamic update of configuration data in those mediums may also be dynamically propagated to the applications. Thus, while configuration data may be accessed upon application initialization, any new changes to configuration data may be dynamically propagated to an application at run time. A ConfigurationRegistry **541** abstraction encapsulates a central registry for accessing configuration information. Calls made on the ConfigurationRegistry **541** return access to a registered MasterConfiguration **542** serving as the root for one or more Configuration object handles. The MasterConfiguration **542** manages access to configuration information across different Configuration instances. A Configuration is a type of Any interface **510** for storing and retrieving information used in configuring an application. Configuration information may be stored in different

underlying mediums **543** such as configuration files, XML documents, databases, statically in code (e.g., class files), or remote servers. Concrete configuration implementations handle mapping the generic configuration calls to specific underlying configuration stores. Third-party configuration sources may also be plugged into this framework by extending the Configuration implementation. Applications and objects that permit themselves to be configured by the Config service **540** implement the Configurable interface.

[108] FIG 10 illustrates the Envoy service. The Envoy service **550** provides a set of abstractions that enable a generic way to communicate with any object in the system in a distributed or decoupled manner transparent to the object code. Hence, application code communicating with an object can be designed to communicate with that object directly in memory using its object interface. During configuration, a handle to the object may be obtained which uses the Envoy service **550** to transparently route any invocations on an underlying client envoy to a target envoy **556** over any type of communications medium. Thus application code can remain unchanged and statically or dynamically configured to route invocation requests to objects that exist somewhere else on a network transparent to the client service. Support for different types of underlying communication mediums (e.g., Web services, CORBA, RMI, serial communications) can be provided using this mechanism. The EnvoyMessage **551** extends the Any service abstractions to encapsulate a message that may be delivered between envoys. The Envoy interface provides the base interface **552** implemented by envoys which allows an envoy to invoke an operation on another envoy by passing it an EnvoyMessage **551** and by receiving a return EnvoyMessage **551**. EnvoyMedium **553** and EnvoyMediumDelegate **554** objects provide handles for underlying concrete envoy medium types. A concrete envoy medium may be a remote Web service medium, a distributed object medium such as CORBA or RMI, a serial communications medium, or some other medium over which Envoy may communicate. The EnvoyDirectory **555** provides a service for registering envoys using a particular envoy medium and for

looking up handles to those envoys via the medium. A TargetEnvoy 556 represents the generic server side of an envoy communication. The TargetEnvoy 556 provides services for registering and configuring an object which provides the actual business logic desired to be invoked. A ClientEnvoy 557 represents the generic client side of envoy communication. The ClientEnvoy 557 provides services for looking up handles to target envoys and provides the root calls that may be made for invoking that target envoy 556. The BaseEnvoy 552 provides services common to the ClientEnvoy 557 and TargetEnvoy 556 for obtaining handles to EnvoyDirectory 555 objects and creating handles for EnvoyMediumDelegate 554 objects.

[109] The Registry service allows objects to be created based on a policy such as in a dedicated, shared, or pooled policy fashion, among other pluggable policies. An ObjectRegistry abstraction provides a means for obtaining handles to existing objects and creating new objects and services given their IDs. The ObjectRegistry uses the Config service 540 to obtain configuration information for a particular object. Hence, object configuration information may be stored in files, XML documents, databases, remote servers, etc. The object handle may be newly instantiated or simply returned if already created. Different policies may be configured for each object type indicating if the object handles should be returned solely for use by requesting client, if it may be shared across other clients, or if it should be returned from a pool of similar objects. Hence, whenever an object or service is to be obtained or created in the system, the ObjectRegistry may be consulted to provide that handle. The ObjectRegistry then handles determining how the object should be returned and may populate it with all of the necessary configuration and initialization information. This configuration information is configurably stored in any type of underlying medium. The ObjectRegistry may provide a handle to an object that exists in memory or perhaps via the Envoy service 550. An ObjectLauncher abstraction provides a generic means for creating a main entry point for starting a process, initiating the configuration of the process using the ObjectRegistry, and for instantiating and managing all root objects for the process.

[110] FIG 11 illustrates the Ap service. The Ap service provides a generic framework for encapsulating applications. An Application abstraction **560** provides a core set of services for launching, initializing, configuring, starting, pausing, stopping, and shutting down an application process. Concrete applications can extend or use this abstraction. A generic means for launching applications is also possible via the ObjectLauncher. The application can create additional application threads to encapsulate a thread within a process. The ApplicationThread **561** abstraction serves as a base generic encapsulation of an application thread. Concrete but generic threads exist for encapsulating synchronous **562**, asynchronous **563**, and real time synchronous threads **564**. The Ap service also provides a means for configurably linking an ApplicationThread to a Component in a system such that a system component can be triggered by the thread according in a configurable manner.

[111] FIG 12 illustrates the System service. The System service provides base abstractions for assembling systems and their components. Envoys **550** are provided which enable remote communication with any sort of system or component to be configured transparently. The System interface **570** and generic SystemGeneric **571** implementation provide base abstractions for configuring and accessing a system of components. The Component interface **572** and generic ComponentGeneric **573** implementation provide base abstractions for linking components together and inducing interactions between components. A Hardware service provides a base Hardware interface and a generic HardwareGeneric implementation encapsulating configurable system components that represent some sort of electronics hardware. Operations common to hardware such as starting up, shutting down, restarting, and failing safe are all supported by this service. Envoys **550** are provided that enable remote communication with any sort of electronics hardware to be configured transparently. The Hardware service extends the system service.

[112] FIG 13 illustrates the Signals service. A Signal **580** represents a unit of information and Signals **581** represent collections of such information used in communication between system components. A SignalBus **582** represents a specific

type of Signals collection for communicating over a randomly accessed system bus. A SignalBuffer 583 represents a specific type of Signals collection for communicating over a buffered sequential access medium. A specific type of signal 580, termed a BinarySignal 584, is used to encapsulate signal information that is binary (0 or 1, false or true) by nature or may have a "floating" state. The Signals Event service provides a means for generically registering interest in events associated with signals 580. Interested listeners for those events may be notified of the events in which they are interested. Notifiers will notify the listeners of the signal events when they occur. Different generic ways to handle signal events are also encapsulated in the Signals Handler service. Common and generic ways to handle signal events such as logging the events, propagating the events to other listeners in a chain, storing events in memory, or parsing events are provided.

[113] A Signals Packet service provides a means for generically lumping signals together into discrete packets. A generic SignalPacket interface and implementation provides a means for collecting Signals into a discrete packet. The packet may have a packet header and may be terminated according to a delimiter or according to a fixed or dynamically defined length. A SignalPackets interface and implementation provides a means for parsing a stream of data into discrete SignalPacket instances. A Signals Mapping service provides a generic means for mapping signals from one form into another. A generic InterfaceMapping interface is concretely realized by a set of generic interface mapping implementations. Generic implementation include means for copying signal data from one Signals object into another, for copying references from one object to another, and for translating binary signals according to Boolean operations. Additional concrete signal mapping implementations are provided elsewhere in the framework or by applications.

[114] FIG 14 illustrates the Signals Message service. The Signals Message service provides a set of abstractions used for generically transforming between Signals 581 and generic Any objects 510. When Signal 580 data is received from an input stream, an InputMessage 590 can be used to generically transform that data into

more easily accessible and logical Any object 510 data. When Signal data 580 is to be delivered to an output stream, an OutputMessage 591 can be used to generically transform that data from the Any object 510 form to the output signal 580 form. A message that has both input and output translation capability is encapsulated by the IOMessage 597. Base classes for handling input and output messages are contained in the BasicInputMessage 592 and BasicOutputMessage 593 classes. Two generic types of concrete message formats are binary and text based messages for which there exists concrete input, output, and IO realizations. A generic way to describe how to parse messages between their Signal 580 form and Any 510 form is provided by a MessageDescriptions 594 abstraction. This abstraction contains one or more MessageDescription 595 objects, each of which describes how to parse an individual message. Each MessageDescription 595 contains one or more MessageElement 596 objects which describe how to parse an individual field element within a message.

[115] FIG 15 illustrates the Comm service. The Comm service provides an extension of the hardware service for encapsulating and managing interfaces to hardware. The Interface 600 and InterfaceGeneric 601 interface and generic implementation, respectively, provide common operations for opening, closing, and resetting interfaces. Common operations also exist for synchronously and asynchronously reading signals 581 from and writing signals to interfaces. Envoys 550 exist for providing a means to transparently communicate with distributed interfaces. The InterfaceManager 602 provides a general mechanism for managing one or more interfaces 600. Either a single or a group of hardware interfaces can be managed by the InterfaceManager 602. Configuration for how the interface(s) is managed is provided by the interface manager. A client can communicate with the InterfaceManager 602 as a single unit whereby, transparently to the client, the manager can be reading information from or writing information to multiple interfaces. The manager can configure whether associated interfaces are pollable, asynchronous, or scheduled, among other pluggable policies. The policy by which signals 580 are parsed to and from packets can also be defined. Clients interested in

accessing interfaces can register themselves with the interface manager in order to be notified of specific events that occur on the interfaces. Numerous concrete interface types exist and can be extended from the interface service. Concrete extensions for serial port interfaces, parallel port interfaces, USB interfaces, Firewire interfaces, digital I/O port interfaces, analog I/O port interfaces, interfaces to joysticks, among others exist or can be plugged in. Interfaces **600** can also be chained together using a special interface chain service which extends from the interface service. With chained interfaces **600**, one interface can be chained to another such that information received from one interface is automatically routed to another.

[116] FIG 16 illustrates the Peripherals service. The Peripheral service provides abstractions for interacting with and managing peripherals external to a system. The Peripheral service's main abstractions are the Peripheral interface **610** and PeripheralGeneric **612** implementation. The Peripheral abstractions extend from the Hardware service abstractions. The ability to configure and create peripherals is inherited from built-in use of the Config **540** and Registry services. Concrete implementations of peripherals may extend from and specialize this service. The PeripheralGeneric **612** abstraction provides a generic basis for defining system peripherals. The Peripheral abstraction **610** is associated with an InterfaceManager **602** and one or more Interfaces. During configuration, the PeripheralGeneric **612** abstraction is associated with an InterfaceManager **602** and these Interfaces in a configurable manner using the Config **540** and Registry services. The Peripheral abstraction **610** provides a number of operations that may be invoked by application clients to read from a peripheral (synchronously or asynchronously), write to a peripheral, get notified of peripheral events, and manage the lifecycle of a peripheral. Because the peripheral services uses the Comm service for interfacing **600**, Clients of the Peripheral service may communicate with the Peripheral service without knowledge or consideration of how the peripheral is physically connected to the system. That is, because the Comm service provides a generic framework for plugging in interfaces, the actual underlying physical means by which a peripheral is

connected (e.g., serial port, USB, etc) is transparent to the clients of the Peripheral service. The Peripheral service also uses the signals 581 mapping service to enable a configurable way to map data to and from an object form semantically meaningful to the peripheral client and the raw form required for external interface communications. Envoys 550 also exist enabling peripherals to be remotely communicated with in a fashion transparent to the client application. A generic Peripherals abstraction 611 also provides services for communicating with and managing peripherals as a collection.

[117] The Measure service provides a set of abstractions commonly used in measurements. Abstractions exist for encapsulating an angle, distance, duration, speed, general rate, a generic unit, rotation, line, linear direction, angular direction, angular speed, among others. A Test service provides abstractions that provide a generic way for testing software. Objects that are testable leverage the Test service to allow the ability to set the test mode of an object, test if it is alive or not, and to inject an object with test data. A Time service provides a generic Time abstraction for recording, reading, and operating on a time value. An EventTime abstraction encapsulates information about a time for which an event may occur which includes a delay time before which it first occurs, an indication if it is periodic or not, an indication if it is indefinite or not, a period if it is periodic, and a duration if it is finite.

[118] FIG 17 illustrates the Timer service. The Timer service provides a generic means for scheduling timers in a system. The TimerAction 621 interface represents a base interface for encapsulating an action to occur at a specific time. Operations are extended to implement the action to execute at a specified time, any preface to execute before an action, any prologue to execute after an action, and an operation to cancel a timer action. The Timer 620 interface provides a base interface for registering timer actions to occur once after a specified delay or at a specified period after an optional delay, optionally after some finite duration, or at some predefined time. Timers may be started, stopped, cancelled, and managed in other ways through this interface. A concrete TimerActionAdapter 622 provides a default implementation

for a TimerAction, 621 a special TimerCancelAction 623 provides a generic way to cancel timers, and other concrete specialized timer actions exist throughout the framework. A GlobalTimer 624 abstraction serves as a base class for scheduling a global timer for a process or thread. The frame size, resolution, period, delay, priority, among other attributes may be set for the global timer. Individual timer actions that are to occur according to the global timer are registered with the GlobalTimer 624. Concrete implementations of the GlobalTimer 624 exist for different operating environments.

[119] FIG 18 illustrates the Schedule service. The Schedule service extends the Timer service by providing additional support for scheduling actions. The Schedule service extends the Timer service by providing additional support for scheduling actions. The Action 632 abstraction implements the TimerAction 621 interface to provide a means for scheduling actions with an event scheduler. An ActionEvent 631 associates an EventTime with an Action. Hence the event time at which an action occurs is encapsulated by an ActionEvent 631. An ActionPlan 630 contains one or more ActionEvents 631 which must take place. Hence, an action plan represents a plan for multiple actions to occur and the event times at which they must occur. An ActionSchedule 633 contains and provides operations to manage one or more ActionPlans 630 which must take place. Hence, an action schedule represents a schedule for multiple action plans. The EventScheduler 634 provides a generic way to create an ActionSchedule 633 and to create concrete Timers 620 based on configuration information provided by the Config service 540 and ObjectRegistry. The EventScheduler 634 then schedules the actions contained in the ActionSchedule 633 with the appropriate timers. A Profile service provides a Profile abstraction which is used to contain and register information according to different code base configuration profiles. Because some run time environments, such as embedded environments or non-deterministic operating systems, have restrictions that other environments may not have, a means for configuring which code base profile is loaded is provided by this service. A Util service provides a means for encapsulating

miscellaneous common system abstractions and system abstractions that may vary by computing platform profile (e.g., floating point support, native mathematic operation support, and system property support).

[120] FIGs 19-31 illustrate general robotics application services. FIG 19 illustrates the general structure of a robotic application, specifically as a robot with sensors 711, actuators 721, and some conduct 702. A robot may have zero or more sensors 711 and zero or more actuators 721 configured with it using the config service 540 and automatically initialized and created using the registry service. The sensors 711 represent the external inputs to a robot for sensing its environment and world. The actuators 721 represent the external outputs from a robot for affecting its environment and world. The operations that occur between sensing and acting with its environment or that occur independent of its sensor inputs are embodied within its conduct. All conduct of a robot inherits from its Conduct services 702. Hence, robot reflexive actions to sensor inputs, robot planning, neural networks, sensor information analysis, rule-based behaviors, and other common robotic conduct services are all embodied by the Conduct service 702 and subclassed in other specific services. A means for launching one or more Robots operating according to the same universal time constraints is embodied by the RobotUniverse 700 and RobotGod 701 abstractions.

[121] A Robot may be configured to have all three services (sensors 711, actuators 721, and conduct 702) or any combination thereof. For example, a Robot that only has Sensors 711 may represent a sensor application with no planning or operations performed on such information but rather the data is just presented via some visual display. Such flexibility allows, for example, for a distributed sensor application to be constructed by configuring only Sensors for an application, some of which may be accessed in a transparent and distributed fashion using the Envoy service. If Conduct 702 is added, a rules-based thought sub-service of Conduct 702 may, for example, analyze that sensor 711 information and categorize it in certain way and then display or log the resultant analysis. If Actuators 721 are added, some operations may

be performed on its environment, such as movement for example, based on the sensed or analyzed information.

[122] FIG 20 illustrates the Sensor service. The Sensor service provides a set of abstractions for generically configuring, managing, and communicating with sensors. A Sensor interface 710 and SensorGeneric implementation extend from the Peripheral service 610. Hence, all of the features and capabilities inherent in the Peripheral service 610 are inherent in the sensor service (*e.g.*, configurability, object registry creation, transparent distributed communication via envoys, transparent hardware interfaces, etc). The Sensor service extends the Peripheral service 610 by allowing for a configurable set of commands to be registered with a sensor 711. These commands may be sent to a sensor 711, transparent to the client, when the client invokes operations on a sensor that are associated with a particular command. The state of a sensor 713 is also encapsulated in generic sensor state 714 abstractions. The sensor state 713 is updated transparently to the client as information is read from the sensor (synchronously or asynchronously). Operations on the sensor interface 710 permit clients to access the sensor's state. Sensors 711 may also be managed as a collection.

[123] FIG 21 illustrates the Actuator service. The Actuator service provides a set of abstractions for generically configuring, managing, and communicating with actuators 721. An Actuator interface 720 and ActuatorGeneric 722 implementation extend from the Peripheral service 610. Hence, all of the features and capabilities inherent in the Peripheral service 610 are inherent in the Actuator service (*e.g.*, configurability, object registry creation, transparent distributed communication via envoys, transparent hardware interfaces, etc). Actuators 721 may also be managed as a collection.

[124] FIG 22 illustrates the Mechanism service. The Mechanism service 730 extends from the System service to encapsulate operations that are performed on and with mechanical components. While the Hardware service encapsulates electronics hardware, the Mechanism service 730 encapsulates mechanical hardware. MechanismGeneric 731 abstractions are used when modeling the behavior and

interactions among mechanical components in a robotic system. Envoys 550 exist to enable transparent distributed communication with mechanisms. A Gear service extends from the mechanism service to provide abstractions for individual gears and gear trains. Generic abstractions for gears are used when modeling the behavior and interactions among gears in a robotic system.

[125] FIG 23 illustrates the Motor service. The Motor service extends from the Actuator service to provide abstractions for motors in a system. A generic Motor interface 735 and generic MotorGeneric 736 implementation encapsulate the common services associated with operating motors. Concrete sub-interfaces and sub-classes of these abstractions provide services specific to operating with different types of motors. For example, a Concrete Motor DC service can provide a software interface for interacting with and operating DC motors. A Concrete Motor Servo service can provide a software service for interacting with and operating Servo motors. A Motor Stepper service can provide a software interface for interacting with and operating stepper motors. Other concrete sub-services for motors extends from the generic Motor service. Envoys 550 exist to allow transparent distributed communication with motors. A Command service provides a set of abstraction used to encapsulate the configuration of commands for various purposes (*e.g.*, sensor commands and movement commands).

[126] FIG 24 illustrates the PWM service. The PWM service provides a set of abstractions used for actuating motors using a pulse-width-modulated method. A Pulse abstraction 741 encapsulates information about a pulse train used to control motors in a system. Motors are often controlled by delivering a pulse train to the motor which controls the motor speed and direction. The pulse train frequency can also affect motor operation efficiency. The Pulse 741 extends from EventTime and provides additional information needed for performing PWM 740 on a motor. The duty cycle (percent time the pulse is active), polarity of the pulse (active when pulse is high or low), and other generically defined conditions of a pulse are provided by the Pulse 741 abstraction. The PWM abstraction 740 provides a base generic abstraction

for configuring, starting, stopping, restarting, and managing a PWM signal stream to a motor. Concrete sub-types of the PWM 740 provide generic ways to manage different PWM approaches. A TimerBasedPWM 742 abstraction provides a way to directly raise high and low the outputs of a motor's interface by interacting with the timer service to schedule updates according to a system timer. The UpdateBasedPWM 743 abstraction provides a way to directly raise high and low the outputs of a motor's interface by relying on an external timer or service to call the abstraction whenever a clock cycle has occurred. The HardwareBasedPWM 745 abstraction provides a way to delegate PWM timing control 742 to a dedicated PWM hardware circuit. The CommandBasedPWM abstraction 744 provides a way to delegate PWM timing control 742 to an external hardware device through a hardware interface.

[127] FIG 25 illustrates the Controls service. The Controls service 750 provides a generic means for defining information related to controlling a system. A ControlLevel abstraction 752 extends the Units abstraction from the Measure service and adds a means for defining a minimum, maximum, and set control point. Operations and queries related to managing and providing status about a control point are also provided. A ControlAction 751 defines a set of ControlLevels 752 that induce some discrete control action. Subclasses of the ControlAction 751 include MovementControl for defining a movement action and RotationControl for defining a rotational control action. Controls define a set of ControlActions 751 that define a sequence or set of control actions to perform. Subclasses of the Controls abstraction 750 include MovementControls for defining a sequence of movement controls and RotationalControls for defining a sequence of rotational controls.

[128] FIG 26 illustrates the Mobility service. The Mobility service provides abstractions for encapsulating configuration and management of a means for mobilizing a robot. A MobilityMechanism 760 and its generic implementation that encapsulates a discrete mechanism that induces movement of some sort. The mobility mechanism contains some Mobilizer 762 (e.g., a wheel or individual leg), a reference to some actuation mechanism, and any mechanical linkages and gears between the

Mobilizer 762 and the actuation mechanism source. The MobilityMechanism 760 makes use of the mechanism service to model mechanical linkages and permit configuration of such linkages in a variety of ways. In such a fashion, a completely generic means for modeling any type of mobility mechanism is provided in a configurable fashion. The actuator that drives the Mobilizer 762 through some mechanical linkage may be directly connected to the Mobilizer 762 or it may be indirectly connected via some mechanical linkage such as a differential gear train. The MobilityPlatform 761 interface and MobilityPlatformGeneric 763 implementation provide a generic means for configuring a mobility platform and for an application client to operate that platform as a whole. The MobilityPlatform 761 is configured with one or more MobilityMechanism 760 components using the Config service 540 and Registry service. Generic MovementControl or MovementControls 750 commands may be issued to the mobility platform requesting that it move in a particular fashion. These commands are translated into commands to associated underlying actuator mechanisms associated with individual mobility mechanisms. The Mobility service has envoys 550 which add support for transparent distributed communication with a mobility platform. The mobility abstractions may be generically configured for use as is or may be subclassed for specific mobility types. As an example, there is exists a mobility wheeled service which extends the mobility service for application to wheeled type mobility of any sort.

[129] FIG 27 illustrates extensions of the Mobility service. A WheeledPlatform 770, WheelMechanism 771, and Wheel 772 all extend from the MobilityPlatform 761, MobilityMechanism 760, and Mobilizer 762 abstractions respectively. A WheeledPlatformGeneric 773 implementation uses the Config 540 and Registry service to read a specific configuration of wheel mechanisms for the wheeled platform. As an example, the wheeled platform may read, via the Config service 540, that it is to be configured using four wheel mechanisms. These mechanisms are then automatically constructed via the Registry service. Each WheelMechanism 771 may also be configured to construct a Wheel object 772 and corresponding Actuator 720

which happens to directly drive the Wheel. Alternately, the WheelMechanism 771 may reference a shared Actuator 720 which drives multiple Wheels through a shared differential GearTrain. Any sort of wheeled configuration can be achieved. Likewise, a LeggedPlatform, LeggedMechanism, and Legged abstractions can exist in a mobility legged service. Likewise, a TrackedPlatform, TrackedMechanism, and Track abstractions can exist in a mobility tracked service. The Mobility service is not limited to ground-based robots and vehicles. The Mobility service is extended to provide services common to air, sea, underwater, space, and any sort of approach for providing mobility. As an example, a FlightPlatform and FlightMechanism provided one type of base aeronautical mobility service. These abstractions are further subclassed into HelicopterPlatform and HelicopterMechanism for helicopter applications.

[130] A Range service extends the Sensor service and provides base abstractions for dealing with range type sensing. Generic Range information, RangeSensor interface and RangeSensorGeneric implementation, RangeSensorState and RangeSensorStateGeneric abstractions exist to encapsulate configuration and operations common to range sensing. A Ladar service extends the Range sensor service and provides base abstractions for dealing with laser radar type range sensing. Generic LADAR interface and LADARGeneric implementation, LADARState and LADARStateGeneric abstractions exist to encapsulate configuration and operations common to laser radar based range sensing. A Ladar sick service extends the Ladar service and provides base abstractions for dealing with LADAR sensing applications using the SICK LMS product. Generic LMS interface and LMSGeneric implementation abstractions exist to encapsulate configuration and operations common to SICK LMS laser radar based range sensing. A Radar service extends the range sensor service and provides base abstractions for dealing with radar type range sensing. Generic RADAR interface and RADARGeneric implementation, RADARState and RADARStateGeneric abstractions exist to encapsulate configuration and operations common to radar based range sensing. A Radar vorad service extends the radar service and provides base abstractions for dealing with

RADAR sensing applications using the Vorad Vbox radar product. Generic Vbox interface and VboxGeneric implementation abstractions exist to encapsulate configuration and operations common to Vorad Vbox radar based range sensing.

[131] A Reference service extends the sensor service and provides base abstractions for dealing with sensing reference points (*e.g.*, position and orientation). Generic ReferenceSensor interface and ReferenceSensorGeneric implementation abstractions exist to encapsulate configuration and operations common to sensing reference points. A Reference abstraction encapsulates a generic point of reference. A Position abstraction extends the Reference abstraction to specify a generic position in space. An Orientation abstraction extends the Orientation abstraction to specify a generic orientation in space. Envoys exist for remotely accessing reference sensors. A Reference geo service extends the Reference Sensor service and provides base abstractions for dealing with geographic reference positioning and orientation. Abstractions for encapsulating the information coming from geographic reference sensors are provided including GeoPosition extending the Position abstraction. A GeoPosition contains Latitude, Longitude, and Altitude abstractions. A GeoOrientation abstraction extends the Orientation abstraction and contains Heading, Roll, and Pitch abstractions. A Reference nmea service provides abstractions that deal with parsing and interpreting GPS type information in the NMEA format. A NmeaMessage abstraction extends from the TextIOMessage provided by the Signals Message service.

[132] A Digital service provides generic means for interfacing with digital I/O pins and ports. Abstractions for digital data (DigitalData), digital I/O points (DigitalPoint), and digital I/O ports (DigitalPort) serve to provide support in this category. An Analog service provides generic means for interfacing with analog I/O pins and ports. Abstractions for analog data (AnalogData), analog I/O points (AnalogPoint), and analog I/O ports (AnalogPort) serve to provide support in this category. A Feedback service and abstractions that extend from it encapsulate sensors and information related to low-level feedback from actuators or a mechanical system. A FeedbackSensor abstraction encapsulates a means for configuring and accessing a

sensor that provides low-level feedback about the state of an actuator, mechanical, or electro-mechanical device. An EncoderSensor abstraction subclasses from the feedback service and encapsulates a means for configuring and accessing a sensor that provides low-level feedback from an encoder. A QuadEncoderSensor abstraction subclasses from the feedback service and encapsulates a means for configuring and accessing a sensor that provides low-level feedback from a quadrature encoder. A CounterSensor abstraction subclasses from the feedback service and encapsulates a means for configuring and accessing a sensor that provide low-level counts of external events. A Filter service provides abstractions for filtering data coming from sensors or events. A DataFilter abstraction provides a generic and configurable means for averaging data and filtering out noise across multiple samples of data from a sensor or external event source. The Fusion service provides abstractions for fusing data received from multiple sensors. A SensorFusion abstraction provides a generic and configurable means for fusing data across multiple sensors or external event sources. A FusionRule abstraction provide the basis for encapsulating discrete rules about how to fuse a particular combination of sensor data. A Watchdog service provides abstractions for realizing watchdog timers in a system. The Watchdog abstraction provides a configurable means for implementing a watchdog timer in a system. Watchdog event, listener, and action abstractions provide the means by which watchdog events are generated, listened for, and acted upon. A Safety service provides abstractions for failing the outputs for a system to a safe state. A SafeInterface abstraction provides a configurable means for safely shutting down a set of outputs to their safe state.

[133] FIG 28 illustrates the Obstacle service. The Obstacle service provides a generic and configurable service for classifying, detecting, and resolving obstacles that a robot may need to avoid or react to. The Obstacle interface 780 and ObstacleGeneric 781 implementation provide base abstractions for defining the characteristics of an obstacle for a robot. Attributes such as obstacle size, position, and confidence in its actually being an obstacle are all encapsulated within this abstraction. The obstacle type is also classifiable using such generic abstractions and

concrete abstractions such as, for example, positive obstacles (*e.g.*, objects in the way), negative obstacles (*e.g.*, ditches or holes to avoid), and surface obstacles (*e.g.*, walls or surfaces to avoid). The Obstacles abstraction **784** encapsulates a collection of Obstacle **780** objects and operations that are performed on such obstacles as a whole. The ObstacleDetection **782** abstraction encapsulates a generic process for detecting obstacles **784**. Specific types of detection based on, for example, laser/radar or radar sensors, may specialize the detection process. The ObstacleResolver **783** abstraction encapsulates a generic process for resolving between multiple obstacles to determine which obstacles are similar **785** and to fuse information between identified obstacles. The parameters of resolution are configurable within the ObstacleResolver **783**.

[134] The Navigation service provides a generic set of abstractions for robotic navigation. FIG 29 illustrates the Navigation Course service, which provides abstractions for encapsulating a route **792** and course **791** over which a robot travels. A Waypoint **790** abstraction encapsulates a position and set of attributes about a discrete location to which a robot travels. A RouteSegment **793** encapsulates a linear route from one waypoint to another waypoint, and attributes about that route such as a collection of features, direction, route segment speed, and length. A Route **792** encapsulates a collection of RouteSegments **793** over which a robot travels. Attributes about the Route **792** include laps, first waypoint, and last waypoint. Operations may be performed on the route to dynamically add, remove, or modify route segments within the route. The route may also be used to track the location of a robot on the route. A TrackSegment **794** is a type of RouteSegment **793** that specifically outlines a desired track over which a robot may or should travel. A TrackSegment **794** defines boundaries within which a robot may travel over a route segment. A Course **791** is a type of Route **792** which defines the TrackSegments **794** over which a robot may or should travel. The actual route taken by a robot may differ from the desired route and the Course **791** defines the boundaries for the robot's travel.

[135] The Navigation Planning service is illustrated by FIG 30A. The navigation planning service encapsulates abstractions used for planning the navigation of a robot. An Opening 805 characterizes a discrete opening through which a robot may traverse on a particular track segment. The Opening 805 is bounded by obstacles and potentially by track boundaries. Openings 801 encapsulate the collection of known openings on a track segment. AdjacentOpenings 804 encapsulate a grouping of openings on a track segment that are adjacent to one another such that the robot must choose a passage between the openings based on the adjacent openings. A PathOption 806 encapsulates a discrete option for a path of robot travel as defined by a sequence of openings. A PathOption 806 defines the BestRoute 807 for the robot to take. A BestRoute 807 defines the best possible route for a robot to take based on a generic description of factors used to make such a determination. PathOptions 803 define all of the possible path options a robot may take along a known route. The Path abstraction 800 encapsulates a process for planning the path a robot will travel. A set of Obstacles 784 are examined and a set of Openings 801 are identified for which the robot may navigate over a course. Those AdjacentOpenings 804 through which the robot may travel are then identified. Any identified impasses are handled by an ImpasseHandler 802. The PathOptions 803 are then identified including the best route to travel out of all of options available.

[136] The Navigation Mapping service encapsulates route planning based on map data. MapData information such as Elevation, Water, and other Features are used to identify Obstacle and Opening information based on MapData. The navigation mapping data easily plugs into the Navigation Planning service and hence enables navigation planning based on information from map data as well as from sensor data.

[137] As shown in FIG 30B, the Conduct 7900 service provides a Conduction interface 7910 and ConductionGeneric 7920 implementation which models the conduct of a robotic process. Conduct represents the behavior and inherent properties of existence for a robot. Upon sensing information, a robot may perform artificial

intelligence operations on that data, reflexively react to such information, or perform some other operation that exudes some conduct on the information. The Conduction operations may also be scheduled or randomly execute based on time or some other stimuli. The Conduction abstractions may result in modifications to the robot state or in stimulating Actuators to perform some action. The Conduction abstractions serve as base abstractions for all operations by a robot that occur between or independently of sensing and acting. The Conduct service extends from the System service abstractions. A generic Conduct abstraction also provides services for communicating with and managing Conduction abstractions as a collection.

[138] A Thought service provides a Thought interface **7940** and ThoughtGeneric **7930** implementation which models a thought process. The generic means for modeling artificial intelligence is achieved in this fashion. Concrete subtypes from this service's abstractions are used to embody different types of thought processes such as analysis, inference, deduction, and planning. The Analysis services provides an Analyze **7950** and AnalyzeGeneric implementation used for encapsulating analysis of information retrieved from a sensor. A Reflect service provides a Reflect **7960** and ReflectGeneric implementation used for encapsulating rules for reflecting on information after it is analyzed in order to generate new information. A Learn service provides a Learn **7970** and Learn Generic implementation used for encapsulating rules for learning and generate knowledge and new state information based on existing information. A Plan service provides a Plan **7980** and PlanGeneric implementation used for planning a course of action based on sensor information, analyzed information, new information, new state information, or new knowledge. A React service provides a Reaction and ReactionGeneric **7990** implementation used for encapsulating a direct reaction on one or more actuators based on some stimuli from a sensor. A Rules service provides a Rule, RuleGeneric, Rules, and RulesGeneric implementation for encapsulating rules of behavior. Proprietary, custom, and third-party rule engines seamlessly plug into the framework using these abstractions. A Neural service provides a Neuron, NeuronGeneric, NeuralNetwork, and

NeuralNetworkGeneric implementation for encapsulating neural networks. Proprietary, custom, and third-party neural networks seamlessly plug into the framework using these abstractions.

[139] The Robot service provides a Robot interface 440 and RobotGeneric 703 implementation which models the generic concept of a robot. The RobotGeneric 703 is a completely configurable abstraction that can be used to model any type of robot. Sensors 711, Conduct, and Actuators 721 are associated with a robot in a configurable fashion. In this way, any type or number of sensors, actuators, and conduct can be configured with the robot and linkages made between them. Upon construction using the Config 540 and Registry service, the robot may be commanded according to its lifecycle to live, wake, sleep, and die.

[140] The robotic God 701 (see FIG 19) service provides the base services used to create and define the universe within which a robot operates. The RobotUniverse 700 abstraction is used to configurably define when and which Robot objects live and die. In this way, a network, local or distributed, of robots can live, perform their missions, operate, and die according to a common universe. The RobotGod 701 abstraction is used to configurably start and stop the RobotUniverse 700. It is essentially a robot universe launcher program.

Operational Aspects

[141] FIGs 31-44 illustrate general embodiments of the invention. FIG 31 shows how any sort of application can be launched generically and configurably using the registry service. The ObjectLauncher 1101 is launched as a program on a system 1001. The ObjectLauncher 1101 then loads the root configuration name and type from the System Properties (part of util service) 1102. The ObjectLauncher 1101 then retrieves a launcher ID and supplies it to the ObjectRegistry 1103 in order to get an object handle. The ObjectRegistry 1103 then reads the object configuration and induces the object to configure itself, wherein here the object to be configured is the Launcher:ObjectLauncher 1105. The Launcher:ObjectLauncher 1105 then sets the

application log level (using the Log service) 1108, sets any application system properties using the util service, and sets the application run policy ID 1109. For each object ID in the configuration properties, the Launcher:ObjectLauncher 1105 gets an object handle from the ObjectRegistry 1103 given an object ID, and registers the object according to its ID 1109 by means of the Any service. The ObjectLauncher 1101 is then able to run. For each object in the managed object configuration, the ObjectLauncher 1101 gets the managed object and starts its operation.

[142] FIG 32 illustrates how any sort of application objects can be automatically created and configured using the registry and config services. The client obtains an object handle from the ObjectRegistry 1050 given its ID. The ObjectRegistry 1050 meanwhile gets a master config handle from the ConfigurationRegistry 1055. If a master config has not yet been created, the ConfigurationRegistry 1055 must get a root config name and type from the System Properties 1060 (util service), and then create a new object given config name and type by means of the MasterConfiguration 1065. A concrete configuration type (*e.g.*, XML Configuration) is created based on this information. Optionally, a special root configuration that collects one or more sub-configurations may also be created. The MasterConfiguration 1065 loads a configuration from the underlying medium (*e.g.*, an XML file). With the master config created, the ObjectRegistry 1050 can now proceed to get an object properties map from the MasterConfiguration 1065, as well as an object reference policy ID from the HashMap 1070. (If this cannot be obtained, it will default to dedicated reference policy.) It will be understood by those skilled in the art that the term HashMap refers to a manner of storing name-value pairs as in a software hash table. An object can be retrieved from the HashMap 1070 collection using an ID or string. In the case of a dedicated reference policy, the ObjectRegistry 1050 gets a class name from the HashMap 1070 and uses this to create a new application object. The object could be in memory or be a client envoy to a remote object. The ObjectRegistry 1050 then attempts to obtain configuration properties from the HashMap 1070. If such properties exist, the application is configured given these properties.

[143] FIG 33 illustrates how peripherals are generically configured and created, including their relation to one or more system interfaces. The Client 1500 begins by inducing the configuration of a PeripheralGeneric object (*e.g.*, via the registry service) 1501, which in turn calls the hardware, component, and system superclass configurations. The PeripheralGeneric 1501 abstraction primarily operates in conjunction with the ObjectRegistry 1502 and InterfaceManager. Specifically, once the PeripheralGeneric 1501 obtains the interface manager object from the ObjectRegistry 1502 given an ID, it can create and configure the InterfaceManager 1504 and the interface management policies. For each interface ID in the configuration list, an interface object is obtained from the ObjectRegistry 1502 (*e.g.*, SerialPort or USBPort object), and the interface is created and configured. The PeripheralGeneric 1501 abstraction must then obtain a few other objects from the ObjectRegistry 1502. An object that maps data used by a peripheral to data used by an interface is retrieved given its ID. An object that maps data used by a interface to data used by a peripheral is also retrieved given its ID. Interface and Peripheral signals handler objects are obtained as well. Finally, the PeripheralGeneric 1501 registers any configured packet handlers.

[144] FIG 34 illustrates how the registry service is used to launch generic robotics applications. The System 1200 initiates the ObjectLauncher 1201, and after the initial loading of the program, an object handle is obtained from the ObjectRegistry 1202 given its launcher ID. The launcher:ObjectLauncher 1204 is configured, and another object handle (*e.g.*, "robot object") is obtained from the ObjectRegistry 1202, this time given its root object ID (*e.g.*, "RobotApID"). A Robot abstraction is created and configured as a managed object, and the object is registered through the AnyInterface 1203 given its recently obtained handle (*i.e.*, "robot object"). Once this object creation has been completed, the ObjectRegistry 1202 will be able to obtain and start the object by means of the AnyInterface 1203 and the recently created managed object's interface.

[145] FIG 35 illustrates how the registry and config services are used to automatically create and configure a general purpose robotics application. The launcher:ObjectLauncher 1301 must get an object handle (*e.g.*, "robot object") from the ObjectRegistry 1302 given a root object ID (*e.g.*, "RobotApID"). The ObjectRegistry 1302 in turn gets an object properties map from the MasterConfiguration 1303, given the object ID (*e.g.*, "RobotApID"), and a class name (*e.g.*, "com.perronerobotics.robot.RobotGeneric") from the HashMap 1304. Given this class name, a new ApplicationObject 1305 is created (*e.g.*, "RobotGeneric"). The ObjectRegistry 1302 configures this new object using properties obtained from the HashMap 1304. The newly created object calls upon the Application superclass in order to initialize and configure the application threads. Sensor configuration information is obtained from the HashMap 1304 and configured using the Sensors service 1306. For each sensor ID, an object handle must be obtained from the ObjectRegistry 1302. The object handle might be a Sensor object, (or a subclass such as a ReferenceSensor object). Conduct is initialized the same way, using the Conduct 1307 service instead of the Sensors 1306 service. Object handles for conduct might include a Thought object or a Plan object. Actuators are initialized similarly, using the Actuators 1308 service. For each actuator ID an object handle is obtained (*e.g.*, a DCMotor object or a ServoObject) and for each actuator plan ID an object handle is obtained (*e.g.*, an ActuatorPlan object).

[146] FIG 36 illustrates an example of how a reference sensor (*e.g.*, for GPS) is created and configured. The Sensors 1401 service gets an object handle (*e.g.*, ReferenceSensor object) from the ObjectRegistry 1402 given a sensor ID (*e.g.*, GPSSensorID). A new object (*e.g.*, ReferenceSensorGeneric) 1403 is created and configured. The object configuration is delegated to the superclass, *i.e.*, SensorGeneric 1404. Sensor commands are configured through the SignalsCollection 1405. Given the sensor state ID (*e.g.*, SensorStateID), an object handle is obtained from the ObjectRegistry (*e.g.*, SensorStateGeneric object) 1402. The SensorGeneric

1404 calls the configuration for the superclass, in this case the **PeripheralGeneric** sensor **1406**.

[147] FIG 37 illustrates an example of how a serial port type of system interface is created and configured. The **InterfaceManager 1601** begins by obtaining an interface object handle (e.g., **SerialPort** object) from the **ObjectRegistry 1602**, based on a config ID. The new interface (i.e., **SerialPortGeneric 1603**) is created and configured. General serial port information, such as the baud rate, will later be configured. The superclass is configured, in this case a **ComputerPortGeneric 1604** interface. General computer port information will later be configured, such as the port name. This computer port interface configures its superclass, in this case an **InterfaceGeneric 1605**. This interface calls its hardware, component, and system superclass configurations, and configures the generic interface policies (e.g., has input only, has output only, has both I/O, etc.). Configuration is then completed.

[148] FIG 38 illustrates an example of how a DC motor actuator type of peripheral is created and configured. The **Actuators 1700** service gets an object handle (e.g., **DCMotor** object) from the **ObjectRegistry 1701**, given a motor ID (e.g., **SteeringMotorID**). A **DCMotorGeneric 1702** actuator object is created and configured. Three superclasses are configured in turn – the **MotorGeneric 1703**, the **ActuatorGeneric 1704**, and the **PeripheralGeneric 1705**. The general properties for the actuator, motor, and DC motor objects are configured. Given a PWM object ID, the **DCMotorGeneric 1702** gets an object handle from the **ObjectRegistry 1701** for a concrete PWM object.

[149] FIG 39 illustrates how a generic robotic application is started. The **ObjectLauncher 1800** starts a **RobotGeneric 1801** managed object. An application superclass **1802** is started. Any configured threads (e.g., synchronous or asynchronous) are started by means of the **ApplicationThread 1803**. The **ApplicationThread 1803** is initialized and the **Application 1802** initialization is overloaded appropriately by the **RobotGeneric 1801** application class. The term "overloaded" is taken from its object-oriented programming meaning. It will be

understood by those skilled in the art that a method on a class can be "overloaded" by a subclass if it is named the same way and shares the same operation signature (input and output parameters). When an object of that class type is invoked, the subclass's method implementation is called instead of or before the superclass's method. The subclass can also invoke the superclass's method from within the overloaded method.

[150] Sensor 1804, Conduct 1805, and Actuator 1806 initialization is performed through their respective initialization interfaces. The application continues running as long as it is told to stay operational. When the status is changed to indicate shutdown, any configured threads are stopped.

[151] FIG 40 illustrates how a sensor is asynchronously updated using a serial port as an interface input example. The SerialPortGeneric 1901 interface is notified of data availability by the Serial Port Provider 1900. It then delegates general event notification to the superclass, the InterfaceGeneric 1902, which determines event propagation policy based on the configuration. This in turn propagates to the generic listener, the InterfaceManager 1904. This process is repeated and the propagation in turn proceeds to the PeripheralGeneric sensor 1905. Any configured sensor conversion is performed via the InterfaceMapping service 1906. The PeripheralGeneric 1905 produces an overloaded call in order to induce conversion to the sensor state via the SensorGeneric abstraction 1907. Conversion to sensor state is delegated to the SensorStateGeneric object 1908. The object reads signals into the state (e.g., TextInputMessage reads state in a configurable fashion) via the InputMessage 1909 function of the Message service.

[152] FIG 41 illustrates an example of how a basic robotic synchronous processing thread is executed generically. A SynchronousApplicationThread 2300 induces a processing cycle on a synchronous basis on an Application managed object 2301. Overloaded processing then results in a call to a RobotGeneric managed object 2302. The RobotGeneric object 2302 performs configured synchronous sensing, conduct execution, and actuation via the Sensor 2303, Conduct 2304, and Actuator 2305 services, respectively.

[153] FIG 42 illustrates an example of how a concrete conduct implementation is invoked in order to implement a GPS-based steering plan. A RobotGeneric managed object **2000** induces a configured synchronous conduct execution via the Conduct service **2001**. This results in execution of a configured Thought process (*e.g.*, a Plan object). This generic PlanGeneric **2002** delegates to an overloaded concrete plan, in this case a GPSSteeringPlan **2003**. The GPSSteeringPlan **2003** gets current and desired position information from the ReferenceSensor **2004** and Route service **2005**, respectively. The Position **2006** service uses this information to compute the direction to the desired position. The GPSSteeringPlan **2003** then gets orientation information from the ReferenceSensor **2004**. After all this information has been obtained, the GPSSteeringPlan **2003** computes the steering difference via the Orientation service **2007** and finally updates the steering plan with the desired steering information through the ActuatorPlan service **2008**.

[154] FIG 43 illustrates an example of how an actuator plan is initiated generically. The RobotGeneric **2100** managed object performs configured synchronous actuation via the Actuator Service **2101**. For each actuator plan, the ActuatorPlan **2102** (*e.g.*, a steering actuator plan) is obtained if scheduled. The physical Actuator **2103** is effected according to its plan (*e.g.*, direction, speed, feedback limits, etc.).

[155] FIG 44 illustrates an example of how a DC motor controller is commanded to perform actuation via a serial port. The Actuator **2200** is effected according to its actuator plan **2201** (*e.g.*, direction, speed, feedback limits, etc.). Calls to the subclass, in this case DCMotorGeneric **2202** are overloaded. This in turn starts PWM **2203** according to the appropriate parameters (*e.g.*, duration, direction, period, etc.) and overloads this to the subclass (*e.g.*, CommandBasedPWM **2204**, HardwareBasedPWM). PWM commands are written to the DCMotorGeneric **2202**, which then delegates write operations to the superclass, PeripheralGeneric **2205**. PeripheralGeneric **2205** performs any configured signal conversions via an InterfaceMapping abstraction **2206**, which writes signals to the InterfaceManager

2207. The **InterfaceManager 2207** determines the appropriate interface **2208** to write these signals, and the writing is delegated appropriately (in this case, to the **SerialPortGeneric interface 2209**). In this example, data is written to the Serial Port (e.g., PWM command to a motor controller) **2210**.

[156] FIG 45 illustrates how a class can be called within a program to automatically generate a specific client envoy, envoy interface, and target envoy given some configuration information. The **ObjectLauncher 2300** is used to start an **EnvoyMaker 2301** instance. The **EnvoyMaker 2301** gets a list of IDs of envoys to create from the **Configuration service 2302**. For each ID, creation information is obtained for an envoy (e.g., interface name) **2303**. The **EnvoyMaker 2301** generates an **Envoy Interface 2303**, and an **Envoy Target 2304**. Finally, an **Envoy Client 2305** is generated.

[157] FIG 46 illustrates how an **ObjectLauncher 2401** configuration can automatically create one or more target envoys in a server process. The target envoys then listen for requests from clients. (This figure illustrates the automated configuration and initialization of an application with target envoy objects. Target envoys can also be explicitly created and configured from within an application without use of the **ObjectLauncher 2401**). The **System 2400** launches the **ObjectLauncher program 2401**, which performs its initial loading. The **ObjectLauncher 2401** obtains an object handle from the **ObjectRegistry 2402**, given a launcher ID. The object is then configured according to its configuration properties. The **launcher:ObjectLauncher 2403** obtains an object handle (e.g., **ReferenceSensorTargetEnvoy** object) from the **ObjectRegistry 2402** given an **EnvoyObjectID** (e.g., **RobotApID**). A managed object (in this case, **ReferenceSensorTargetEnvoy**) **2405** is created and configured. The **launcher:ObjectLauncher 2403** then registers the object (i.e., **ReferenceSensorTargetEnvoy**) via an **AnyInterface 2404** according to its ID. This process is repeated for each object handle. The **ObjectLauncher 2401** is then ready to

launch. If the launcher policy is to loop upon managed object creation (*e.g.*, as with a remote object), the looping occurs and target envoys field any remote requests.

[158] FIG 47 illustrates background processes that occur when a target envoy is created and configured. The figure illustrates how a generic superclass (TargetEnvoy), which is part of the Envoy service, generically configures and registers a target envoy object with an envoy directory. The specific example illustrates a distributed reference sensor (*e.g.*, a GPS Sensor) that is created as an RMI server and registered with an RMI directory server using the Java JNDI service. RMI is a type of distributed communication methodology. It will be understood that the target envoy can be created using any underlying medium, not only RMI. The target could alternatively be created as a Web service, CORBA service, TCP/IP service, serial communications service, etc., and registered with an envoy directory appropriate for that specific medium (*e.g.*, a UDDI directory service for Web services, a CORBA Naming Service for a CORBA service). The TargetEnvoy and BaseEnvoy are generic classes in the Envoy service. The RMI and JNDI classes are generic classes provided inside GPROS as well. It will be understood by those skilled in the art that any sort of object can be created as a target envoy. For robot and automation applications, the target envoy might be a sensor, or an actuator, or a conduct object.

[159] In the figure, the ObjectLauncher 2500 configures a managed object 2501, in this case "ReferenceSensorTargetEnvoy". This operation is delegated to the superclass, here TargetEnvoy 2502. The configuration provides the real target object ID, and an object handle (*e.g.*, ReferenceSensor object) is obtained from the ObjectRegistry 2503 given the object ID (GPSSensorID). The superclass ("BaseEnvoy") 2504 is called to create an envoy medium delegate 2505. Either an envoy medium ID or class name is obtained from the configuration, and this information is used to obtain an envoy medium delegate (*e.g.*, RMIMediumImpl) 2505 from the ObjectRegistry 2503. This envoy medium delegate 2505 is used to register the target envoy 2502. The TargetEnvoy 2502 calls the superclass ("BaseEnvoy") 2504 to connect with an envoy directory 2506. The envoy directory

ID is obtained from the configuration **2507**. Based on this envoy directory ID, an object directory object (*e.g.*, JNDIEnvoyDirectory) is obtained from the ObjectRegistry **2503**, and connection is initiated. Finally, the TargetEnvoy **2502** obtains an envoy medium bind name ID (*e.g.*, RemoteGPSSensorA) from the configuration **2507** and registers the envoy medium delegate with the directory using the envoy medium bind name ID.

[160] FIG 48 illustrates a connection to an envoy directory service. In the illustrated example, a JNDI directory service is connected via an underlying mapping to an RMI directory service provider. Alternatively, for example, a UDDI directory service could have been used for a Web service envoy medium. In the figure, a TargetEnvoy managed object **2600** calls the superclass ("BaseEnvoy") **2601** to connect to an envoy directory. The superclass then obtains an envoy directory ID from the Configuration **2602** and utilizes it to obtain a directory object (*e.g.*, JNDIEnvoyDirectory) **2604** from the ObjectRegistry **2603** and then create and configure the object. The JNDIEnvoyDirectory **2604** in this case delegates configuration to the superclass envoy directory **2605**, which creates an EnvoyMessage **2606**, reads the directory service connection info (*e.g.*, RMI URL and RMI Directory Service Driver name) from the configuration **2602**, and passes all connection parameters to the created EnvoyMessage **2606**. In this example, the BaseEnvoy **2601** connects to the JNDIEnvoyDirectory **2604**, which connects to JNDI service using the connection information. The original Target Envoy **2600** obtains the envoy medium bind name ID and utilizes it to register the envoy medium delegate with the directory.

[161] FIG 49 illustrates a JNDI directory service binding a server object to a name for lookup by remote clients. A TargetEnvoy managed object **2701** registers the envoy medium delegate with the envoy directory (*i.e.*, JNDIEnvoyDirectory) **2702** using the envoy medium bind name ID. The envoy directory binds the envoy medium delegate (*e.g.*, an RMIMediumImpl) to the JNDI directory service given the ID name.

[162] FIG 50 illustrates how an envoy client is created, configured, and utilized to obtain a handle to an underlying envoy medium client. The figure illustrates how a

distributed client creates a handle to a reference sensor (*e.g.*, a GPS Sensor). The client code does not need to know if it is communicating with a local (in-memory) or a distributed GPS sensor. Although an RMI medium is presented in the figure, the client could also have been configured to communicate with a GPS sensor via Web services, CORBA, TCP/IP, etc. A client class, in this example Sensors 2800, obtains an object handle (*e.g.*, ReferenceSensorClientEnvoy) 2801 from the ObjectRegistry 2802 given a Sensor ID (*e.g.*, GPSSensorID). The ObjectRegistry 2802 creates and configures the ReferenceSensorClientEnvoy object 2801, which delegates the configuration to the superclass, ClientEnvoy 2803. This sensor ClientEnvoy 2803 calls the superclass ("BaseEnvoy") 2804 to connect to the envoy directory. The ClientEnvoy 2803 obtains the envoy medium bind ID (*e.g.*, RemoteGPSSensorA) from the Configuration 2805, and given this information, looks up the envoy medium client (*e.g.*, RMIMedium) via the EnvoyDirectory (here, "JNDI EnvoyDirectory") 2806. This EnvoyDirectory 2806 looks up an envoy medium client (*e.g.*, RMIMedium) 2807 from the JNDI directory service 2806. After this is completed, the ClientEnvoy 2803 calls the superclass to create an envoy medium delegate 2807. The Base Envoy 2804 obtains either an envoy medium ID or a class name from the configuration 2805 and obtains an envoy medium delegate object (*e.g.*, RMIClientEnvoy) 2807 from the ObjectRegistry 2802 based on the envoy medium ID or class name. Finally, the ClientEnvoy 2803 associates the envoy medium client (*e.g.*, RMIMedium) via the envoy medium delegate 2807.

[163] FIG 51 illustrates the procedure of the envoy client when a client envoy is invoked. Zero or more input parameters may be sent by the client envoy and zero or more output messages may be received and returned by the client envoy. A client class, in the figure a Sensors abstraction 2900, obtains its current position from a ReferenceSensorClientEnvoy 2901. Because the ReferenceSensorClientEnvoy 2901 implements the ReferenceSensor interface, the client class is unaware that it is communicating with a client envoy, *i.e.*, the remoteness is transparent. The client envoy method implementations are automatically generated using an automated

software utility (*e.g.*, EnvoyMaker). In the figure, the ReferenceSensorClientEnvoy 2901 creates an envoy message 2902 for the client envoy method ID. Any input values of an EnvoyMessage are set via an input ID 2903. Generic invocations of the superclass (ClientEnvoy) 2904 are called with this input EnvoyMessage 2903. The superclass, here a sensor ClientEnvoy 2904, invokes an envoy medium delegate (*e.g.*, RMIClientEnvoy) 2905 with an input message and returns any output message 2906. This envoy medium delegate invokes an envoy medium (*e.g.*, RMIMedium) 2907 with the input message and returns any output message 2906. The underlying message stub is called to transmit the message. Any return message is returned. Upon the completion of these tasks, the ReferenceSensorClientEnvoy 2901 obtains any output values returned via the output Envoy message (*e.g.*, position) 2906. This information is returned to the initial client class 2900.

[164] FIG 52 illustrates the procedure of the envoy target side when a target envoy is invoked. Zero or more input parameters may be received by the target envoy and zero or more output messages may be returned and sent by the target envoy. In the figure, a distributed runtime (*e.g.*, RMI runtime) 3000 invokes an EnvoyMediumDelegate (in this case, RMIMediumImpl) 3001 with any input messages and returns any output messages. The EnvoyMediumDelegate 3001 invokes a target envoy managed object 3002 with inputs and any outputs are returned. The target envoy methods are overloaded by a subclass, in this example a ReferenceSensorTargetEnvoy 3003, a managed object. This managed object gets a message ID and any input values. A target 3004, for example a ReferenceSensor, is invoked via a proper method with input values 3006 and any output values are obtained 3007. The ReferenceSensorTargetEnvoy 3003 creates an output message for this message ID and sets any output values for an output EnvoyMessage 3005. Any output messages are returned to the ReferenceSensorTargetEnvoy 3003.

[165] Speaking now in general terms based on the above disclosure, certain embodiments discussed thus far illustrated how the GPROS can be realized and used to implement a robotics application. That is, for example, an unmanned ground

vehicle (UGV) application can use a standard GPROS profile on a main processor platform, running Linux, and using a Java Platform, Standard Edition to specify the configuration of sensors for GPS, inertial navigation and orientation, multiple laser range finders, RADAR; configuration of actuators with command based PWM configurations for brake, steering, shifting, and throttle actuation; conduct planning for synchronous waypoint navigation and asynchronous obstacle avoidance. A micro GPROS profile can also be used in multiple micro-processors running a Java Platform, Micro Edition to specify the configuration of sensors for receiving actuation commands, motor feedback, and vehicle state sensors; configuration of actuators with hardware based PWM configurations directly driving brake, steering, shifting, and throttle motors; and conduct planning for asynchronous motor command handling and real time synchronous feedback control of motors.

[166] The same GPROS profiles may be used for Unmanned Air Vehicle (UAV) helicopter platforms by defining a configuration largely similar to the UGV application but instead loads a configuration with longer range laser range sensors, uses actuators for controlling helicopter rotors and blades, and implements conduct planning for UAV navigation and low-level feedback controls.

[167] Similarly, for an automation application requiring only distributed sensing and no actuation, the GPROS may be configured to load only sensors that have distributed envoys, each with their own underlying communications standard, and to load conduct analysis behavior which takes the distributed sensor information, analyzes it, and presents it in a unified fashion via a graphical user interface.

[168] Likewise, for applications that are not robotics or automation related, the generic application services can be used. For example, in a business-to-business (B2B) application, a means using GPROS for reading information from a mobile phone interface peripheral may be configured, a conduct planning behavior for rendering a user interface may be configured, and a client envoy to a distributed Web service may be configured. GPROS on the server side may also be used and configured with a target envoy to receive invocations from client envoys, a conduct planning behavior triggered by pooled asynchronous application threads may be

configured to handle such requests, and the any service used to transparently record requests to a database.

[169] Thus, one embodiment of the invention is a method for building vertical robotics application framework (VRAF) instances which extend the GPROS for specific vertical robotics applications. One embodiment of the invention is to provide a general purpose robotics hardware interface (GPRHI) for connecting robotics hardware to standard computing platforms. A feature of the technology that includes vertical robotics applications is mine analysis and detection. Robot mobilization and mine detection are two important examples of the actuation and sensing functionality that form the core part of a mobile autonomous robotics platform applied to mine analysis and detection. An example application of the invention is an autonomous unmanned ground vehicle (UGV) application for traversing a long distance within a route corridor while avoiding obstacles. Similarly, the same common GPROS robotics software services may also be leveraged by an autonomous unmanned air vehicle (UAV) application.

[170] It should thus be evident that the present invention provides an operating system that provides individual services and the combination and interconnections of such services using built-in service extensions, built-in completely configurable generic services, and a way to plug in additional service extensions to yield a comprehensive and cohesive framework for developing, configuring, assembling, constructing, deploying, and managing robotics and/or automation applications. The invention provides services that are common to any robotics or automation application, and encapsulates them separately, while providing them as a complete package to enable programmers to write programs in any language for any device or peripheral and plug those programs into the system to achieve a goal. One advantage provided by the invention is that it provides a software engine for programmers, allowing them to focus on minimal business logic specifications and letting the software of the present invention integrate each programmer's product into a functional end-product. In one configuration, the software and system of the invention includes one or both of a general robot service and an automation service,

which extend and use the general application services to provide powerful and useful software and software/hardware solutions. The ability of the present invention to use object-oriented schemes to allow peripheral services to link external peripherals and applications advances the art of robotics and automation. It also allows for cohesive and comprehensive integration of different and disparate third party, proprietary, open source, and other modules (software and hardware, such as third-party rules engines, third-party neural networks, different interface protocols, different distributed communication protocols, different sensor types, different actuator types, different styles of motor control, different robotics application logic, different configuration data sources, different logging mechanisms, and the like), to enable extensibility and other advantages.

[171] In addition, because the peripheral service provides a way for applications to communicate with external peripherals in an object-oriented way, it permits decoupling of the communication from the underlying physical communication interface, and complete configurability.

[172] It will be apparent to those skilled in the art that various modifications and variations can be made in the practice of the present invention and in construction of the device without departing from the scope or spirit of the invention. Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the invention being indicated by the following claims.

CLAIMS

1. A general purpose robotics and/or automation operating system (GPROS) comprising:

a set of application services that provides access to configuration data using a generic abstraction, wherein the application services are independent of any underlying hardware platform and allow for any combination of communication or operational conduct for any communication or operational task.

2. The GPROS of claim 1, wherein the set of application services comprises one or more of the following services: a sensor service, an actuator service, a conduct service, a robot service, an obstacle service, a navigation service, a mobility service, a thought service, a plan service, a rules service, a neural service, a motor service, a pwm service, a god service, a mechanism service, a gear service, a reference service, a range service, a ladar service, a radar service, a feedback service, a digital service, an analog service, a fusion service, a watchdog service, and a safety service.

3. The GPROS of claim 1, wherein the service is one or more of the following services: range; ladar; ladar sick; radar; radar vorad; reference; reference geo; reference nmea; mechanism, gear; actuator; motor; timer, pwm; conduct; and/or mobility services.

4. The GPROS of claim 1, wherein the set of application services comprises at least one service that utilizes a wheeled platform; utilizes a legged platform; utilizes a tracked platform; utilizes flight operations; provides navigation; provides robot god; and/or provides rules, neural.

5. The GPROS of claim 1, wherein the operating system is a robotics operating system that allows for any combination of communication or operational conduct for any communication or operational task.

6. The GPROS of claim 1, wherein the set of application services is completely configurable and can be adapted statically and dynamically.

7. The GPROS of claim 1, wherein the GPROS provides individual services and the combination and interconnections of such services using built-in service extensions, built-in completely configurable generic services, and a way to plug in additional service extensions to yield a comprehensive and cohesive framework for developing, configuring, assembling, constructing, deploying, and managing robotics and/or automation applications.

8. A general purpose applications services operating system comprising: a set of application services that provides access to configuration data using a generic abstraction, wherein the application services are independent of any underlying hardware platform and allow for any combination of communication or operational conduct for any communication or operational task.

9. The operating system of claim 8, wherein the set of application services comprises one or more of the following services: a config service, a registry service, a comm service, an ap service, an envoy service, a peripheral service, an any service, a signals service, a signals.message service, a signals.mapping service, a hardware service, a system service, an id service, and an automaton service.

10. The operating system of claim 8, wherein the operating system provides individual services and the combination and interconnections of such services using built-in service extensions, built-in completely configurable generic services, and a way to plug in additional service extensions to yield a comprehensive and cohesive framework for developing, configuring, assembling, constructing, deploying, and managing robotics and/or automation applications.

11. A method for using a general purpose robotics and/or automation operating system (GPROS), the GPROS comprising:

providing a set of application services for accessing configuration data using a generic abstraction, wherein the application services are independent of any underlying hardware platform and are capable of performing any communication or operational conduct for any communication or operational task; and
executing at least one application service of the set of application services.

12. The method of claim 11, wherein executing comprises executing at least one of the following services: a sensor service, an actuator service, a conduct service, a robot service, an obstacle service, a navigation service, a mobility service, a thought service, a plan service, a rules service, a neural service, a motor service, a pwm service, a god service, a mechanism service, a gear service, a reference service, a range service, a ladar service, a radar service, a feedback service, a digital service, an analog service, a fusion service, a watchdog service, and a safety service.

13. The method of claim 11, wherein executing comprises executing at least one of the following services: a service that utilizes a wheeled platform; a service that utilizes a legged platform; a service that utilizes a tracked platform; a service that utilizes flight operations; a service that provides navigation; a service that provides robot god; and/or a service that provides rules, neural.

14. The method of claim 11, wherein the set of application services are robotics application services and the operating system is a robotics operating system.

15. A device comprising:
software for a general purpose robotics and/or automation operating system;
and
hardware upon which the software resides.

16. The device of claim 15, wherein the hardware retains the software indefinitely.

17. The device of claim 16, wherein the hardware is a computer hard drive or memory stick.

18. The device of claim 15, wherein the hardware retains the software ephemerally.

19. The device of claim 18, wherein the hardware is one or more banks of random access memory.

20. The device of claim 15, wherein the hardware is a central processing unit.

21. The device of claim 15, wherein the hardware comprises a mechanical component capable of movement.

22. The device of claim 21, wherein the mechanical component comprises an articulated joint, a wheel, a leg, a wing, a rudder, an arm, a knob, or a pivot point.

23. The device of claim 15, which is an autonomously controlled device.

24. The device of claim 23, which is a robot.

25. The device of claim 23, which is an unmanned ground vehicle (UGV) or an unmanned air vehicle (UAV).

26. The device of claim 15, wherein the software is capable of being updated or otherwise modified before, during, and after fabrication of the device.

27. The device of claim 26, wherein the device is capable of learning by way of updates or modifications of the software, either through human intervention or autonomously.

28. An article of manufacture comprising:
a medium for storage of computer software; and
computer software for a general purpose robotics and/or automation operating system.

29. The article of manufacture of claim 28, wherein the medium is capable of storing computer software by magnetic means or optical means.

30. The article of manufacture of claim 28, wherein the medium comprises a floppy disk, a hard drive, a memory stick, a tape, or a CD.

31. A method of controlling an autonomously controlled device, said method comprising:

providing a set of instructions in the form of computer software that is functionally connected to the device; and
executing the software to effect desired action by the device.

32. The method of claim 31, further comprising modifying the software.

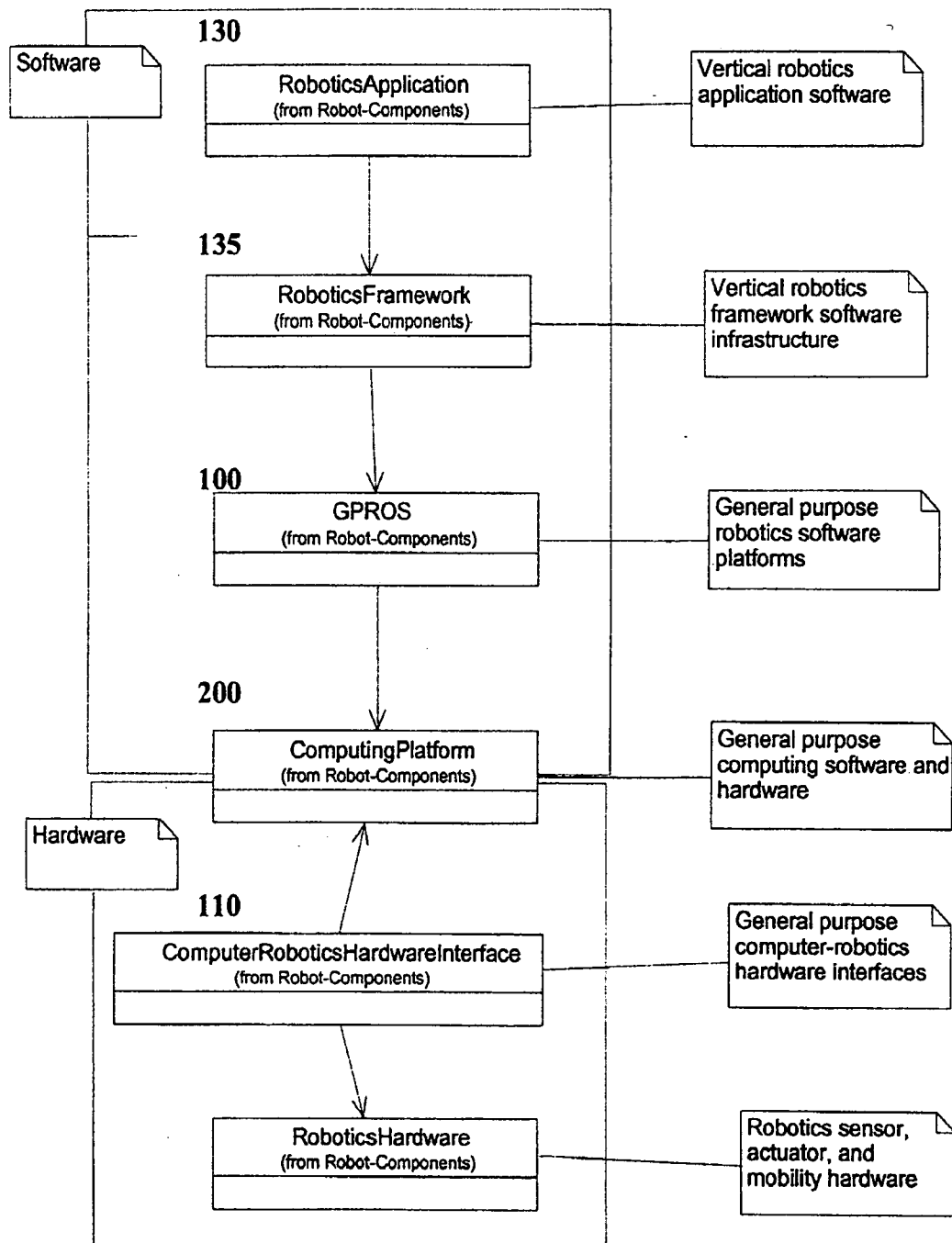
33. A general purpose robotics and/or automation operating system (GPROS) comprising:

a set of application services that provides access to configuration data using a generic abstraction, wherein the application services are independent of any underlying hardware platform and allow for any combination of communication or operational conduct for any communication or operational task; and
a general purpose applications services operating system comprising:

a set of application services that provides access to configuration data using a generic abstraction, wherein the application services are independent of any underlying hardware platform and allow for any combination of communication or operational conduct for any communication or operational task,
wherein the GPROS extends, uses, and is combined with the general purpose applications services operating system.

34. The GPROS of claim 2, further comprising a set of application services comprising one or more of the following services: a config service, a registry service, a comm service, an ap service, an envoy service, a peripheral service, an any service, a signals service, a signals.message service, a signals.mapping service, a hardware service, a system service, an id service, and an automaton service,
wherein the GPROS services of claim 2 extend, use, and are combined with the additional application services.

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**FIGURE 1**

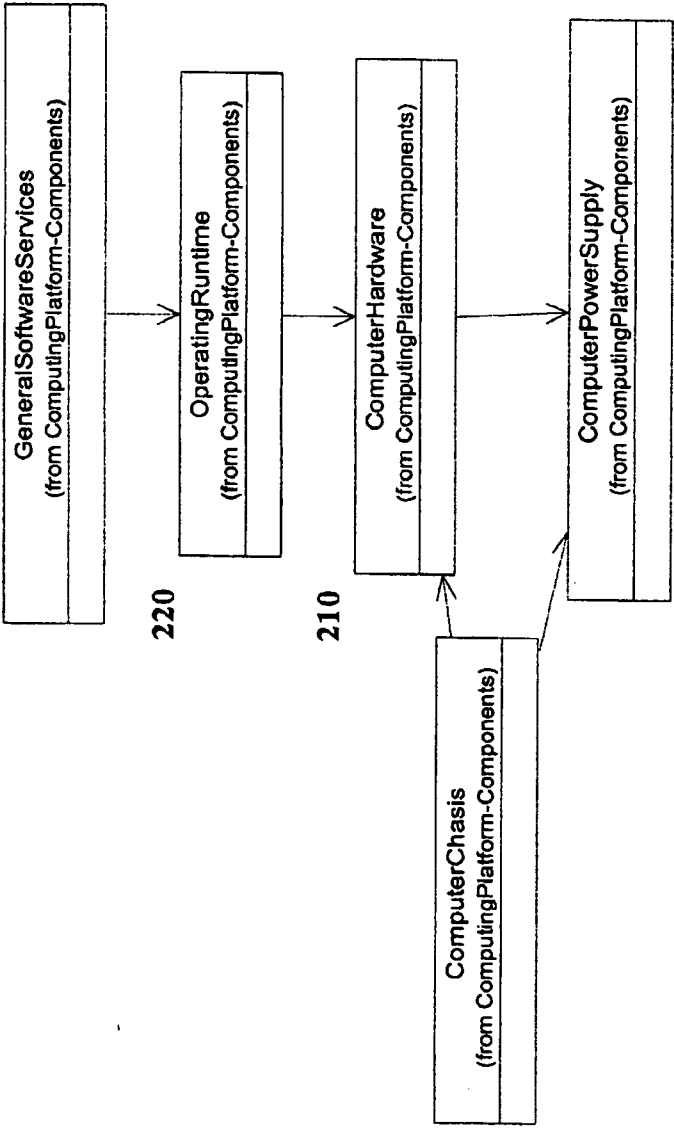


FIGURE 2

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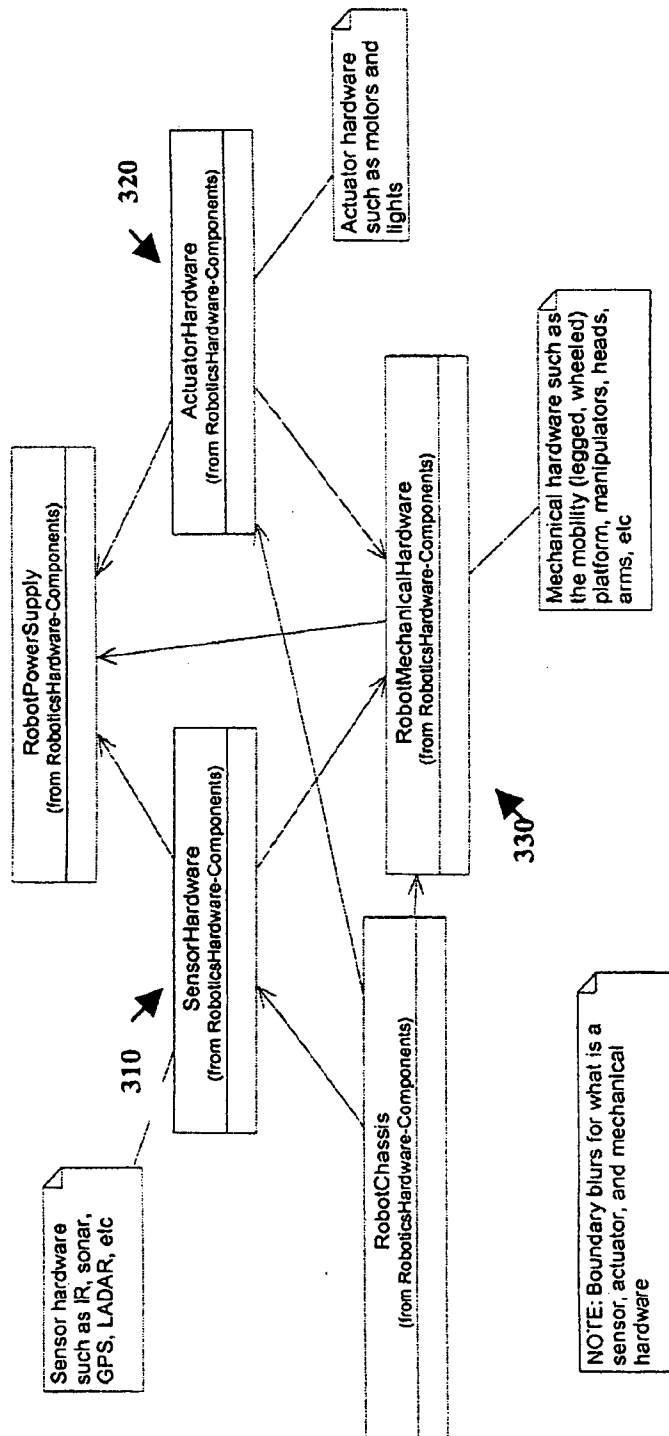


FIGURE 3

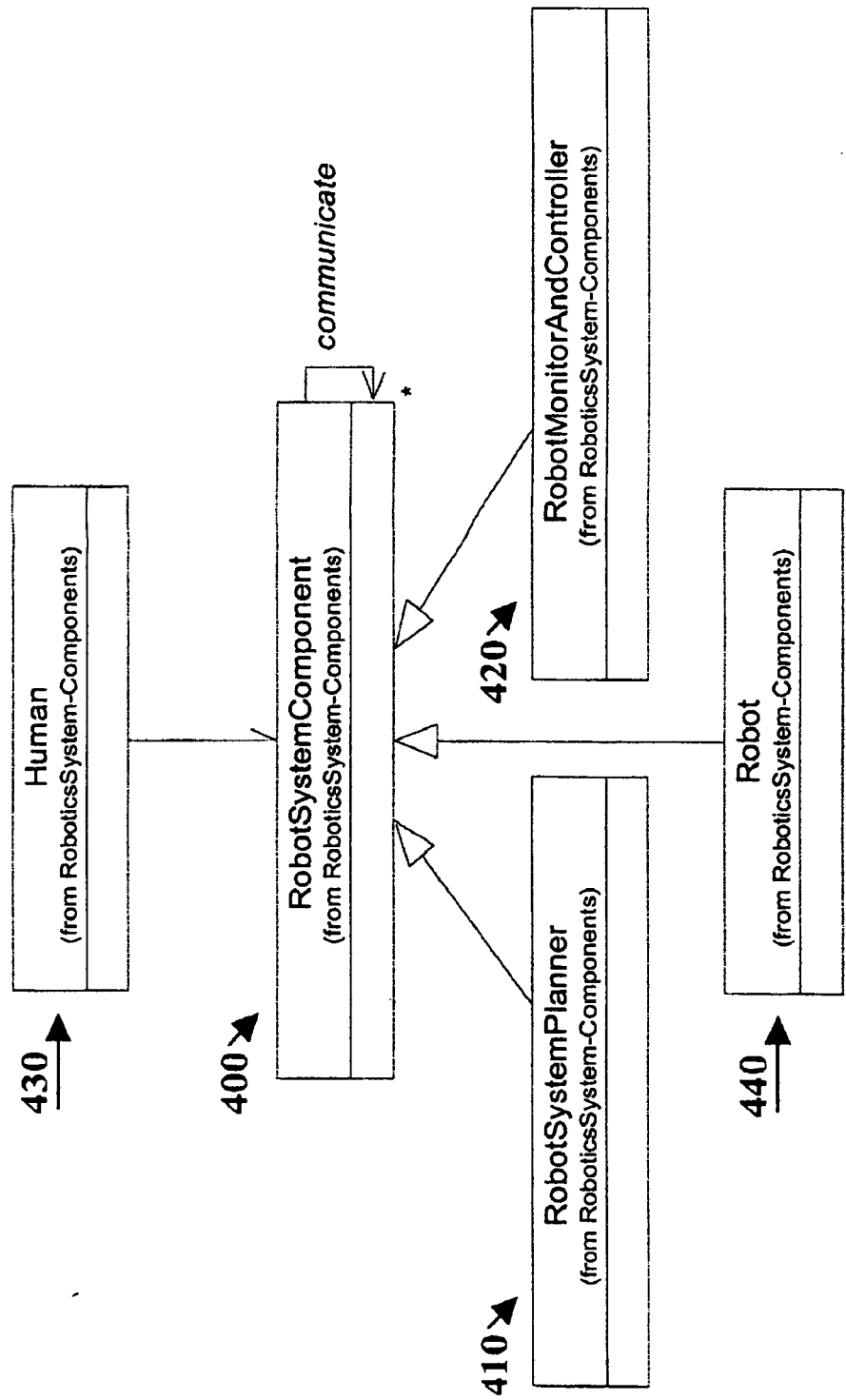
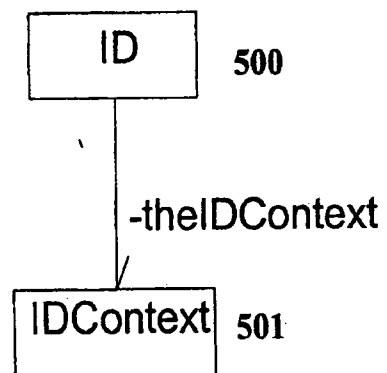


FIGURE 4

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**FIGURE 5**

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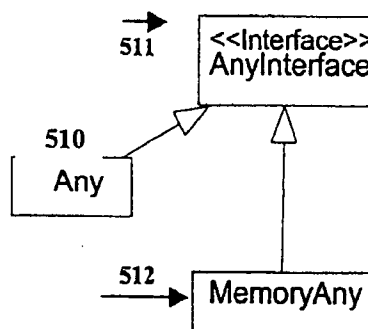


FIGURE 6

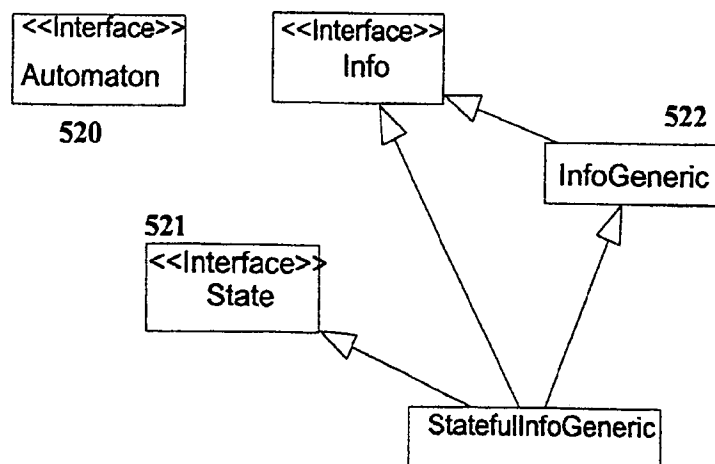


FIGURE 7

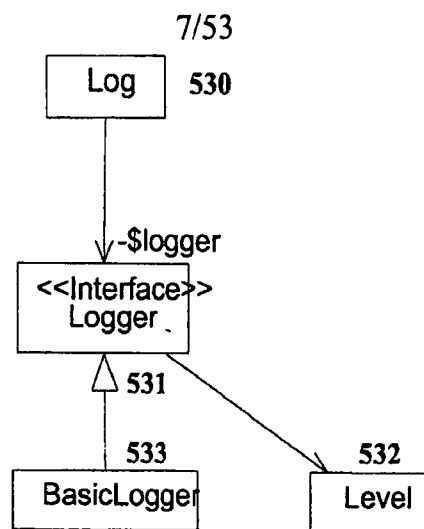


FIGURE 8

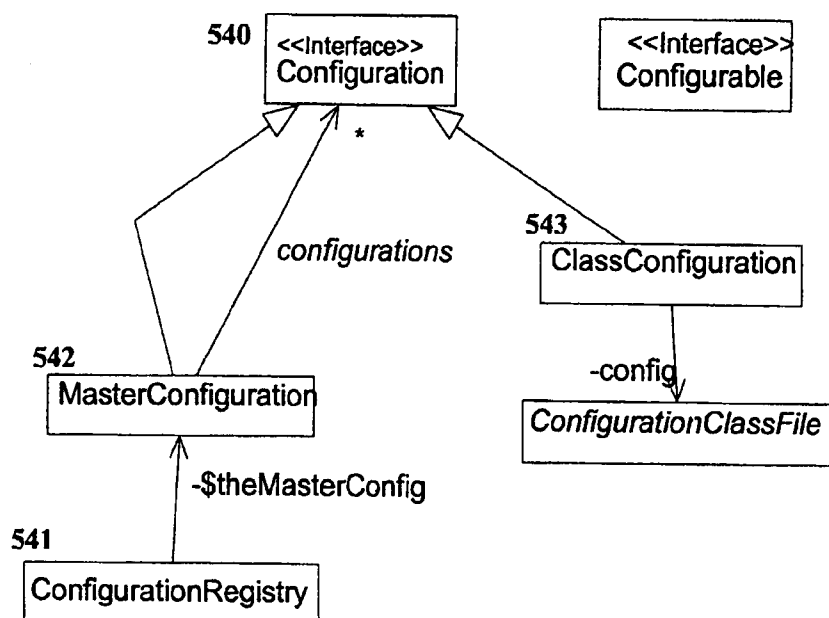


FIGURE 9

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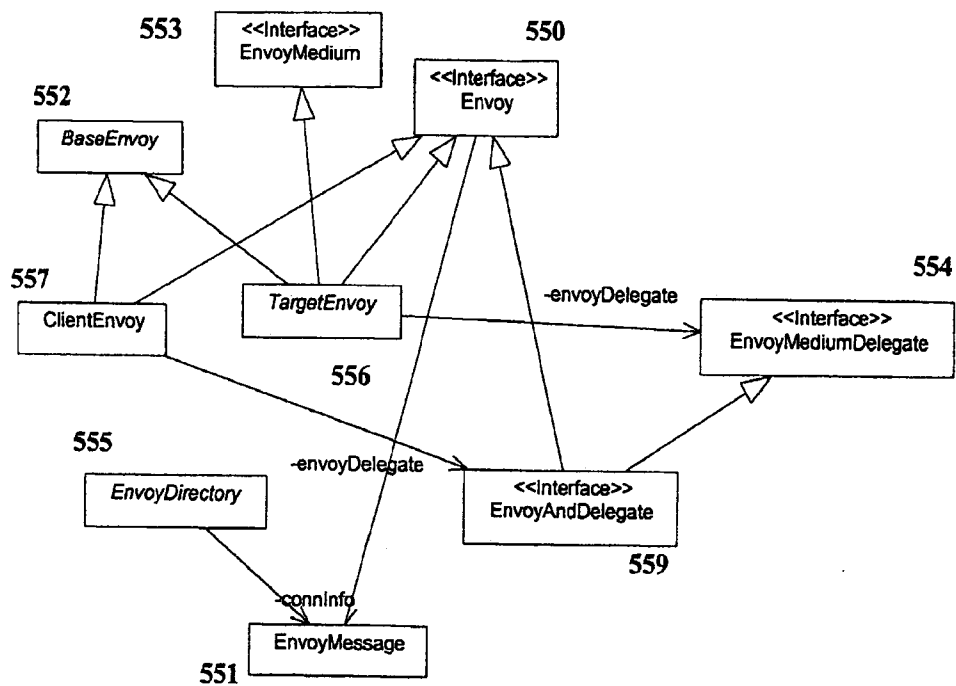


FIGURE 10

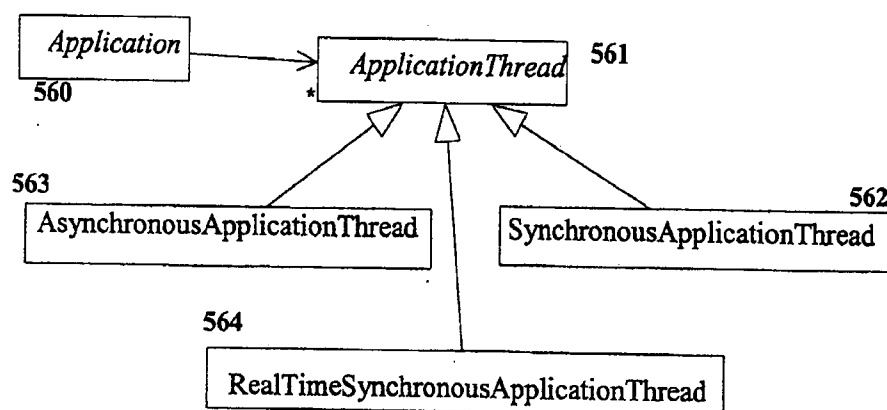


FIGURE 11

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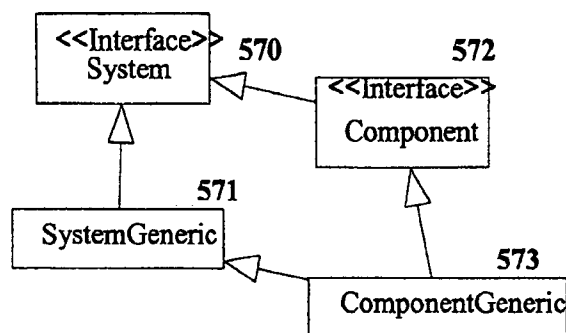


FIGURE 12

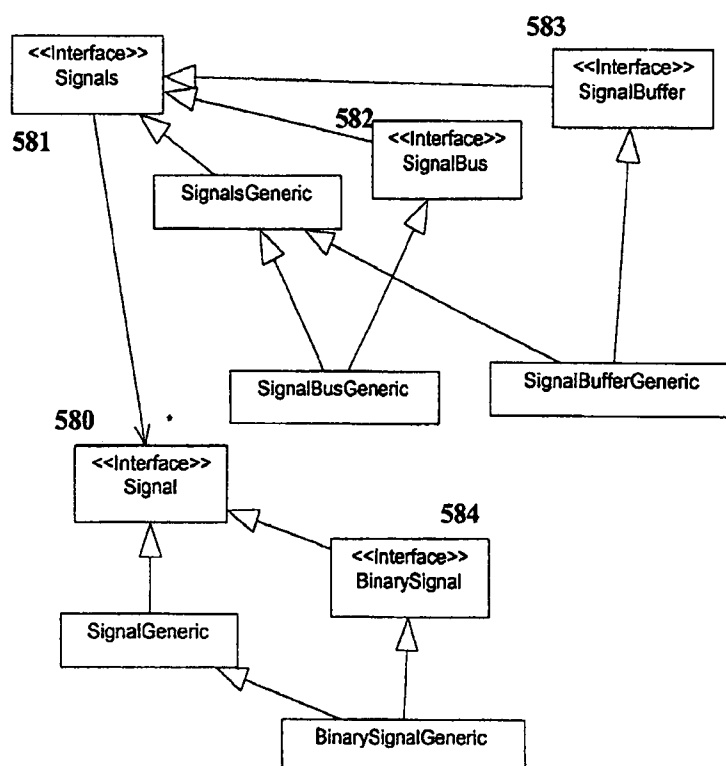


FIGURE 13

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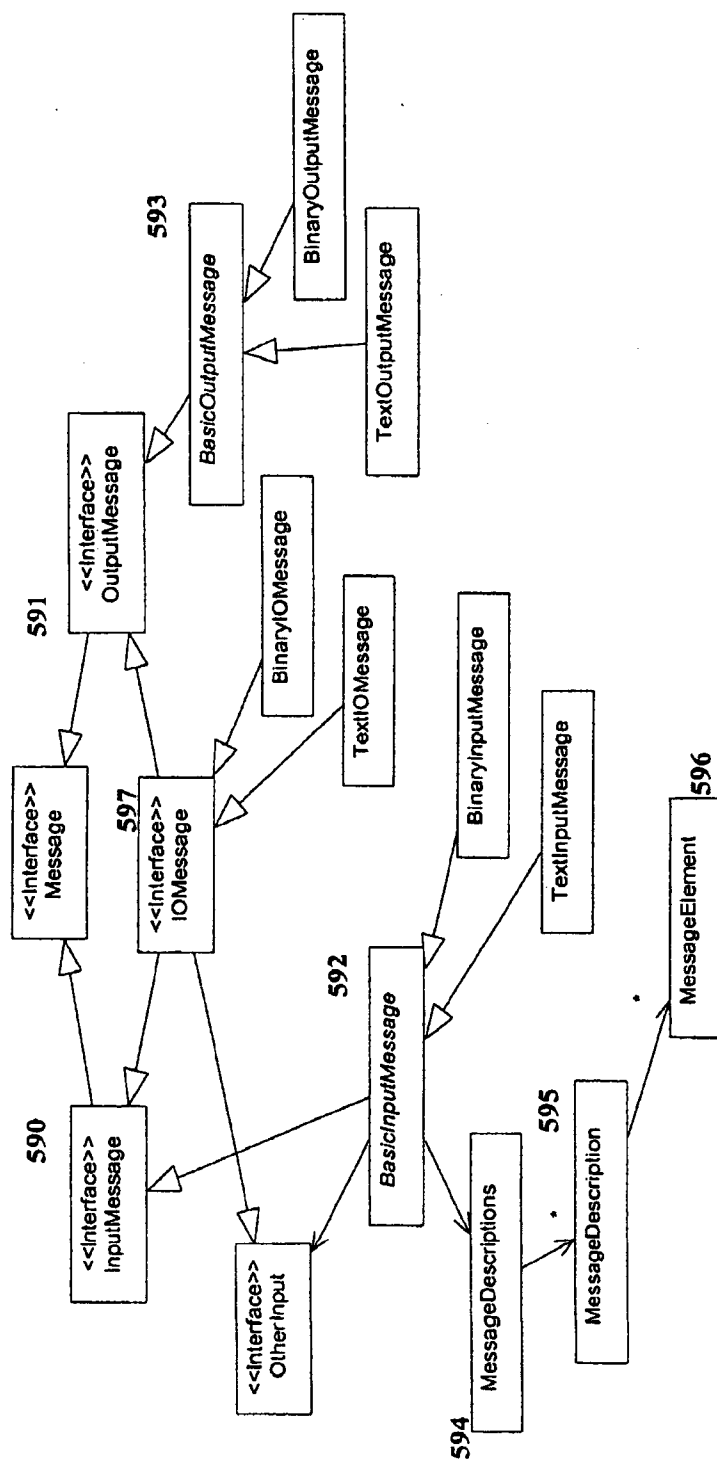


FIGURE 14

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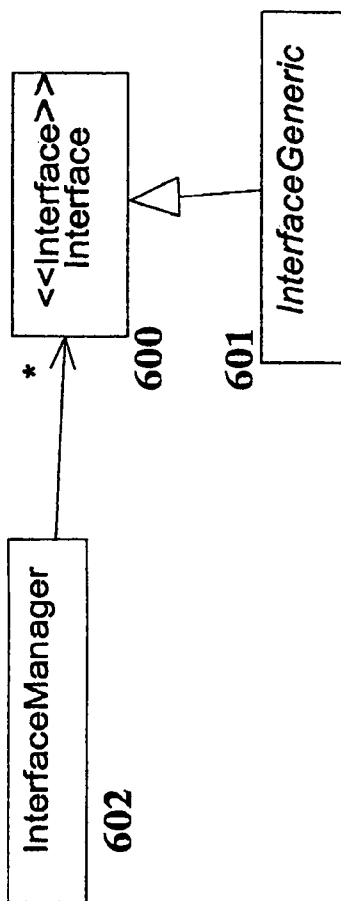
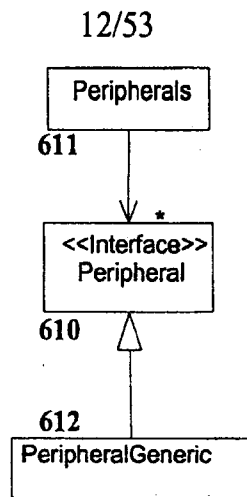
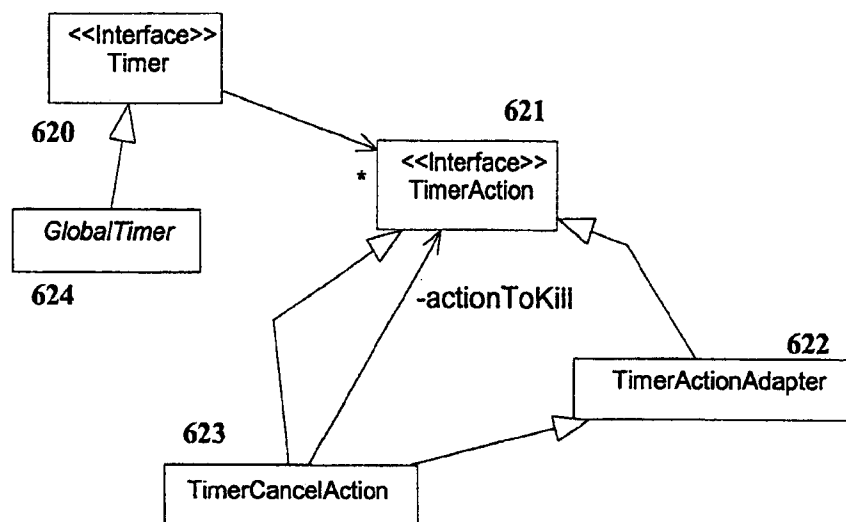
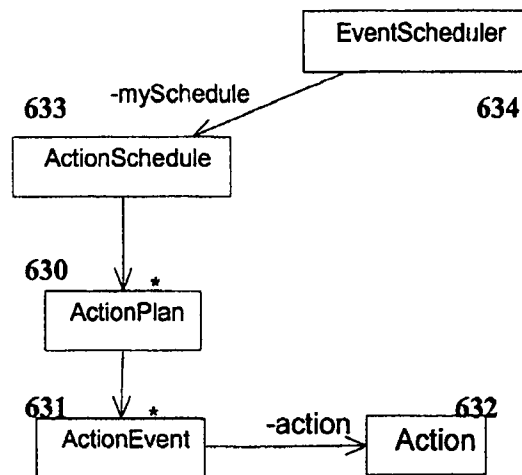
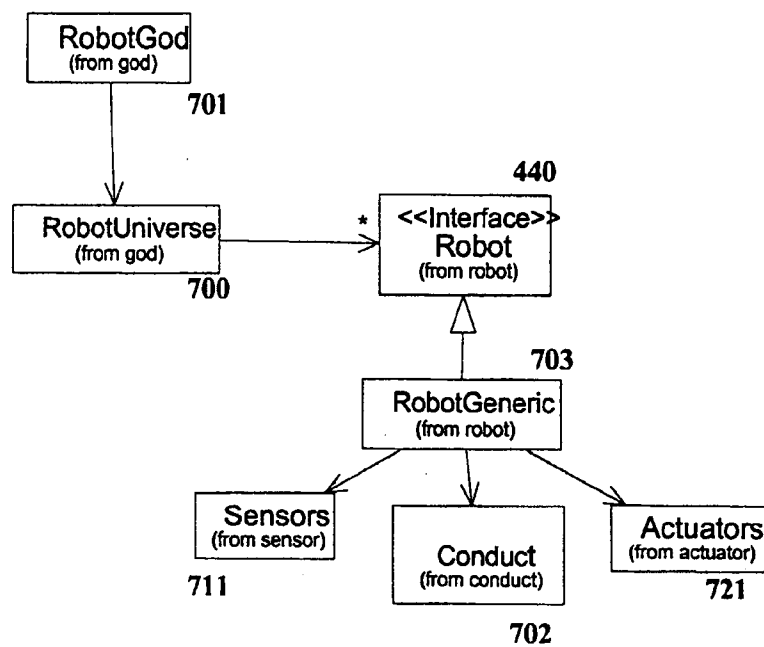
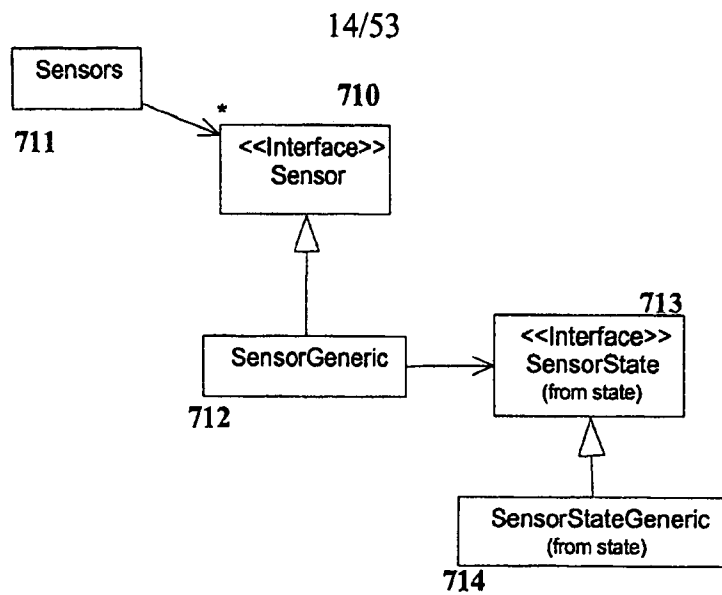
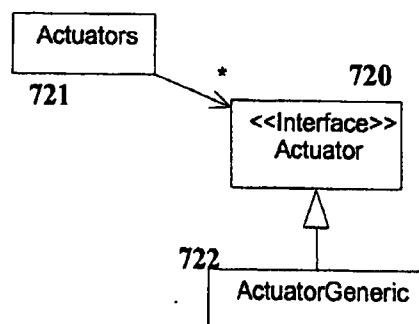


FIGURE 15

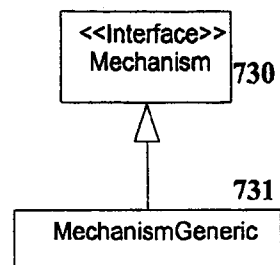
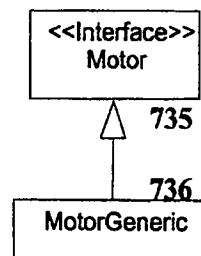
**FIGURE 16****FIGURE 17**

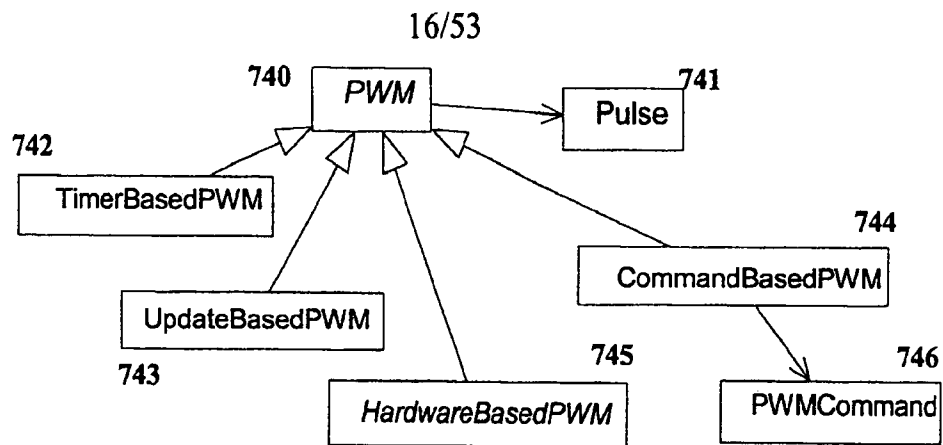
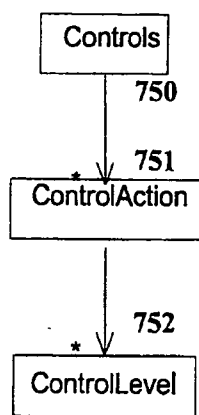
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**FIGURE 18****FIGURE 19**

**FIGURE 20****FIGURE 21**

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**FIGURE 22****FIGURE 23**

**FIGURE 24****FIGURE 25**

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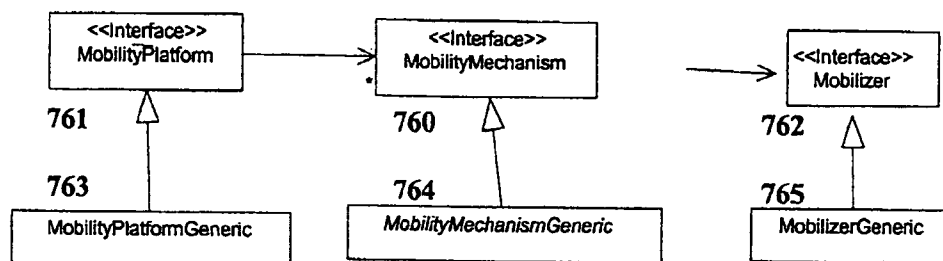


FIGURE 26

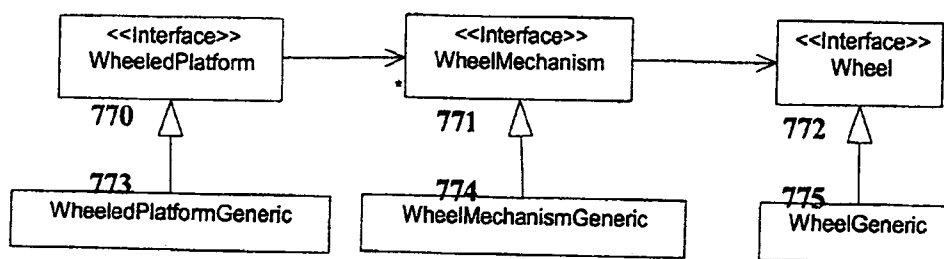


FIGURE 27

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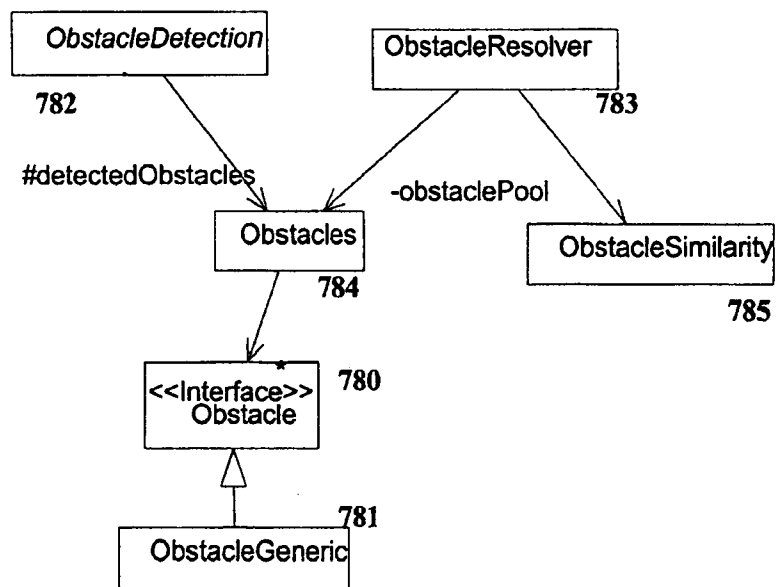


FIGURE 28

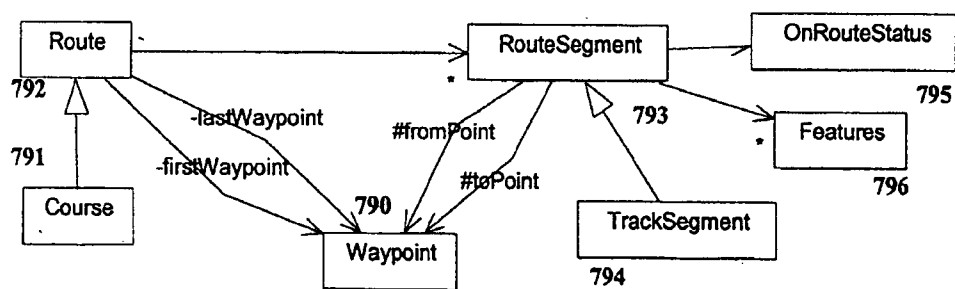


FIGURE 29

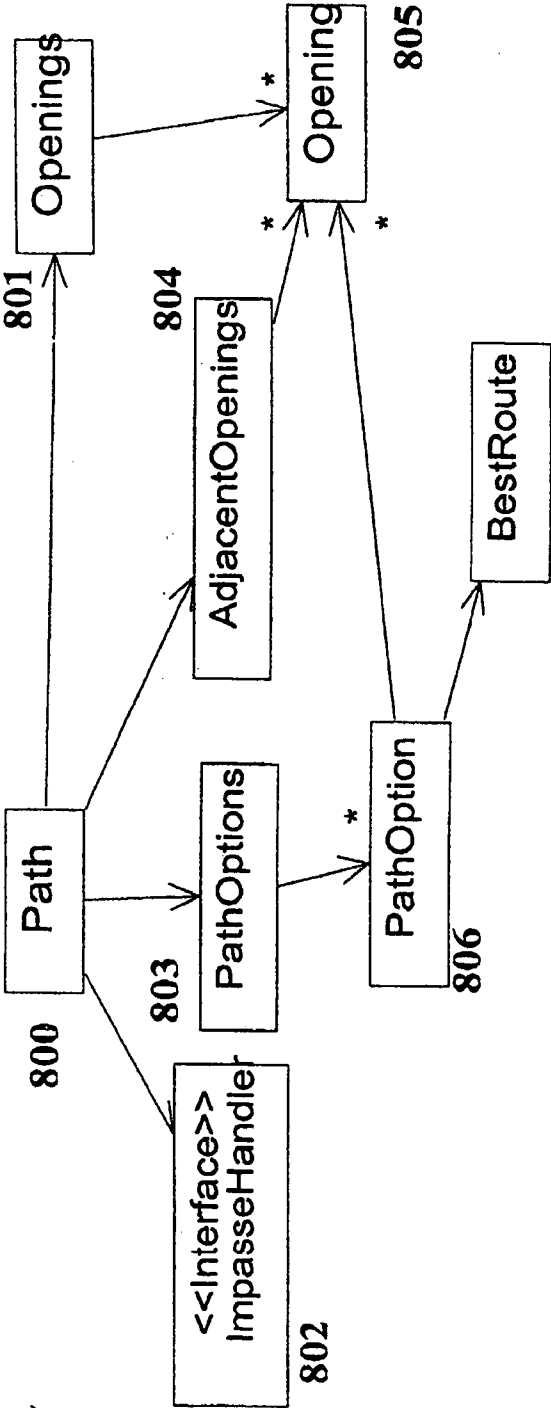


FIGURE 30A

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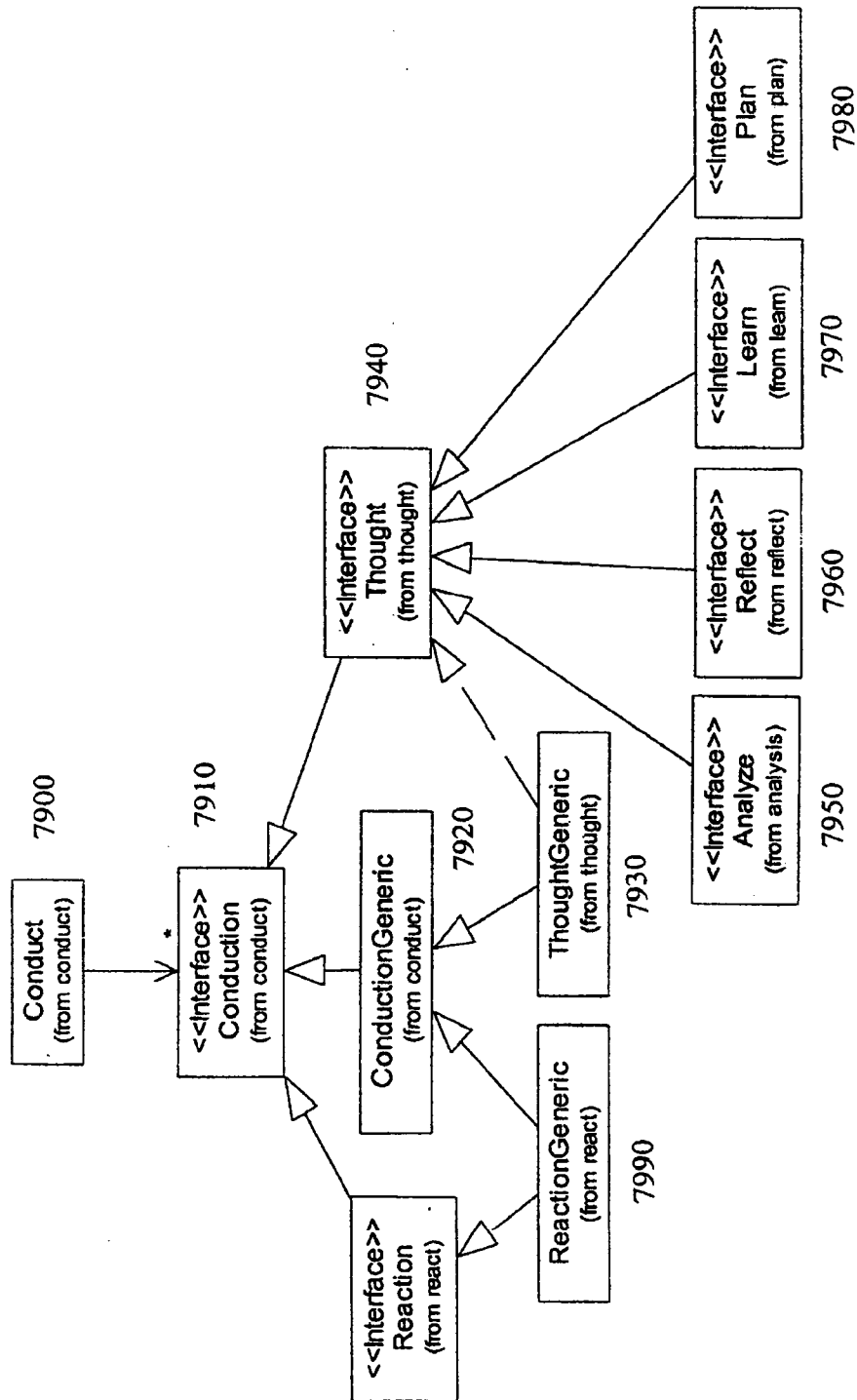
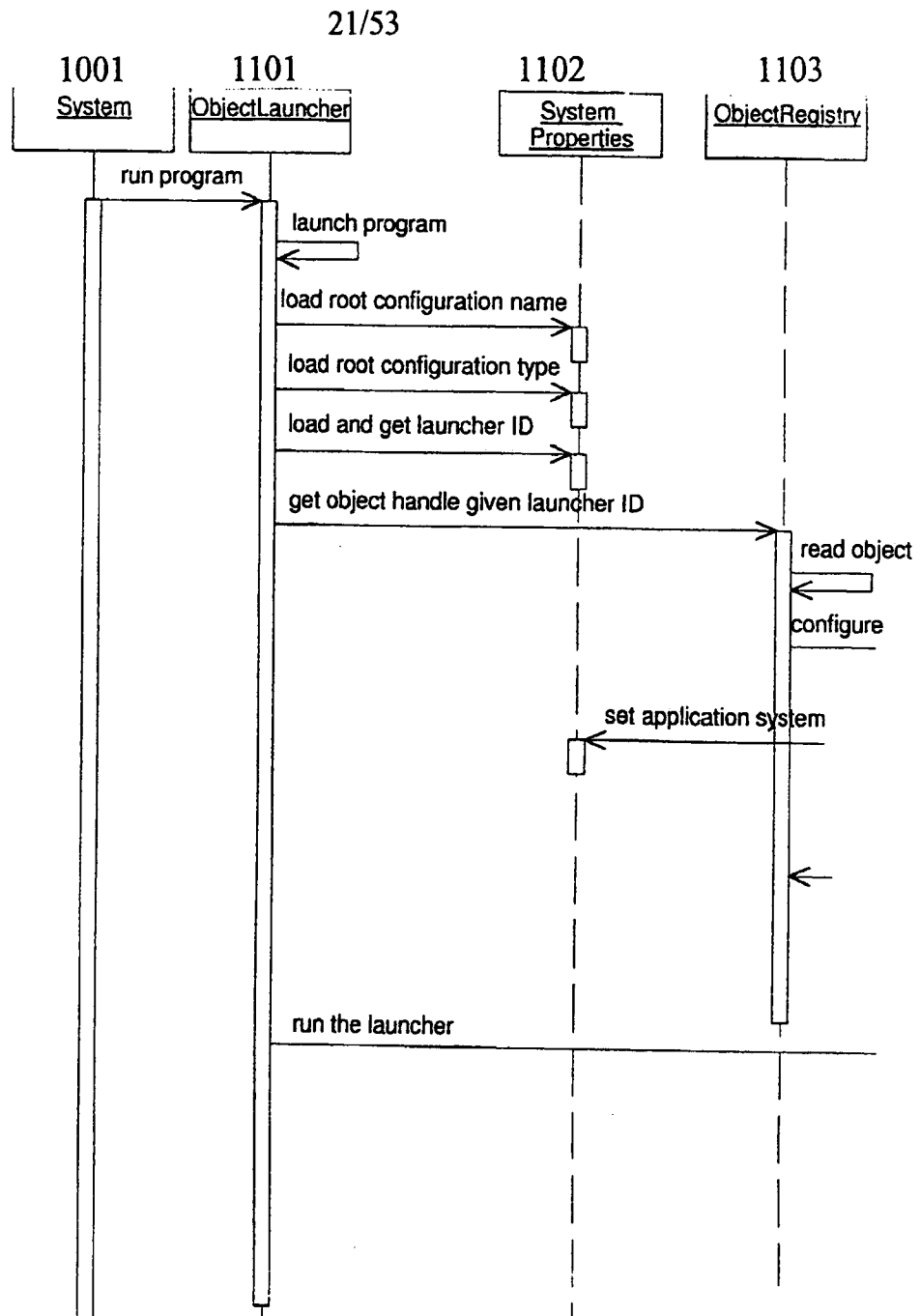


FIGURE 30B

**Figure 31**

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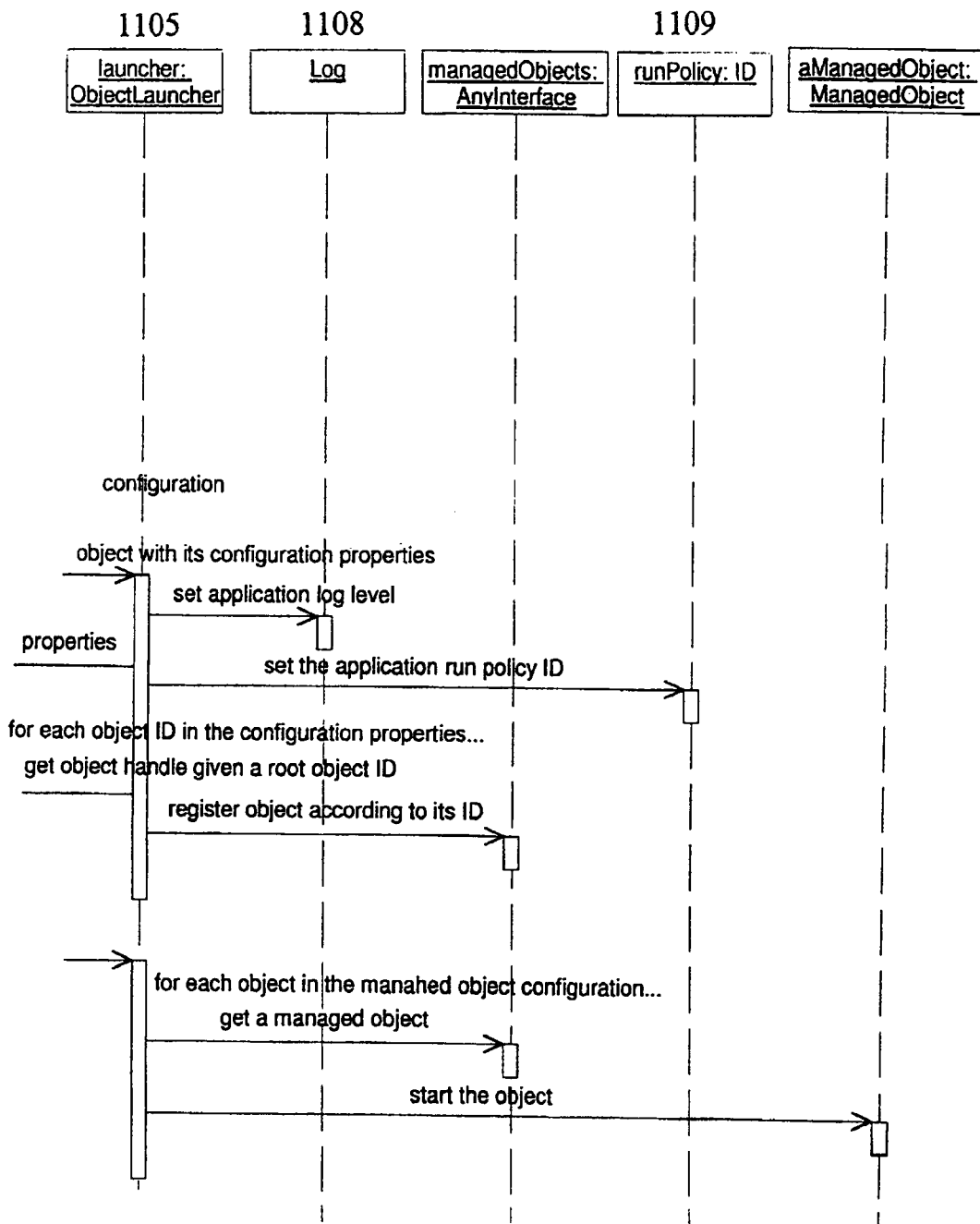


Figure 31 (cont.)

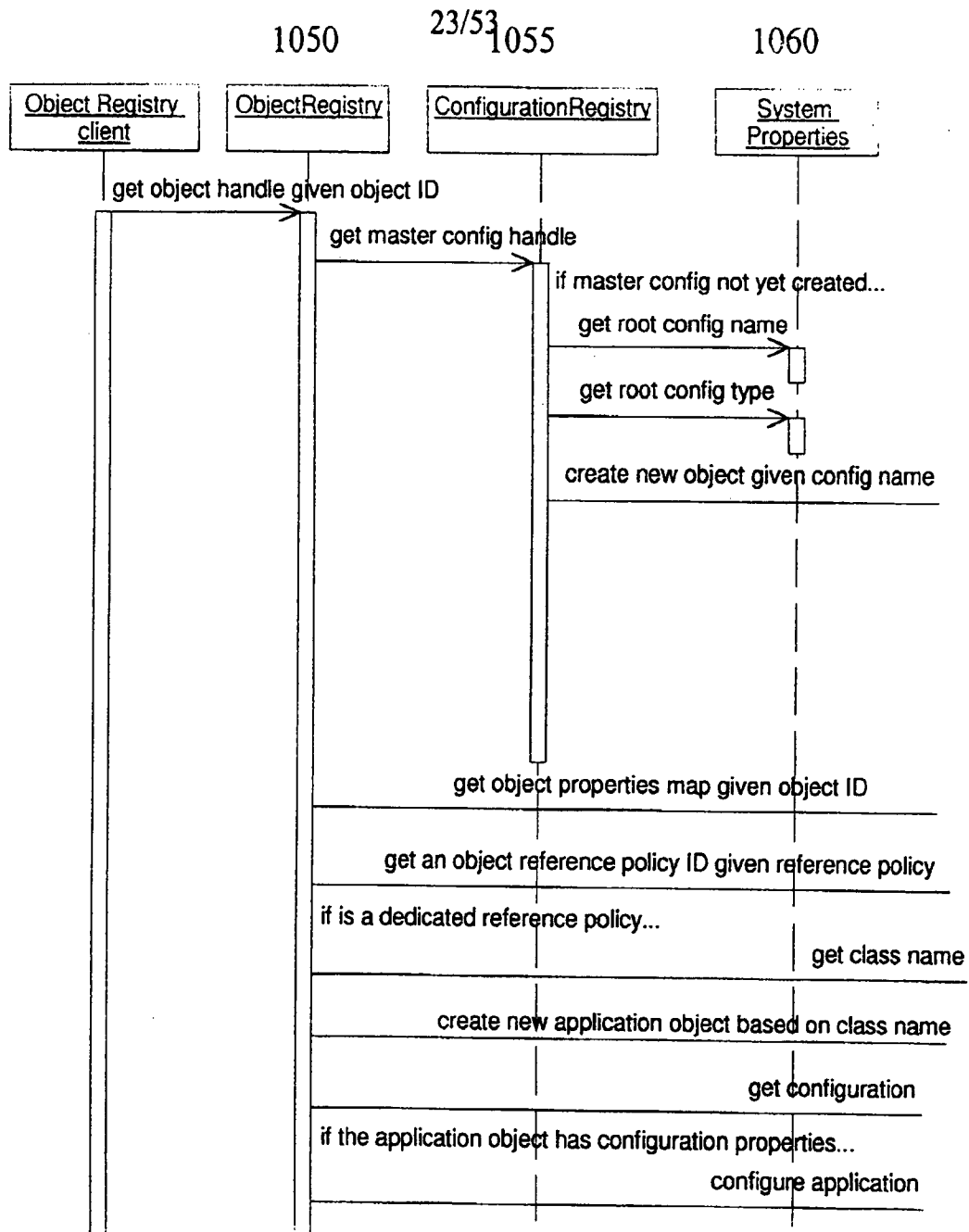


Figure 32

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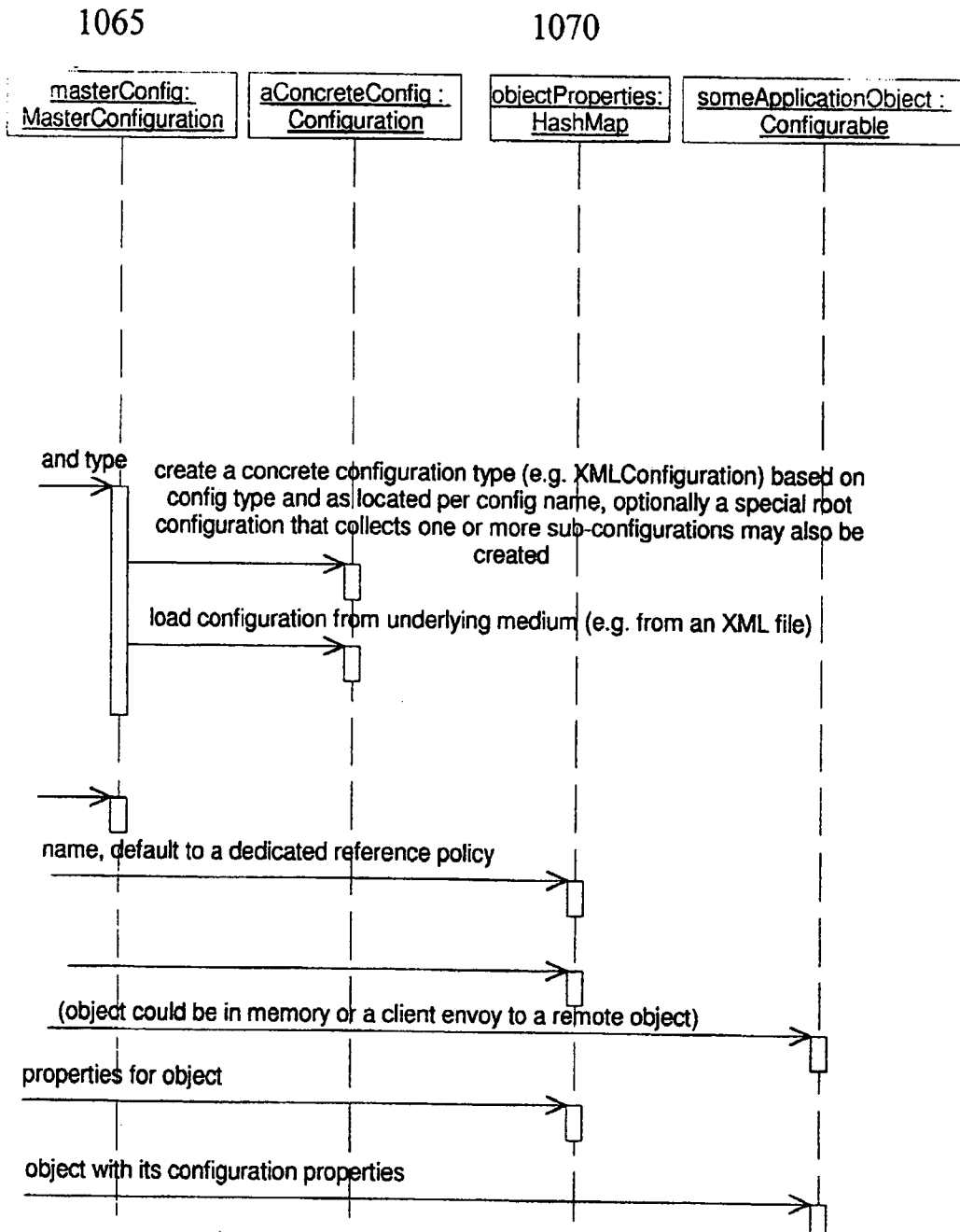
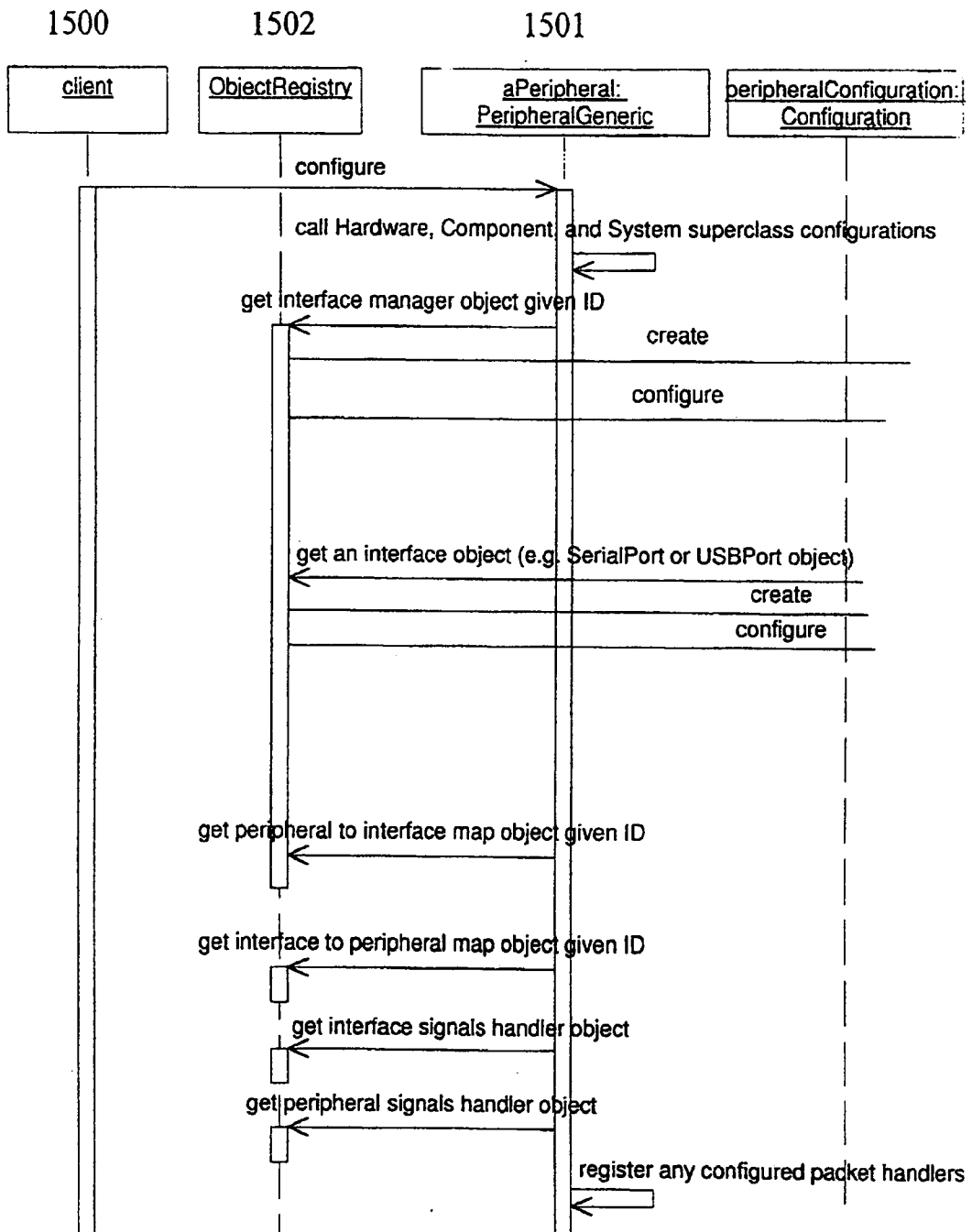


Figure 32 (cont.)

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**Figure 33**

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1504

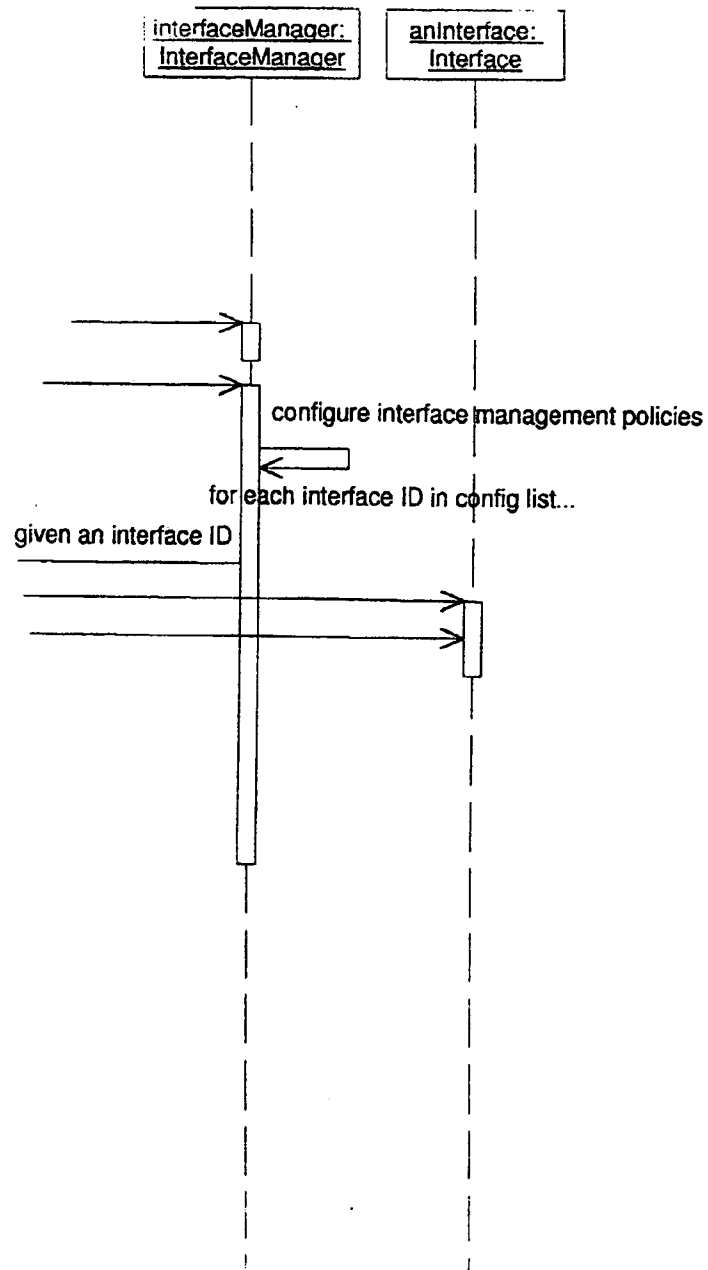


Figure 33 (cont.)

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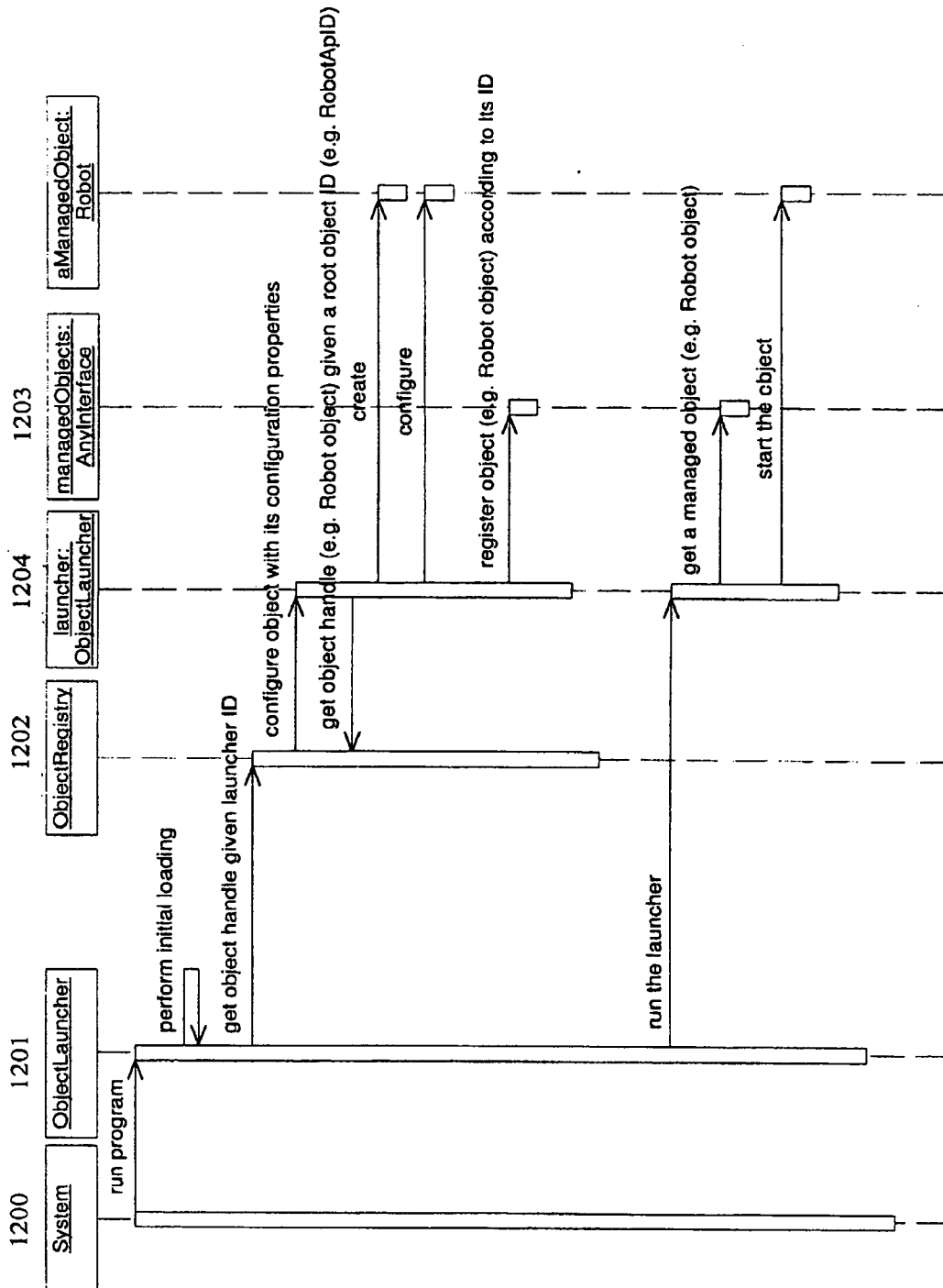


FIGURE 34

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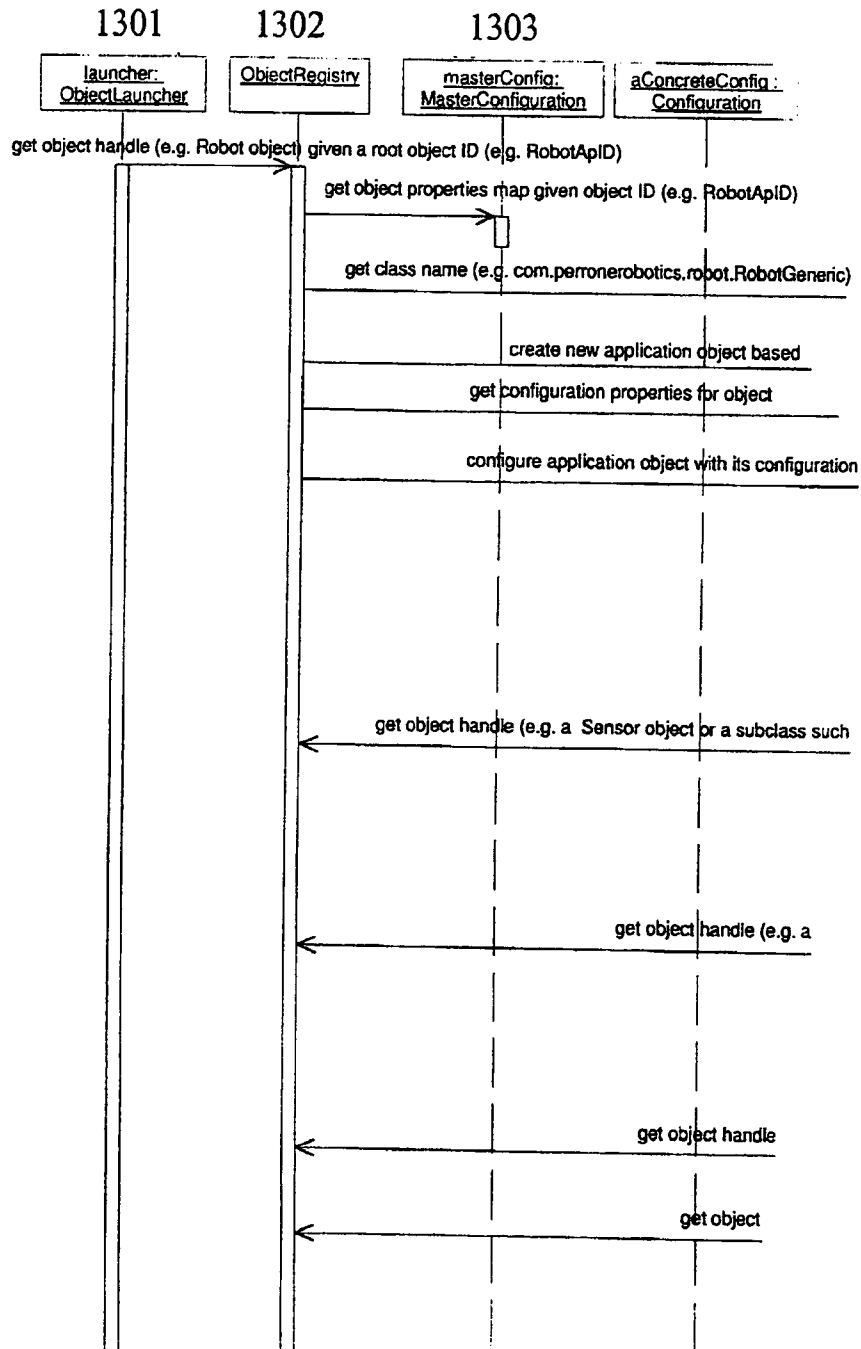


Figure 35

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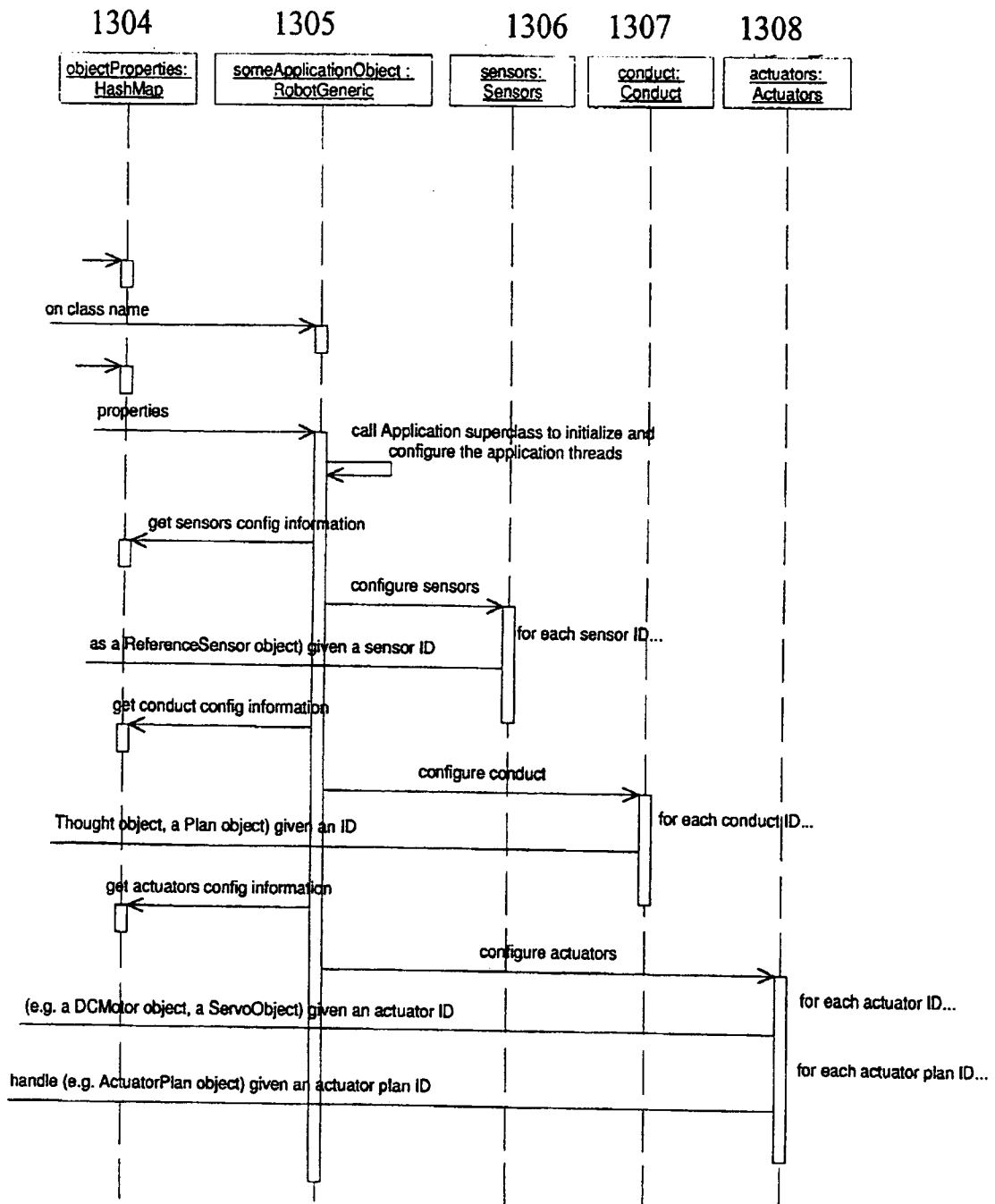


Figure 35 (cont.)

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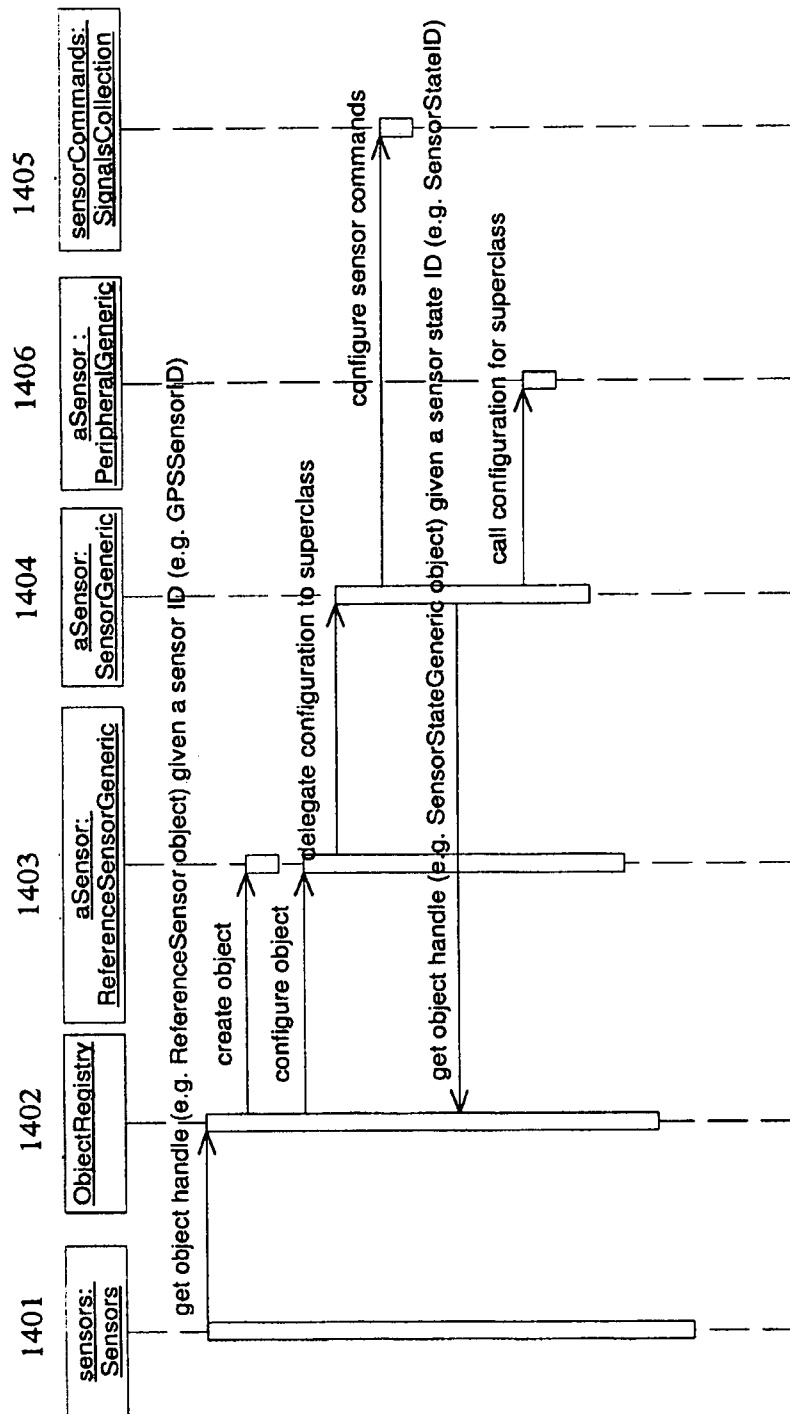


Figure 36

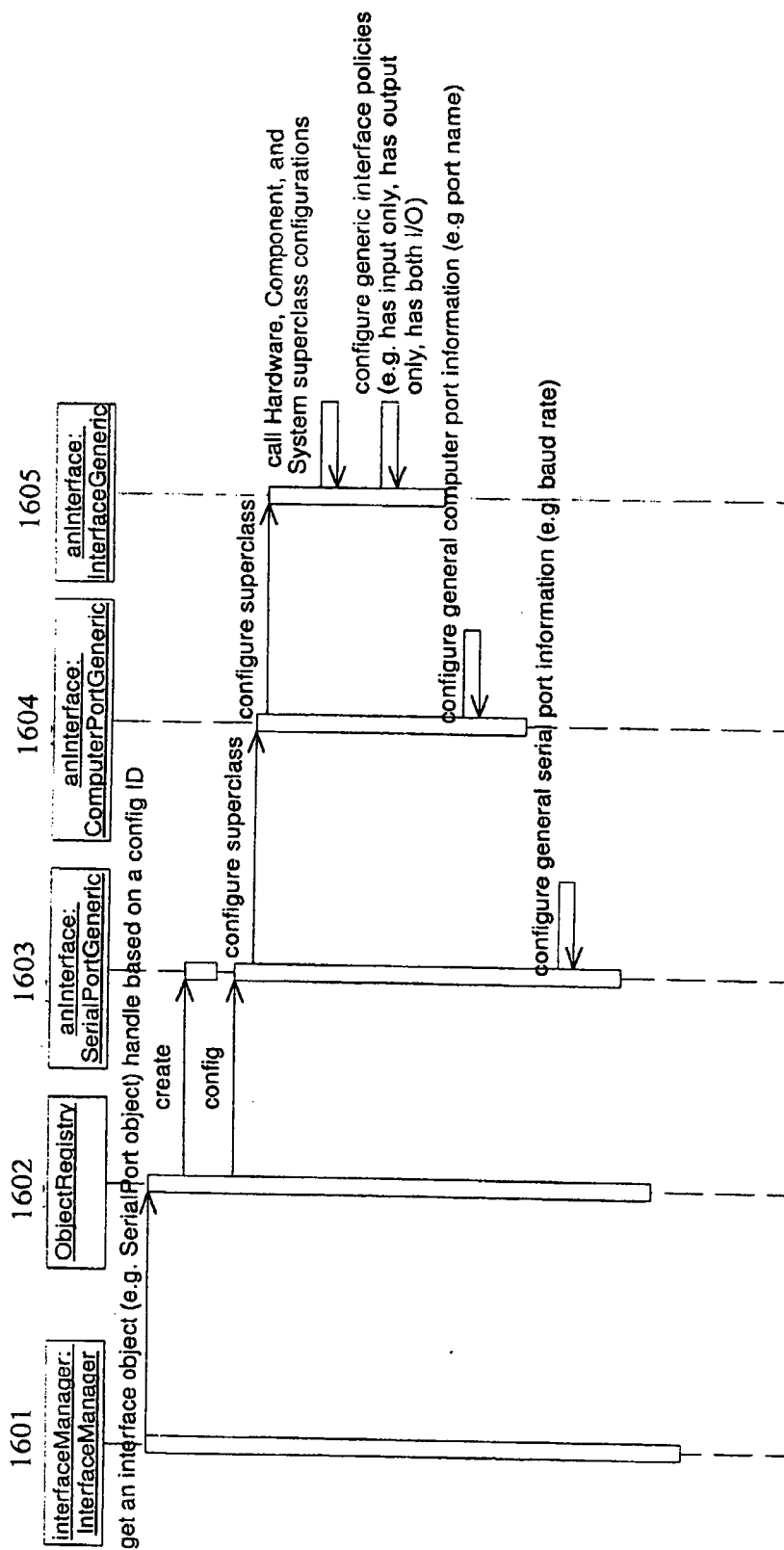


Figure 37

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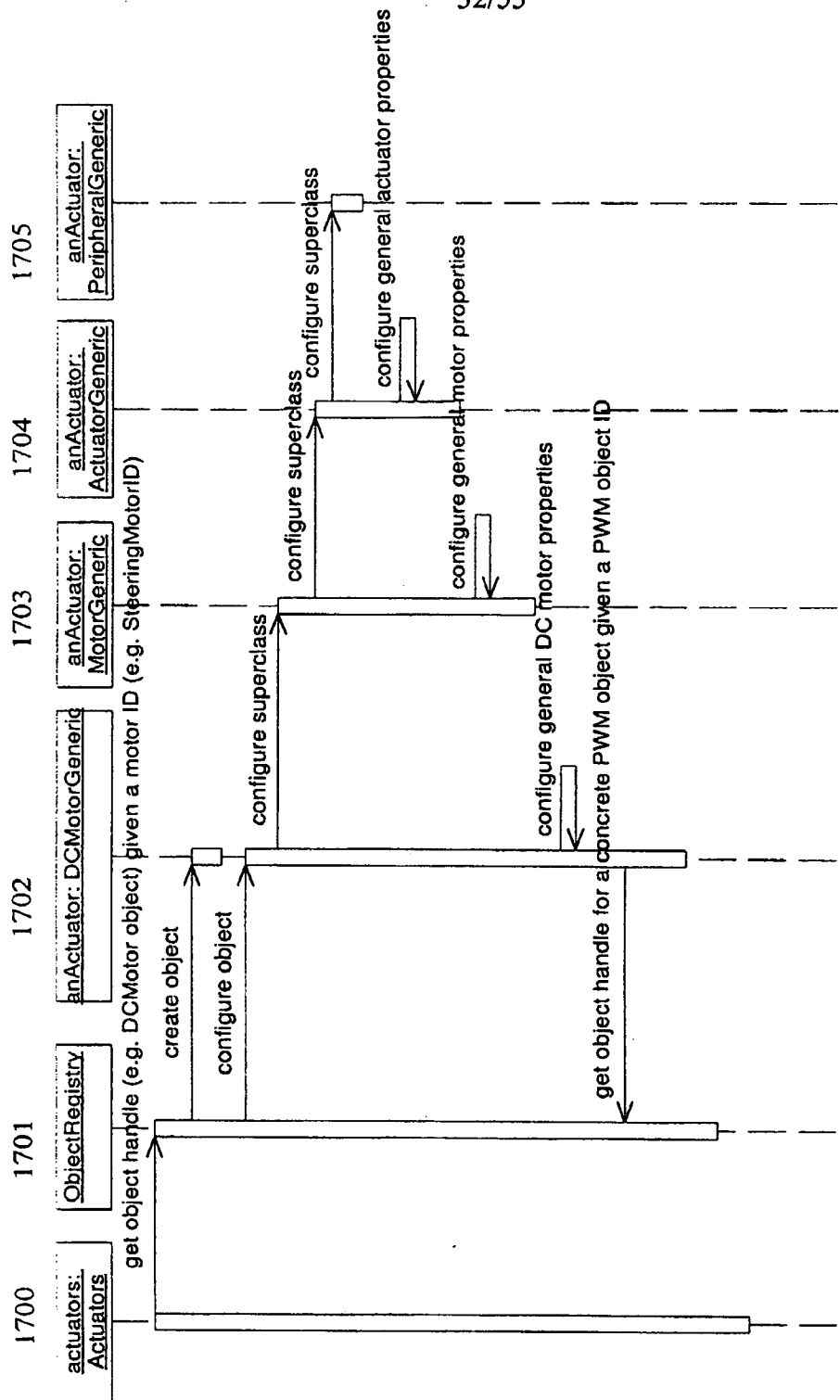


FIGURE 38

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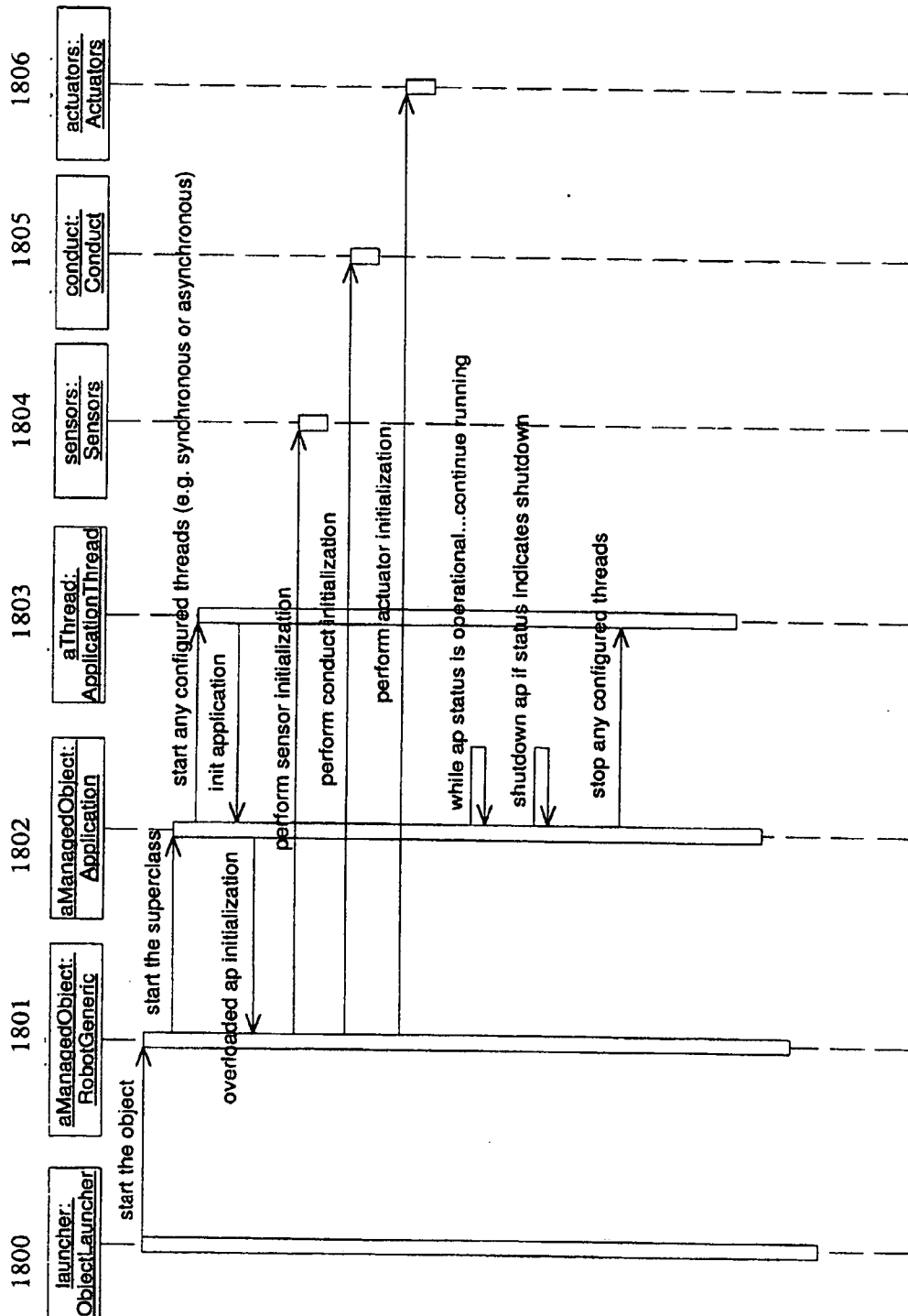
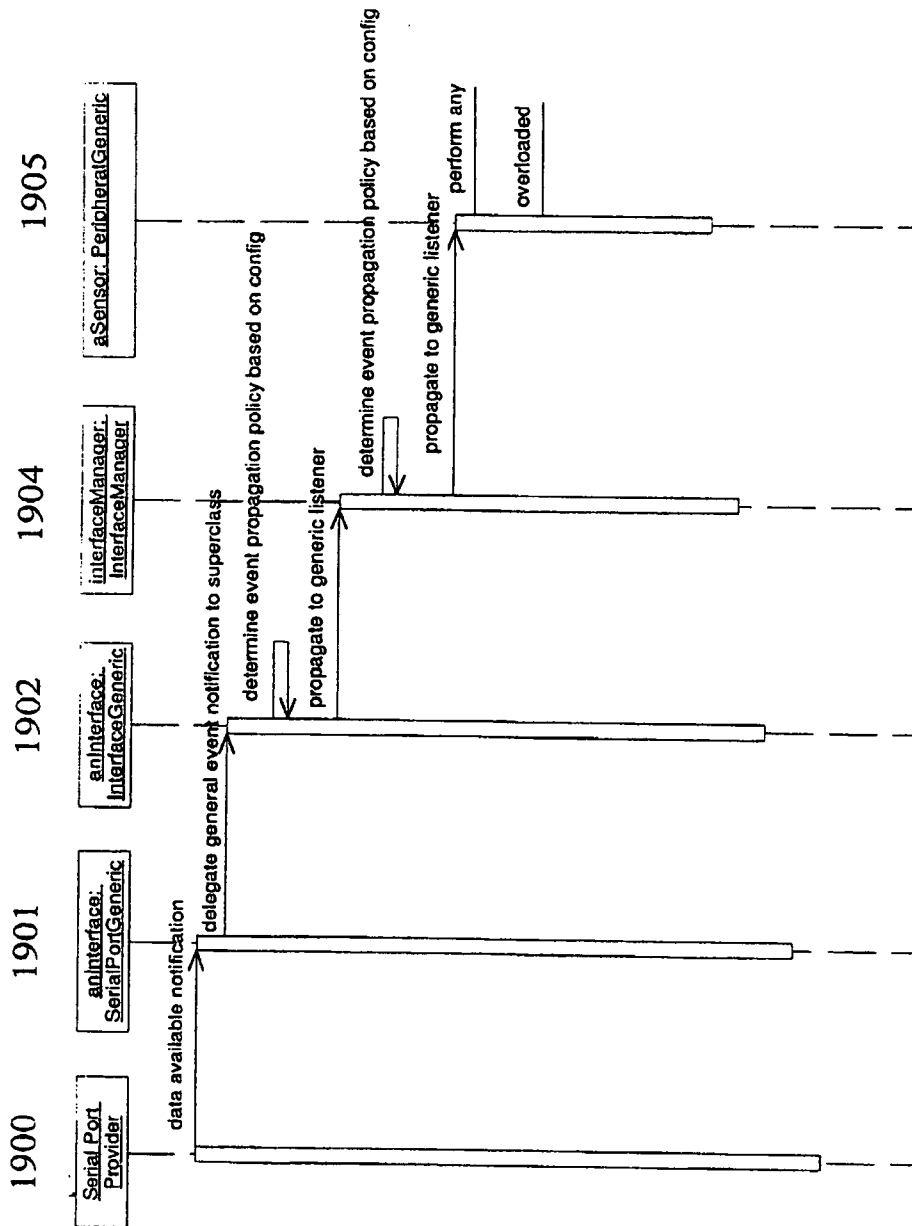


FIGURE 39

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**Figure 40**

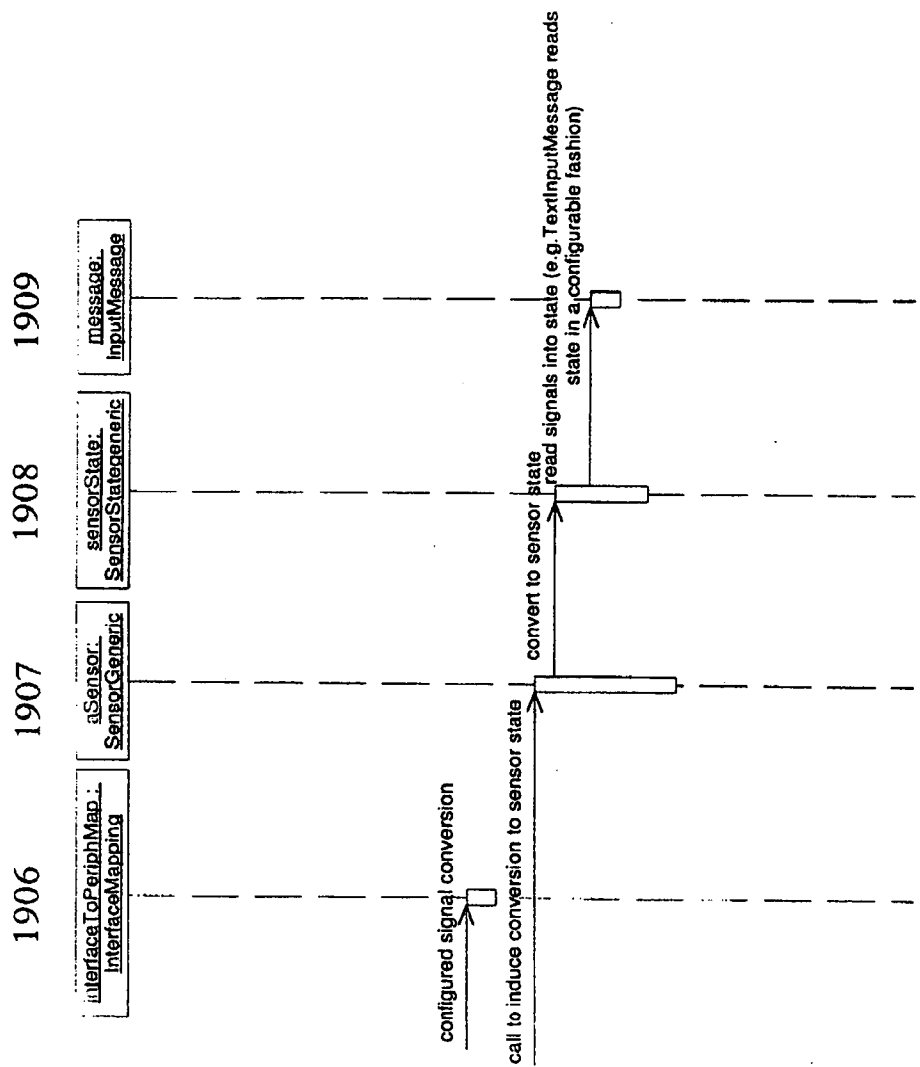


Figure 40 (cont.)

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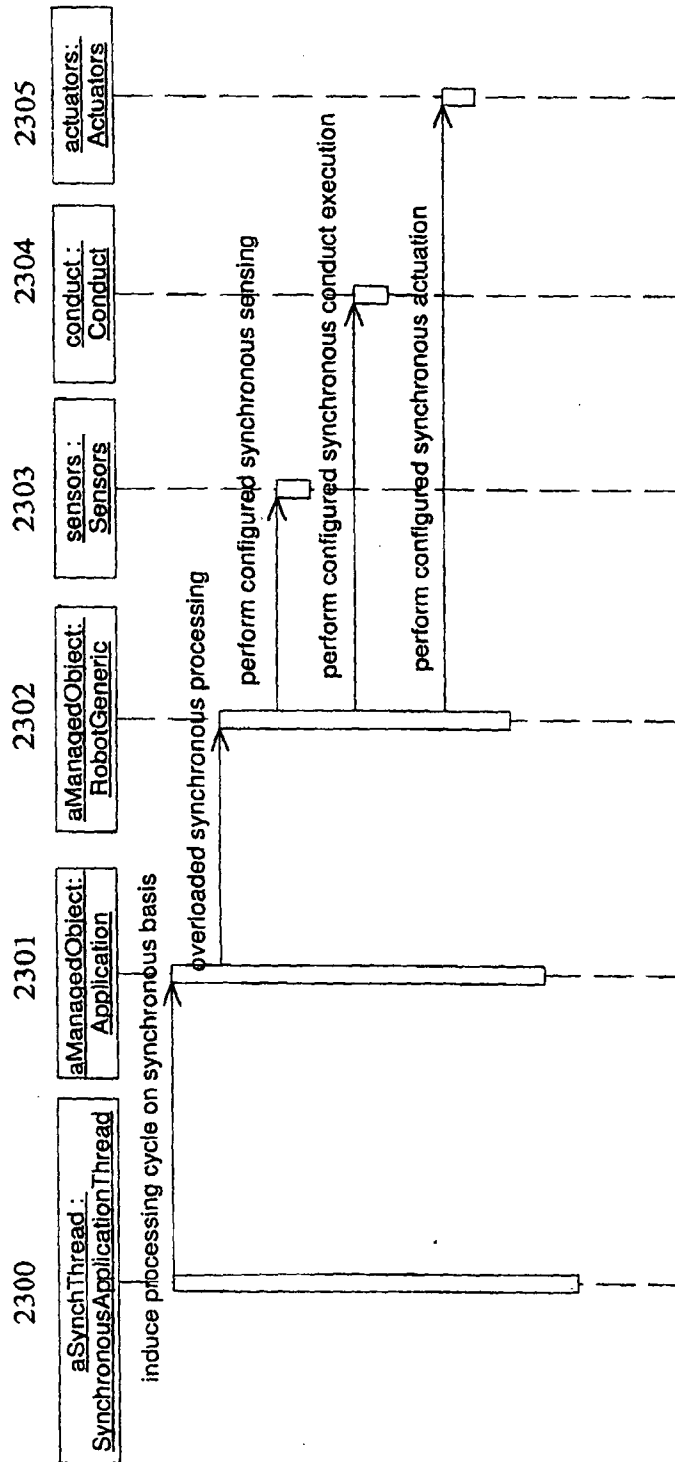


FIGURE 41

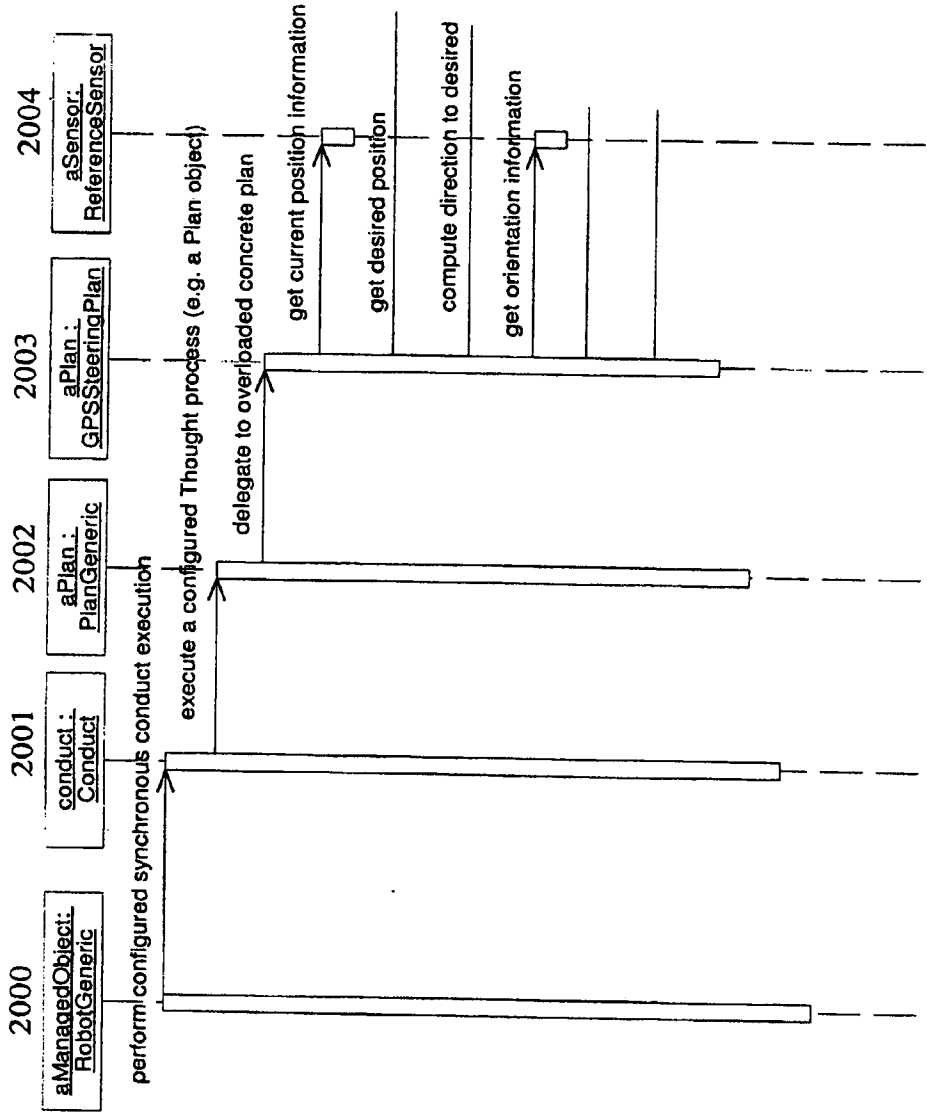


Figure 42

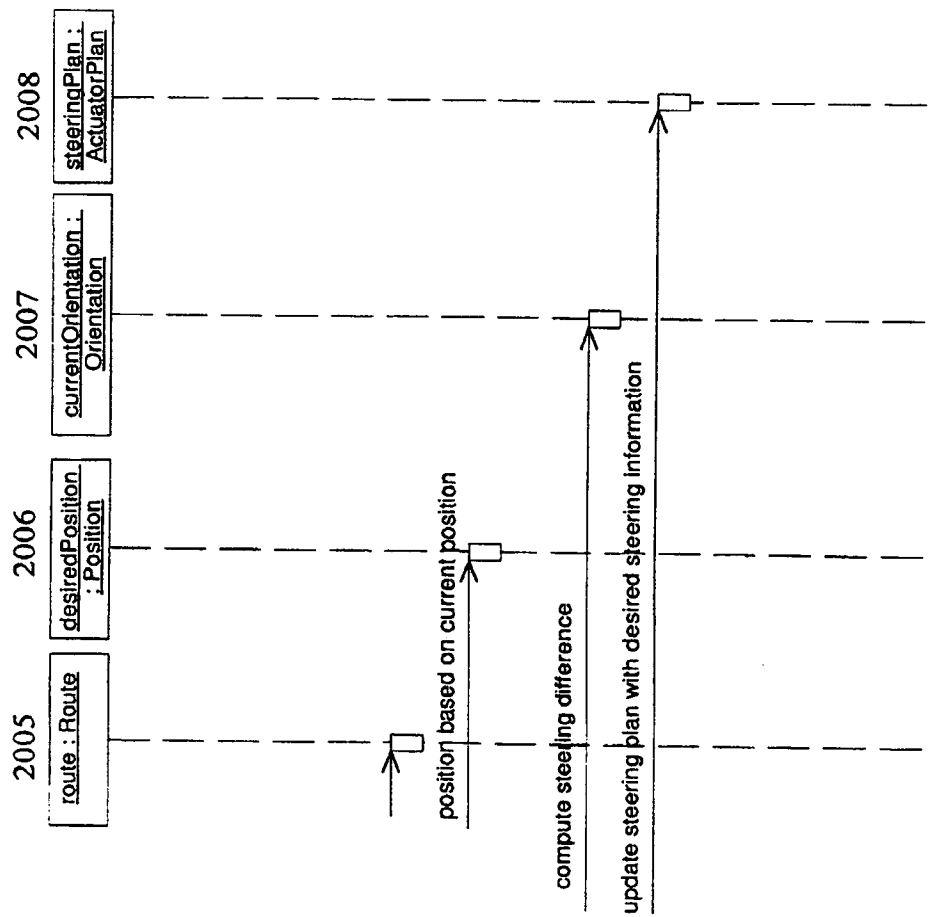


Figure 42 (cont.)

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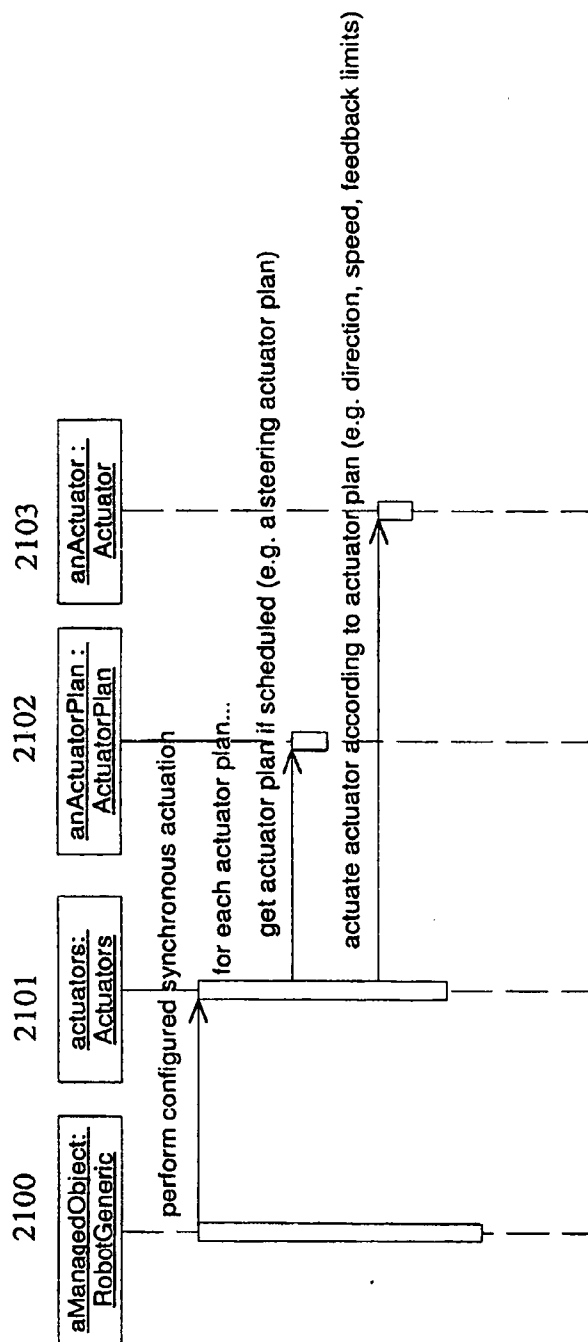


FIGURE 43

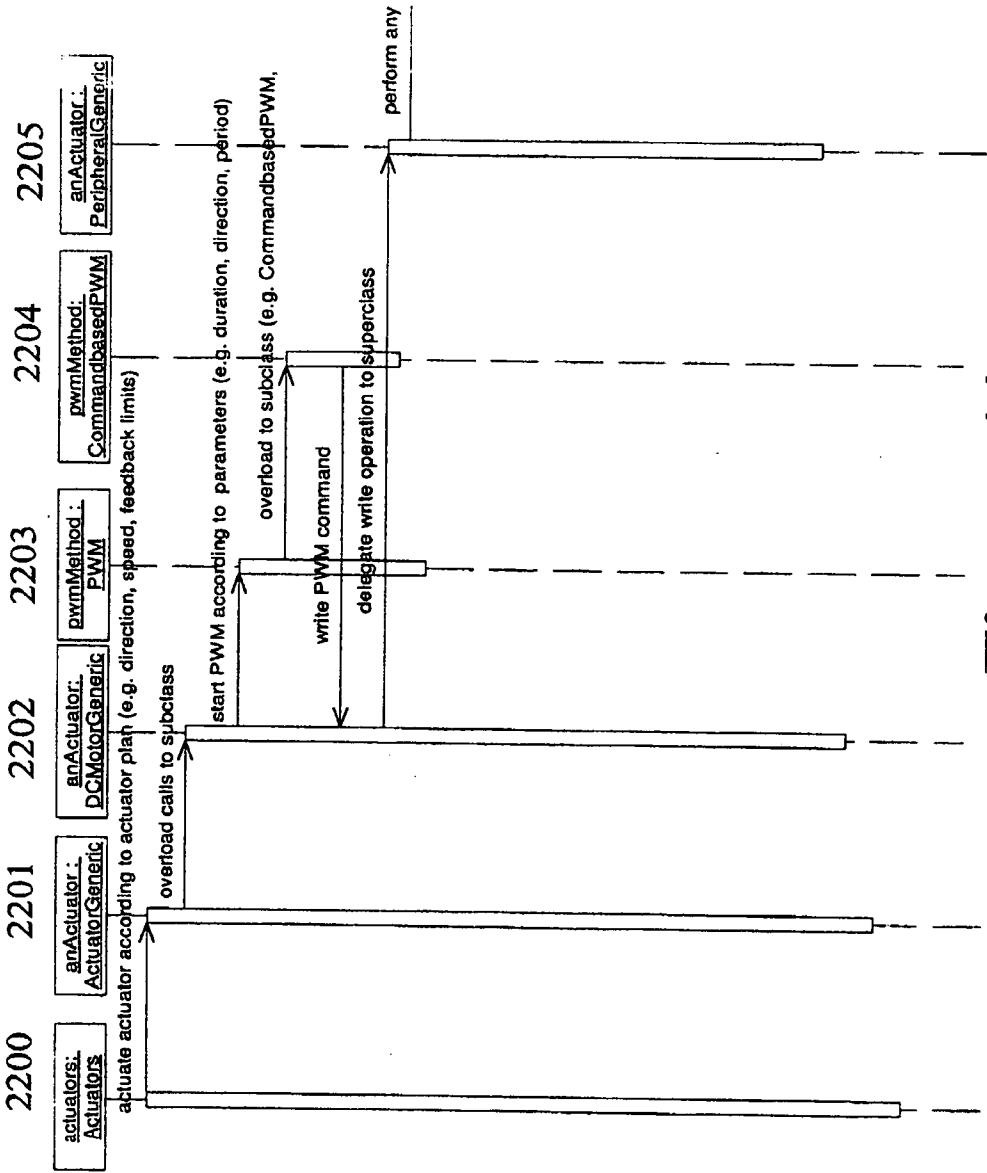


Figure 44

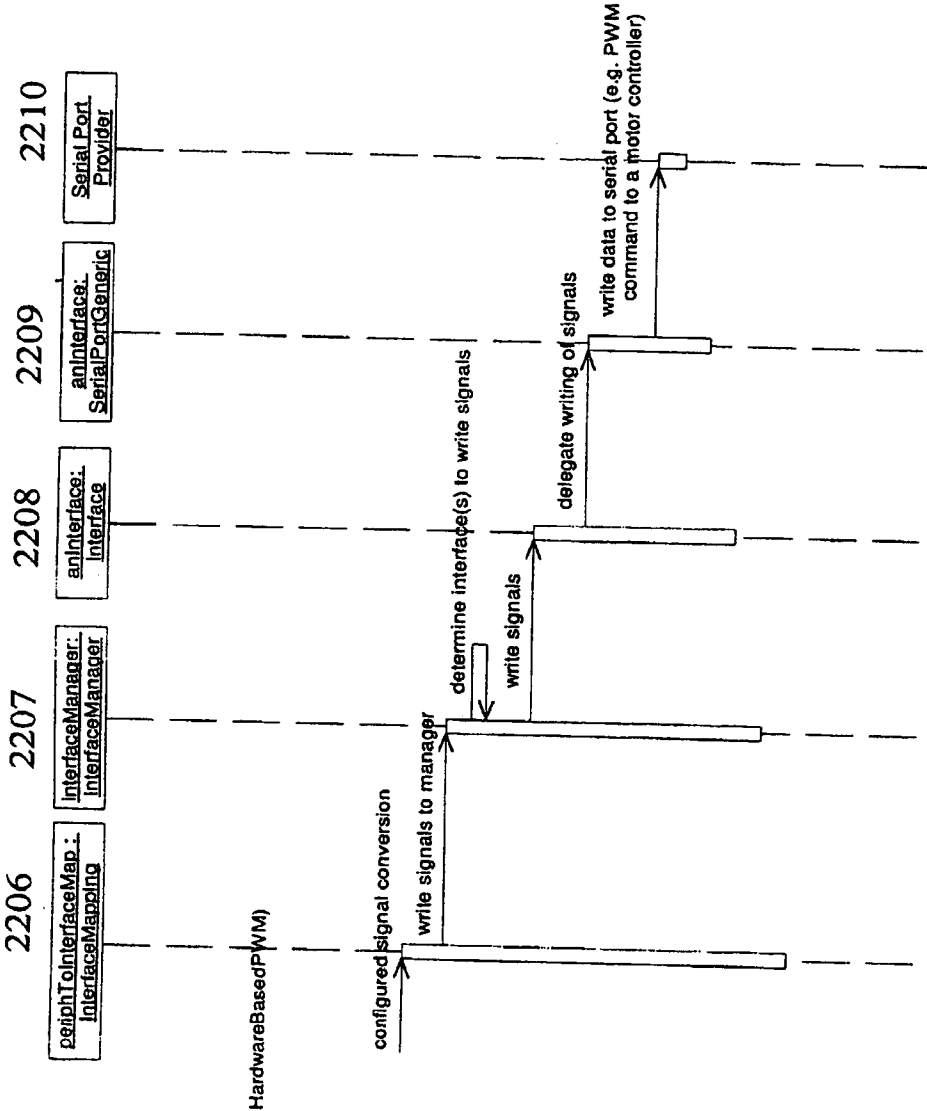


Figure 44 (cont.)

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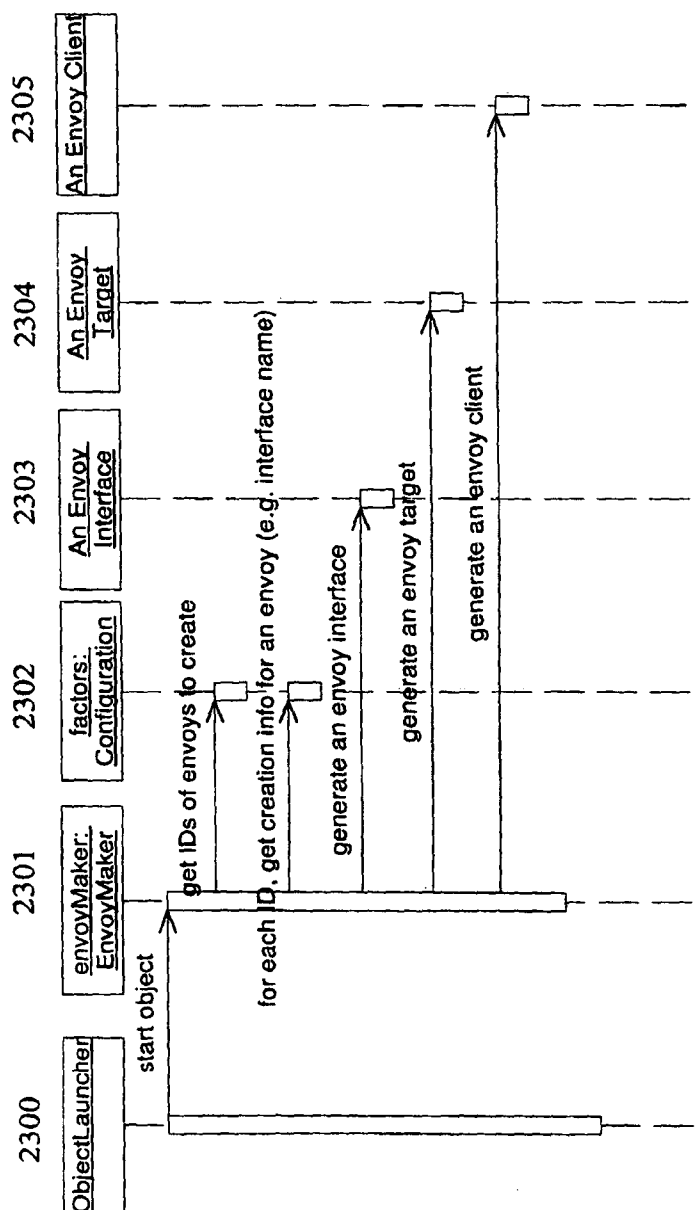


FIGURE 45

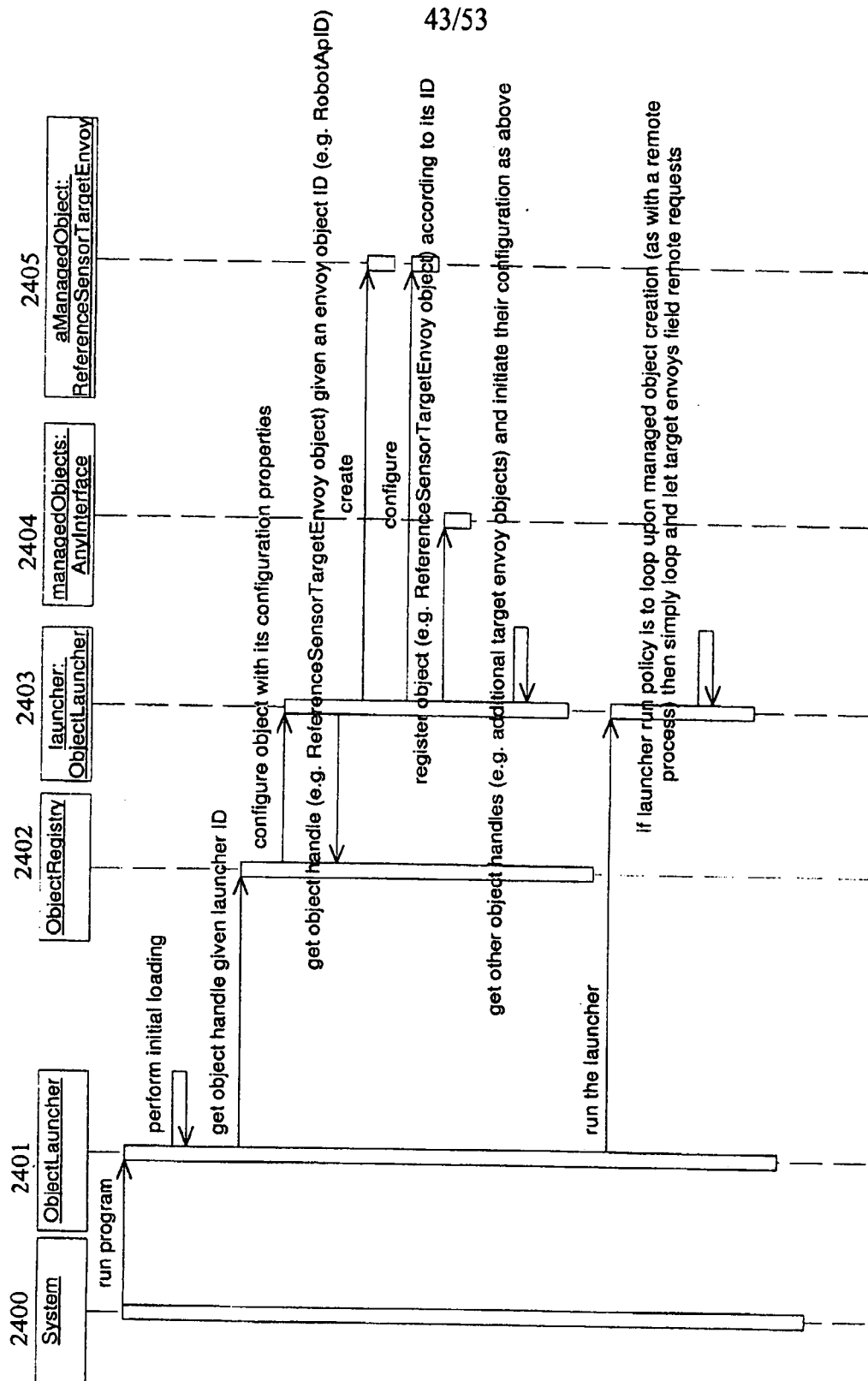


FIGURE 46

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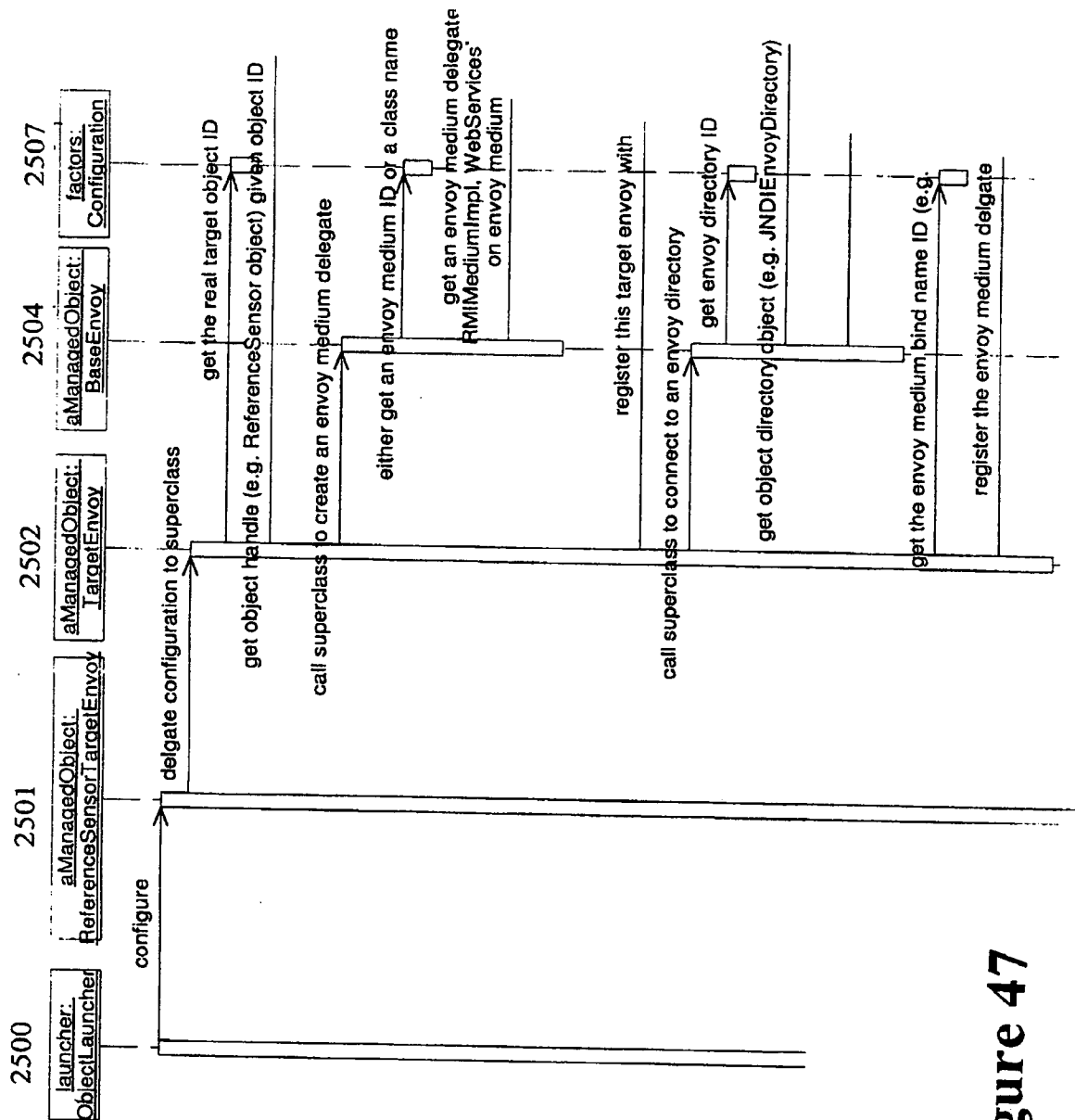
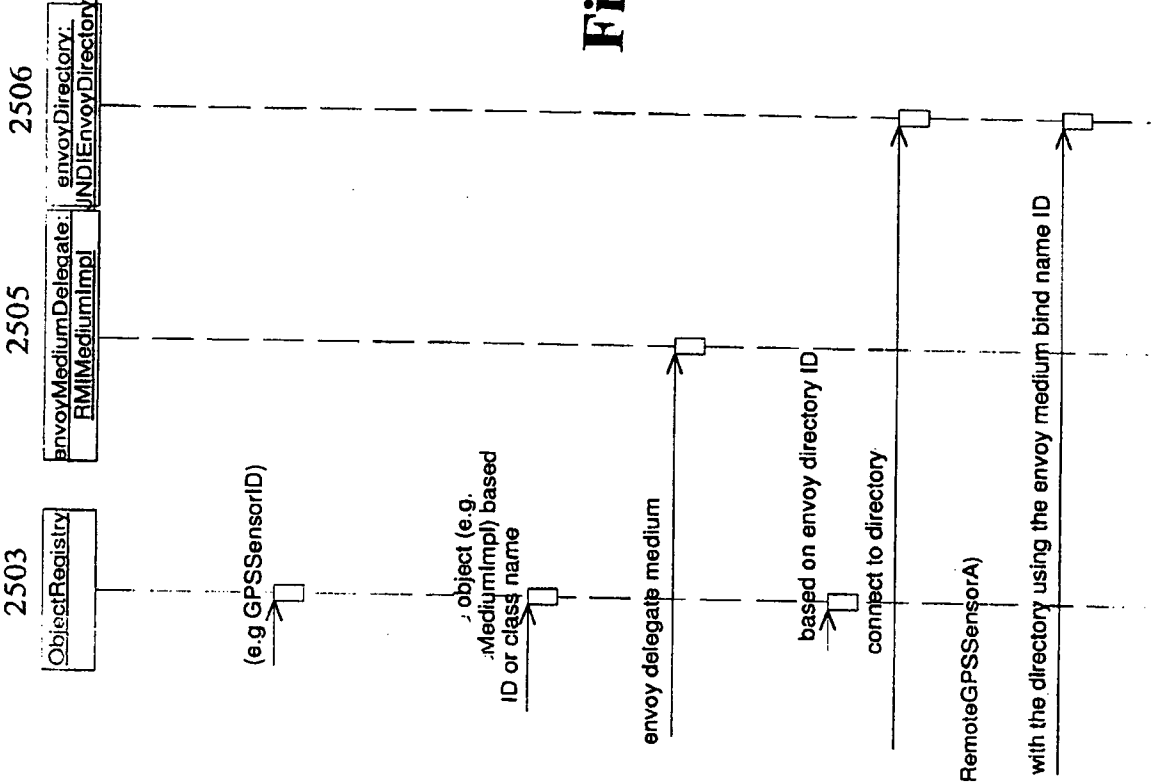


Figure 47

Figure 47 (cont.)



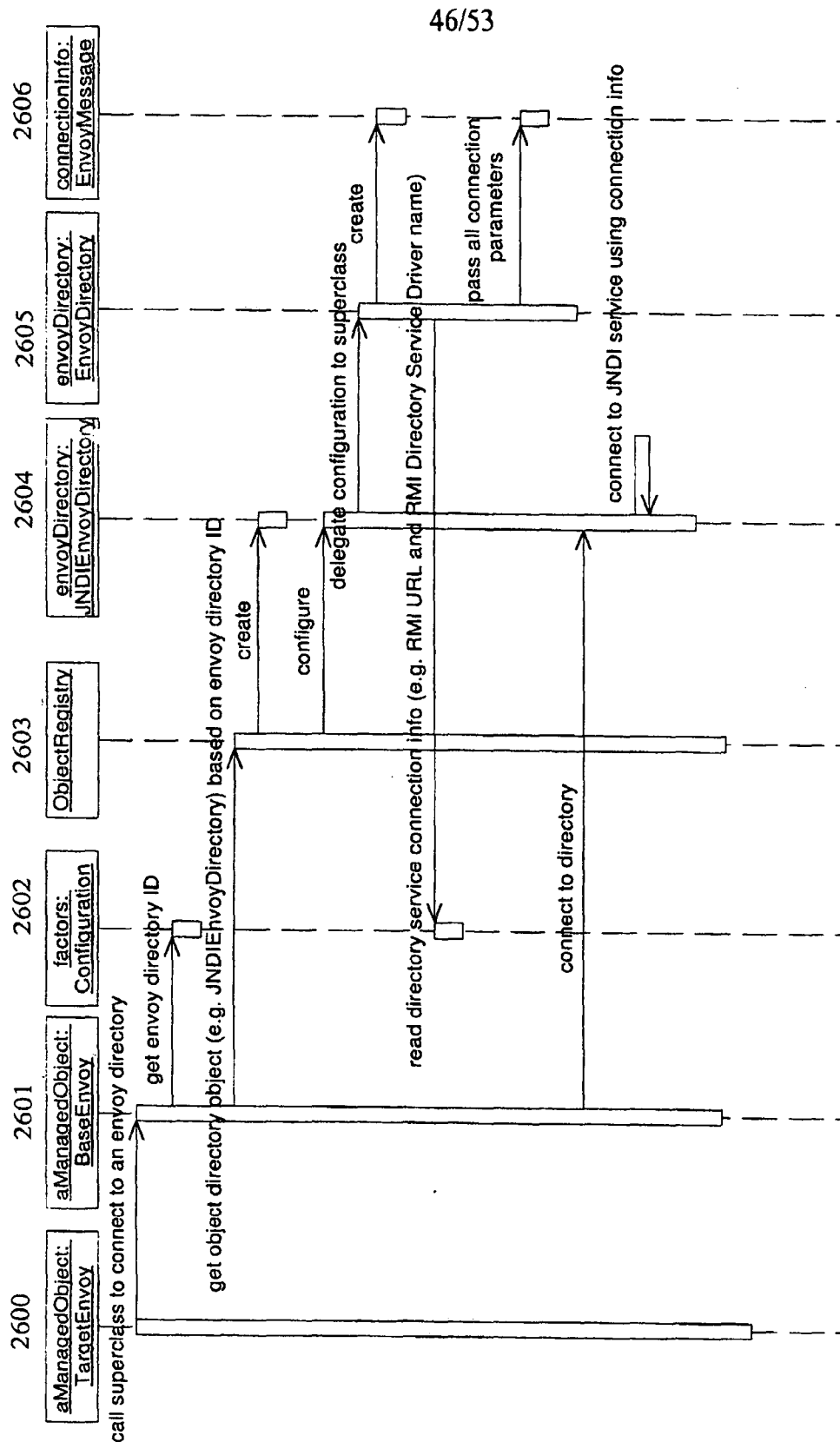


FIGURE 48

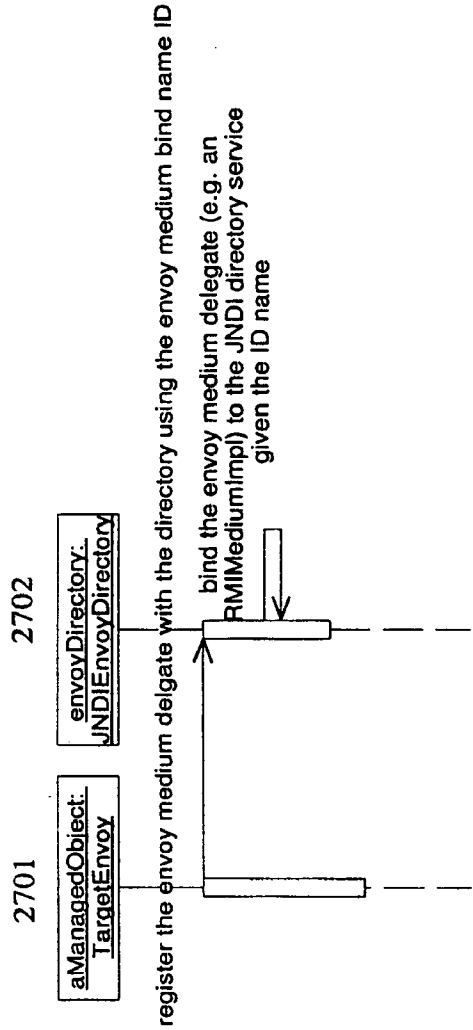


FIGURE 49

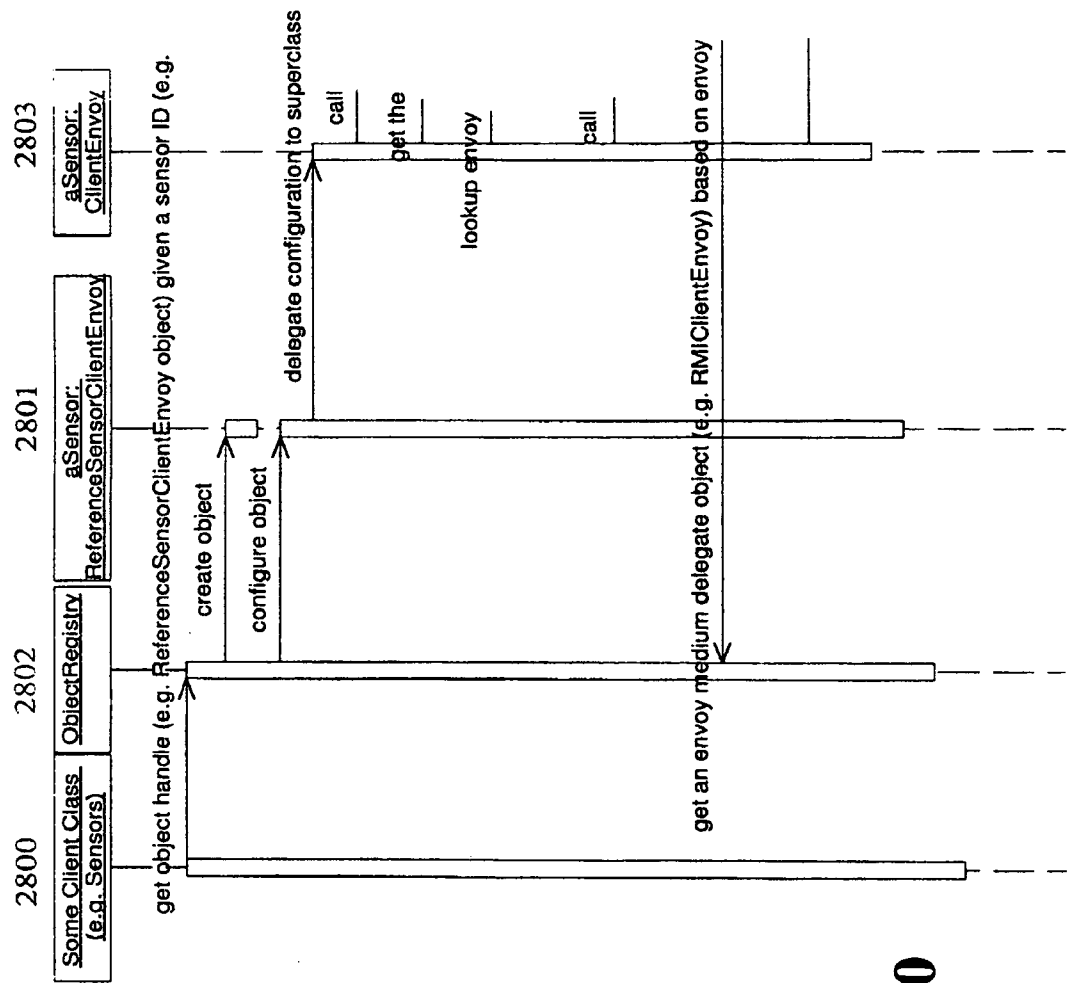


Figure 50

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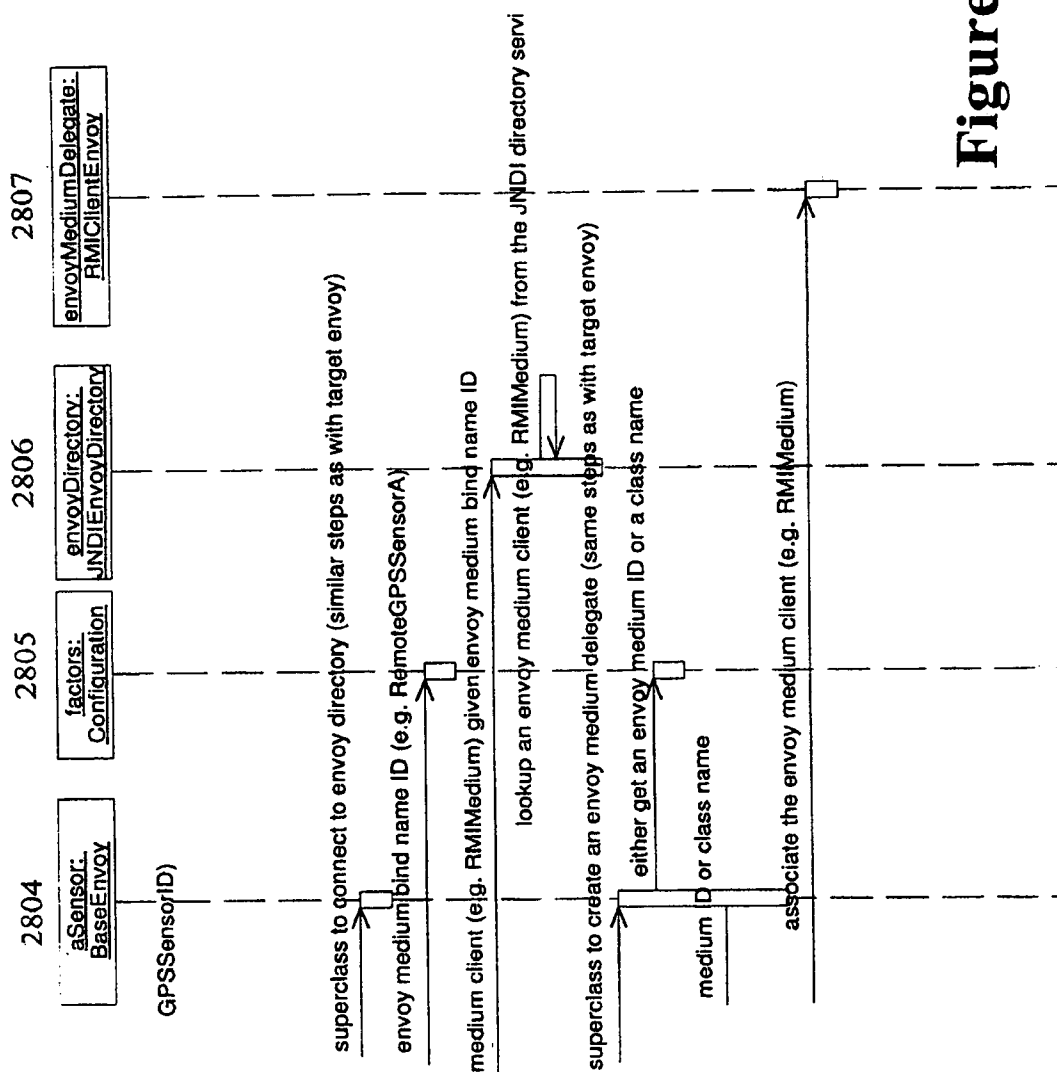


Figure 50 (cont.)

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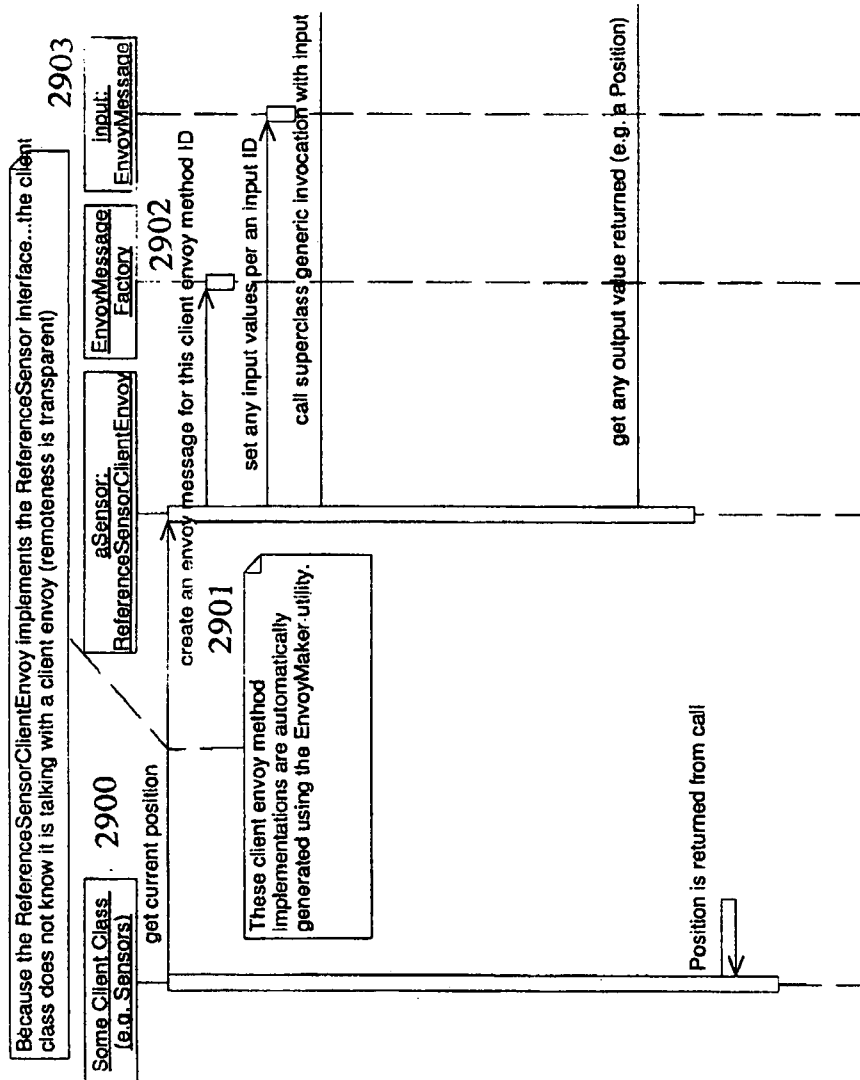
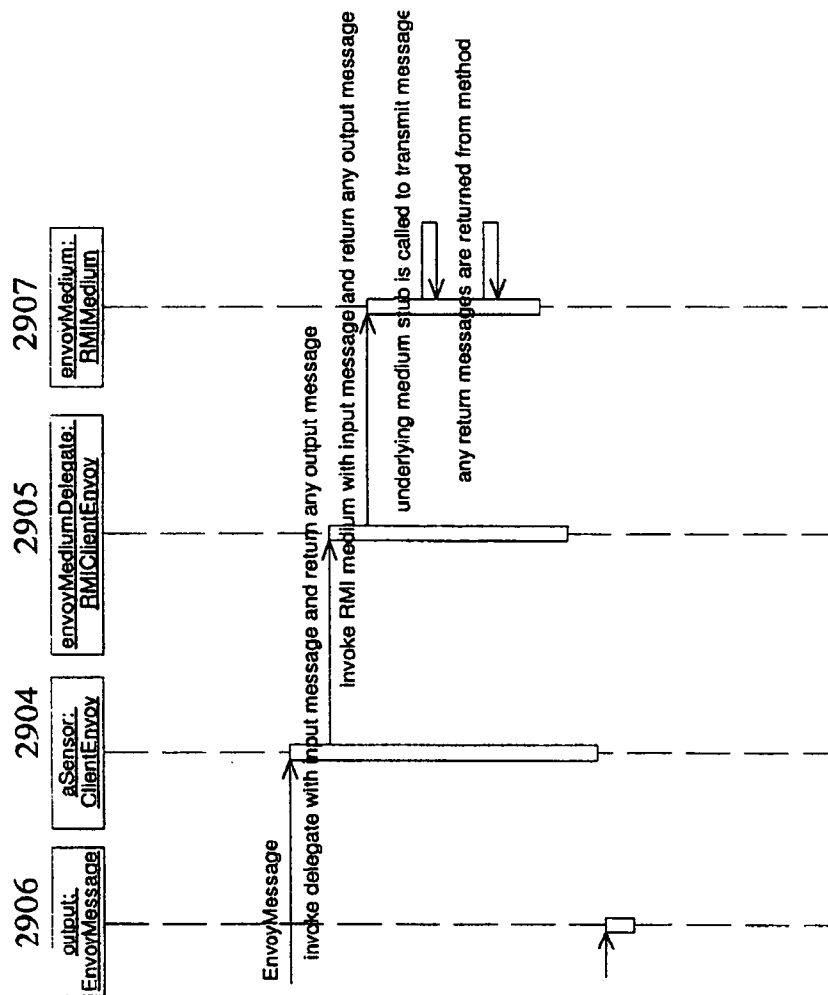


Figure 51

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**Figure 51 (cont.)**

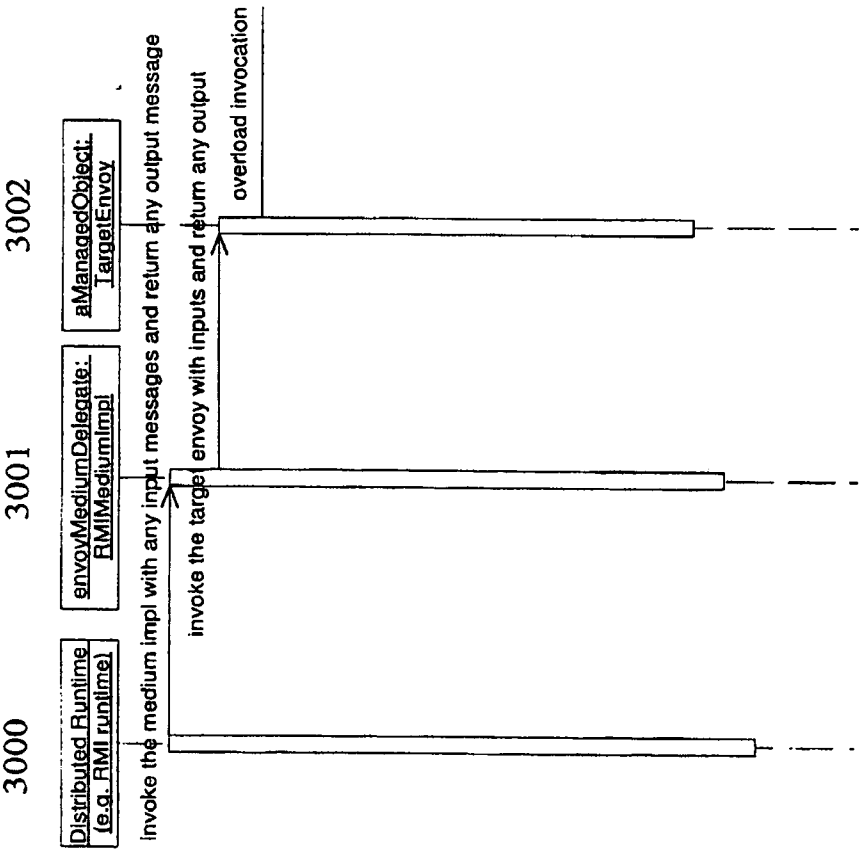


Figure 52

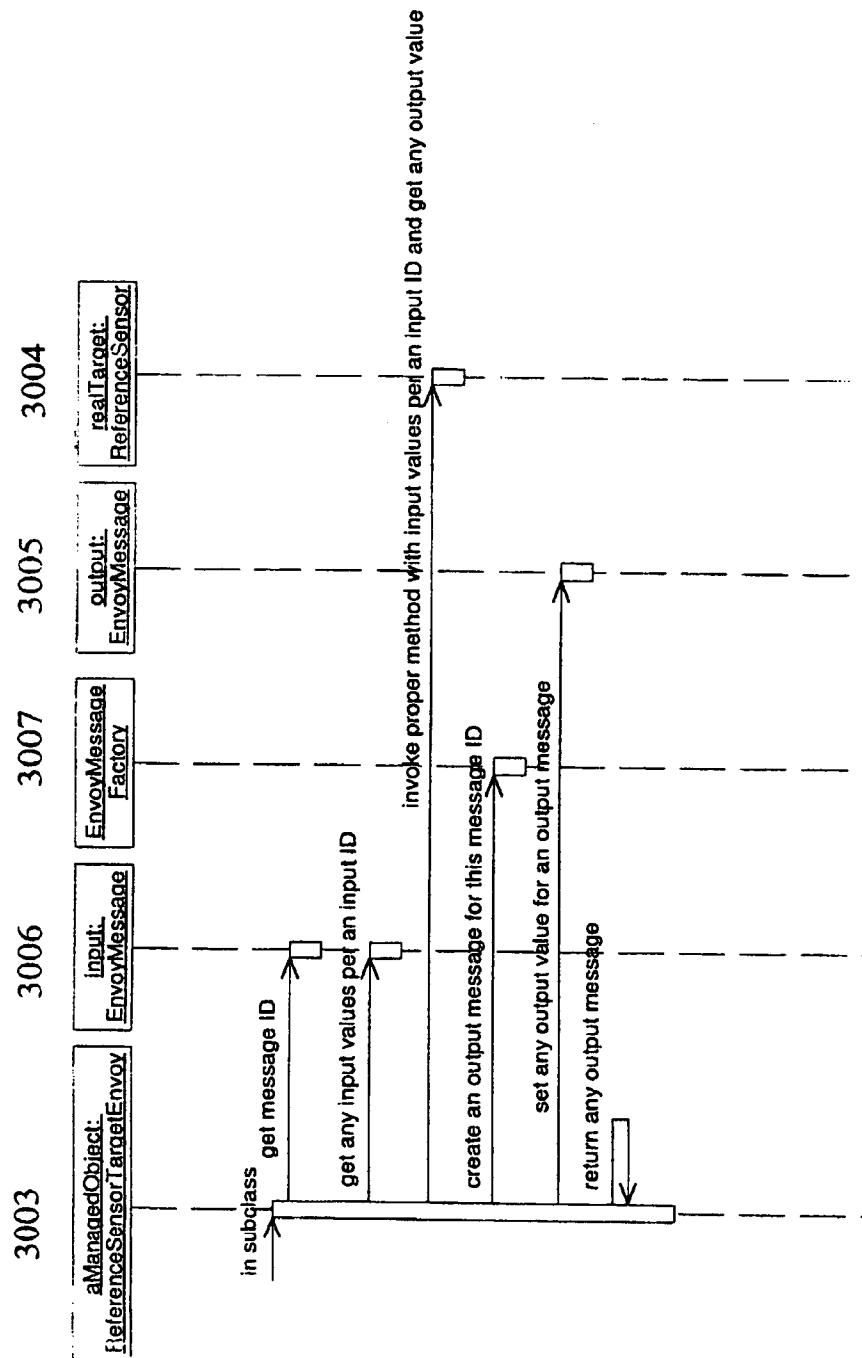


Figure 52 (cont.)