Distributed State Machine Supervision for Long-baseline Gravitational-wave Detectors with the Guardian Automation Platform

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The Laser Interferometer Gravitational-wave Observatory (LIGO) consists of two identical yet independent, widely-separated, long-baseline gravitational-wave detectors. Each Advanced LIGO detector consists of complex optical-mechanical systems isolated from the ground by multiple layers of active seismic isolation, all controlled by hundreds of fast, digital, feedback control systems. This article describes a novel state machine-based automation platform developed to handle the automation and supervisory control challenges of these detectors. The platform, called *Guardian*, consists of distributed, independent, state machine automaton nodes organized hierarchically for full detector control. User code is written in standard Python and the platform is designed to facilitate the fast-paced development process associated with commissioning the complicated Advanced LIGO instruments. While developed specifically for the Advanced LIGO detectors, Guardian is a generic state machine automation platform that is useful for experimental control at all levels, from simple table-top setups to large-scale multi-million dollar facilities.

I. INTRODUCTION

The Laser Interferometer Gravitational-wave Observatory (LIGO) has just completed its first observing run with its new second-generation instruments. During this run, Advanced LIGO made the first ever direct observation of gravitational waves from a binary black hole merger[1–3]. This detection heralds a new era of gravitational wave astronomy, where gravitational wave detectors like LIGO will operate as true astronomical observatories, continuously listening to the cosmos for gravitational-wave events.

Achieving the scientific goals of LIGO requires robust detector operations. LIGO consists of two identical yet independent 4-km baseline Michelson-type interferometric detectors, located in Livingston, LA, and Hanford, WA, USA[4,5]. The detectors directly measure the strain of passing gravitational waves as they modulate the length of the two Michelson arms. The detectors are complex opto-mechanical systems consisting of multiple subsystems whose actions and configurations need to be coordinated to acquire and maintain the operating configuration needed to detect gravitational waves. Getting the detectors to their operating point quickly and robustly is critical for maximizing observation time and scientific output.

While many large physics experiments rely on some form of real-time control at the machine interface level to handle fast event sequencing (e.g. in particle accelerators or extreme light sources), LIGO is somewhat unique in the prominent role that feedback plays in overall detector control. In general, though, regardless of the low-level controls architecture, all large physics experiments require some kind of supervisory control layer to coordinate actions between subsystems and to achieve global operating configurations from "cold boot" conditions.

In Initial LIGO[6], detector feedback control systems were simple enough to be supervised by a small set of shell scripts and a single daemon program that monitored detector state and executed the appropriate scripts as needed. Advanced LIGO, however, is significantly more complex than Initial LIGO, employing roughly 100 times the number of feedback control loops. The Initial LIGO supervision system was therefore inadequate to meet the needs of Advanced LIGO.

The Virgo project[7], which operates an interferometric gravitational wave detector similar to those used by LIGO, developed its own unique supervisory system, called *Alp*, to handle automation of their first generation detectors[7,8]. Alp, while successful in automating the initial Virgo detectors, is specific to the inner workings of the Virgo data acquisition system and relies on a custom network communication layer. It is unclear how much this system will be used for the Advanced Virgo project[9], which is now in its commissioning phase.

The standard for industrial automation and slow control are programmable logic controllers (PLCs), typically embodied by the IEC 61131 standard[10]. Because of their ubiquity in industry they are frequently used in large physics experiments as well[11,12]. While they can be used for higher-level supervision tasks, PLCs are usually fully integrated systems that are less well suited for large distributed applications that frequently require operation under some level of partitioning. They are therefore generally reserved for low-level slow controls and machine protection.

A class of supervisory control and data acquisition (SCADA) systems has been developed specifically to meet the needs of large physics experiments. The primary examples of these systems are the Experimental Physics and Industrial Control System (EPICS)[13,14] and TANGO[15,16]. These systems are designed for distributed control of large numbers of independent devices and typically include network message passing infrastructures as

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ALS	arm length stabilization
BS	beam splitter (mirror)
BSC	basic symmetric chamber (vacuum)
DIAG	diagnostic
ETM	end test mass (mirror)
IFO	interferometer
IMC	input mode cleaner
ISC	interferometer sensing and control
ISI	internal seismic isolation
ITM	input test mass (mirror)
HAM	horizontal access module (vacuum)
HEPI	hydraulic pre-isolation
OMC	output mode cleaner
PR[M]	power recycling [mirror]
PSL	pre-stabilized laser
SEI	seismic isolation
SR[M]	signal recycling [mirror]
SUS	suspension
TCS	thermal compensation system

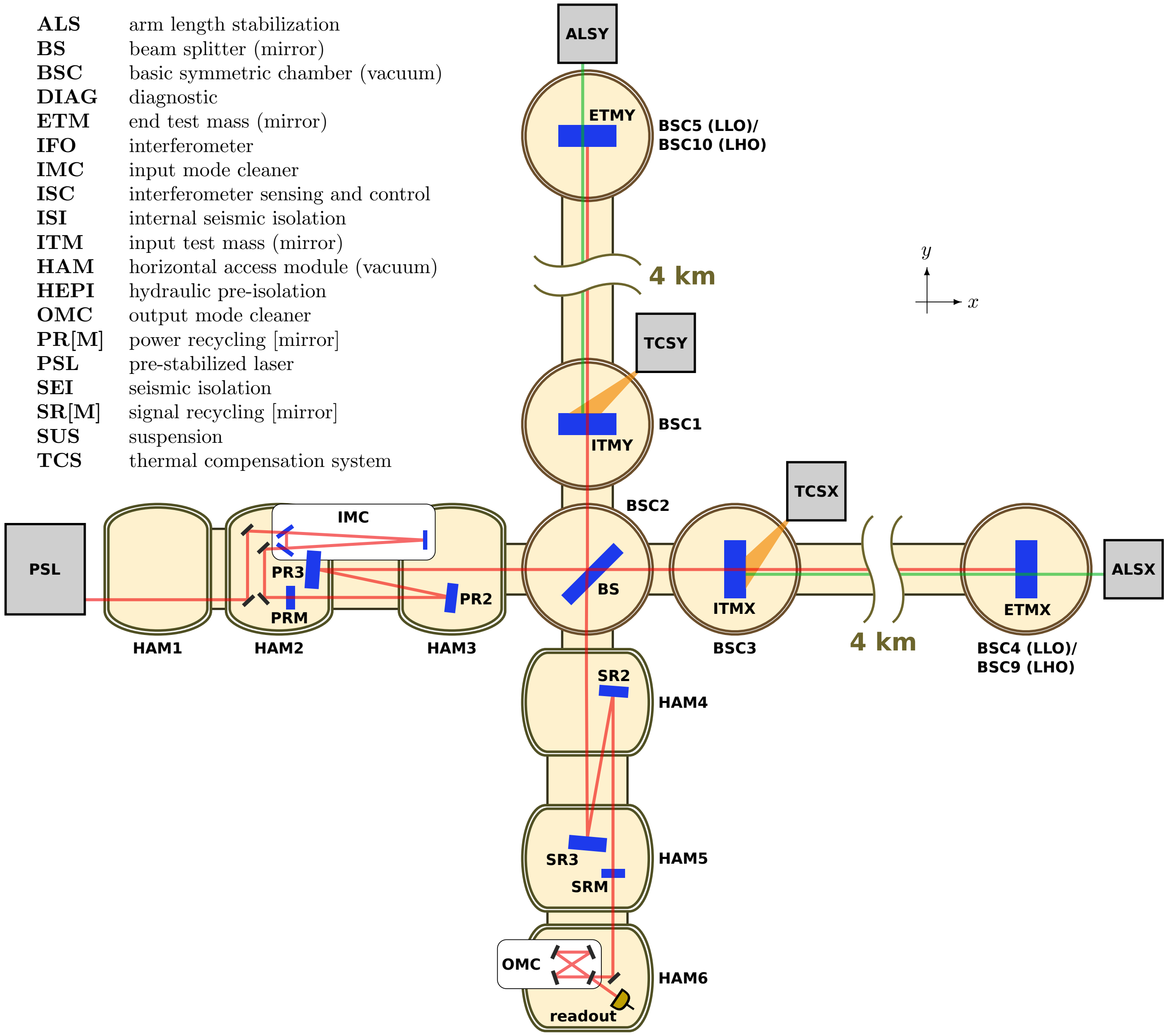


FIG. 1: Overview of the Advanced LIGO vacuum envelope (tan) and optical configuration, and glossary. The circular vacuum chambers are called BSC chambers, and the rectangular ones are called HAM chambers. All vacuum chambers contain active seismic isolation (SEI) platforms that support the optics and their suspension (SUS) structures (represented by blue rectangles). The red lines represent the path of the primary laser beam (emanating from the PSL), while the green lines represent the laser beams for the arm length stabilization (ALS) system. Illuminating the input test masses (ITMX and ITMY) is the thermal compensation system (TCS).

well as sequential logic programming tools for device-level automation. LIGO relies on EPICS as the primary communication layer for supervisory control. However, while these SCADA systems provide suitable mediums for supervisory control, they don't provide much in the way of structure or functionality for the development and management of higher level supervision tasks.

A common model used to represent automation systems is the *finite state machine*. Finite state machines are naturally represented by graphs, where states corresponding to particular configurations of, or commands on, a system are represented by nodes in the graph, connected together by directed edges defining allowable transitions between states. Finite state machine representations are quite powerful and intuitive and are well suited for many automation tasks. Finite state machines are found in various experiments at the Large Hadron Collider (LHC)[11,17–20].

In order to meet the unique supervisory requirements of the Advanced LIGO detectors, LIGO has developed a novel state-machine based automation platform, known as *Guardian*. Guardian consists of a distributed hierarchy of independent automaton processes. Each automaton process is a state machine execution engine handling control of a particular sub-domain of the full system. A hierarchy of nodes control the full instrument. Guardian's highly distributed architecture allows large systems to be easily partitioned and re-unified as needed. It is also scalable, able to handle systems from a single automaton up to the hundreds required for large facilities like LIGO. Guardian was designed to be flexible and accessible, which is important for facilitating the unique commissioning process of long-baseline interferometers where the full automation procedure is not known *a priori* and automation logic changes need to be made quickly and frequently.

This article describes the Advanced LIGO requirements that led to the development of this new platform, the technical design of Guardian itself, and how Guardian was deployed to fully control the Advanced LIGO detectors.

II. ADVANCED LIGO SYSTEM DESCRIPTION AND AUTOMATION REQUIREMENTS

At the core of the Advanced LIGO detectors is a dual-recycled Michelson interferometer with Fabry-Pérot arm cavities[4,5]. To isolate the interferometer from ground motion, all main optical components are suspended by pendulum systems hung from active seismic isolation platforms and can be actuated on in angle and length. The primary laser light source provides up to 180 Watts of input light power to reduce the effects of quantum shot noise at the detector. A thermal compensation system uses various thermal actuators to counteract the effects of laser heating in the core optics. Figure 1 shows a schematic overview of the detector, as well as a glossary for abbreviations and acronyms used in this article.

Figure 2 shows a cartoon overview of the Advanced LIGO control and supervision architecture. Signals from sensors in the interferometer (labeled "physical plant" in the diagram) are digitized and fed into a custom real-time control system[21]. From the digitized error signals the controls system calculates control signals that are fed to actuators that affect the interferometer and its various subsystems. A Beckhoff industrial PLC-based control system[22] handles low-level slow control of some discrete components of the system.

The dashed box in the top of the diagram in Figure 2 encloses the supervisory control layer. The real-time control system exposes signal readbacks and parameters of the fast control as channels in the EPICS network message passing infrastructure[13,14]. These channels are made available to automation and supervisory control processes (e.g. Guardian, shown as blue circles), as well as to human operator interfaces. Compatibility with EPICS was a fundamental requirement for the Advanced LIGO automation system.

A. Lock acquisition and global control

The nominal operating point of the instrument—where all interference conditions in the interferometer are such that it is maximally sensitive to differential length changes of the Michelson arms—is susceptible to external disturbance and must be maintained via fast feedback control loops that "lock" all global length and angular degrees of freedom to their desired set points[23]. The subsystem that handles all interferometer global degrees of freedom is called interferometer sensing and control (ISC).

To achieve lock, the overall global control system and all detector subsystems must progress through sequences of states in a well orchestrated manner. Initially independent components must be controlled to progressively tighter degree by increasingly interdependent control loops. This process is known as *lock acquisition*. Developing the lock acquisition procedure is one of the more difficult challenges in the commissioning of long-baseline gravitational wave detectors and is the primary automation task during operation.

Multiple detector subsystems are either directly involved in overall continuous global control or are in some way involved in the lock acquisition process: power levels are set depending on the current lock state (PSL[24], TCS[25]); optics are continuously actuated on for stability and global control (SUS, SEI/HEPI/ISI); various sub-cavities are locked at different stages (ISC, IMC[26], ALS[27,28], OMC[29]).

Eventually something will cause the global interferometer control loops to lose control authority (i.e. "lose lock"). This is usually due to external disturbances that cause controller outputs to run into dynamic range limits. The automation system must be able to identify that a lock loss has occurred, reset all controllers and subsystems appropriately, and then reacquire lock as fast as possible so as to minimize downtime.

B. Suspensions and Seismic isolation

The Advanced LIGO test masses are isolated from the ground via seven stages of active and passive seismic isolation, distributed among three discrete subsystems: test mass/optic suspensions (SUS), internal seismic isolation (ISI) platforms, and hydraulic external pre-isolation (HEPI) systems. The terms "external" and "internal" in this context are relative to the vacuum envelope. The HEPI and ISI systems together constitute the overall seismic isolation (SEI) subsystem.

All test masses and auxiliary optics are suspended from multi-stage pendulum suspensions. The core test masses are hung from four-stage suspensions[30] while the various

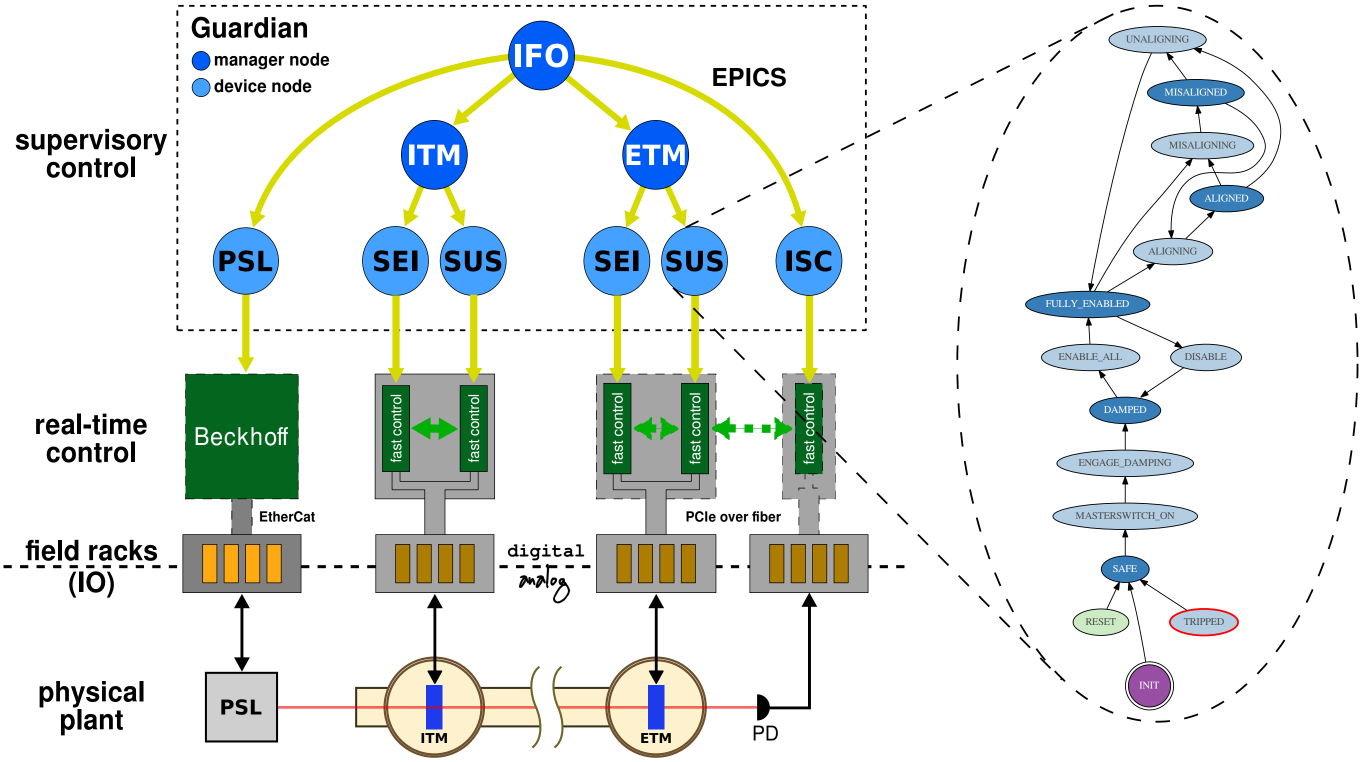


FIG. 2: Overview of the Advanced LIGO digital control and supervision architecture. The LIGO interferometer itself is represented by the "physical plant" layer at the bottom. The input/output and "real-time" digital controls (also referred to as "front end" systems) are represented by the gray boxes in the middle layer. Supervisory control is handled by Guardian, which is shown in the dashed box at the top. The blue circles represent individual Guardian nodes (labeled with hypothetical subsystem names). All communication between Guardian nodes and between Guardian and the front-end systems is handled via EPICS. At the right is an example state graph for one of the nodes.

auxiliary optics are hung from three-, two-, and single-stage suspensions. The suspensions incorporate various sensors and actuators on multiple different stages that are used for local motion sensing. Magnetic and electrostatic actuators are used for pushing on the stages to control the pitch, yaw, and longitudinal degrees of freedom. The suspension systems are the primary actuators for global control of the full interferometer. They also use feedback from the local sensors to damp various mechanical modes.

The ISI systems provide either one or two stages of active isolation for six degrees of freedom[31]. They are located inside the vacuum enclosure and directly support the test mass and auxiliary optic suspension structures. There are five two-stage ISIs for the five core test masses (BS, two ITMs, and two ETMs), and five single-stage ISIs for five of the auxiliary optic chambers (HAMs 2-6).

The HEPI systems are located outside the vacuum enclosure between the primary support pillars attached to the ground and the cross beams that support the ISI platforms in vacuum. They provide gross DC alignment and low-frequency isolation for six degrees of freedom using hydraulic actuation[31]. There is one system for every vacuum chamber in the system, for a total of 11 units in the full system.

The HEPI and ISI systems have similar control system architectures for each individual stage. They both utilize damping loops to damp rigid body modes and structural resonances. The ISI systems additionally have isolation loops for inertial isolation of the payload from input ground motion. These control loops must be engaged in a specific order to maintain stability: damping loops must be engaged first for all stages, moving from outer stages to inner, followed by the isolation loops which must be engaged in the same order.

All SUS and SEI systems include software watchdogs that automatically shut off all actuator outputs if control signals surpass certain thresholds. Operator intervention is required to reset the watchdogs, after which all control loops must be reengaged.

C. User interface

While the lock acquisition sequence and controls necessary to realize low-noise operation are understood in principle beforehand, the ultimate implementations used during operation are discovered over the course of an intensive multi-year commissioning process. Any supervision system must support the fast turn-around pace of commissioning. The system should have a clean, standardized interface and be capable of incorporating code changes quickly and robustly so that new ideas can be tested at a fast pace.

III. GUARDIAN STATE MACHINE SUPERVISION

Many options were considered when looking for a supervisory solution for Advanced LIGO. The primary requirement was that the system work with the existing EPICS framework in the real-time control system. This restriction narrowed down the options considerably. The solution also needed to be scalable to handle a large number of independent components and flexible enough to allow partitioning of the system so that sub-components could be commissioned independently. This pointed to a distributed architecture that would allow separate systems to function independently, yet unify as a whole for full detector control. Finally, the system needed to support fast turnaround for code changes—lengthy recompilation should not be necessary to incorporate new logic. Ultimately it was determined that no existing system fit these requirements, leading to the development of an entirely new system: *Guardian*.

The basic concept of Guardian is that of a distributed hierarchy of state machine automata. Each automaton handles control of a specific sub-domain of the full system to be controlled, and a hierarchy of automata can be used to control larger systems.

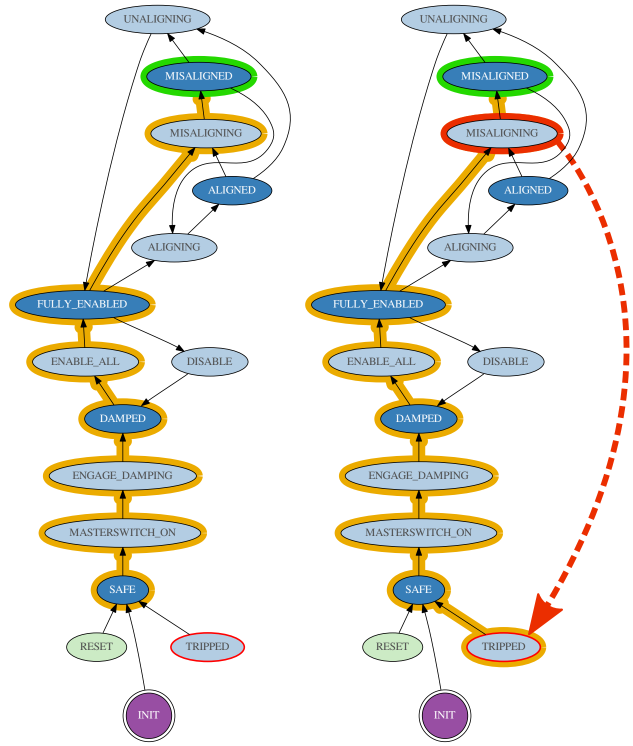
The core of Guardian—the automaton—is the **guardian** program, a stand-alone state machine execution engine with an EPICS control interface. When launched, the program loads user code that defines a state graph for the system being controlled (see section III A). The program knows how to traverse the user-defined state graph to move from whatever state the system is in to a desired final state.

In a typical large-scale deployment, such as that of Advanced LIGO, a hierarchy of **guardian** processes—each referred to individually as a *node*—control the entire instrument (henceforth referred to as the *plant*). Higher-level *manager* nodes control lower-level *subordinate* nodes, down to *device* nodes that talk directly to the front-end systems. The blue circles in the top box in Figure 2 each represent a node in a full hierarchy. Figure 7 shows two actual sub-hierarchies used in the full Advanced LIGO Guardian implementation.

All Guardian user code is written in standard Python[32] (as is the core **guardian** program itself). The full suite of standard Python libraries are available to the user code, as are special libraries designed specifically for interacting with the LIGO control system.

A. State graphs and system dynamics

The user code for each node is a Python module that defines state classes describing the action for each state



(a) path (b) jump transition

FIG. 3: State graph of the Advanced LIGO suspension (SUS) Guardian systems. The colored ovals represent states of the system, and the arrows connecting states represent allowable transitions between states. (a) Directives take the form of state *requests* (green halo). Guardian calculates the shortest path through the graph (orange halos) to reach the requested state. (b) Any state may return a *jump target*, which causes Guardian to immediately transition to that state.

(see section III B) and a list of tuples that represent directed edges—or allowable transitions—between states. When the module is loaded the states and edges are extracted and assembled into a *state graph* for the given system. An example of a state graph for the Advanced LIGO suspension system is shown in Figure 3.

Directives to individual nodes take the form of a *state request*. When a state request is received by a **guardian** process (via its EPICS control interface) the process calculates the shortest path in the state graph between the current state and the requested state using a standard Dijkstra algorithm[33]. An example path is shown in Figure 3a. Once the currently executing state indicates that it is complete, the process immediately transitions to the next state in the path and begins executing the new state's code. This repeats until the requested state is reached.

At any time, the currently executing state code may return the name of a particular state, indicating that the system should immediately transition to the returned state. This is known as a *jump transition* and is used to bypass the normal edge dynamics of the graph. Jump transitions allow Guardian to respond immediately to undesired or unexpected changes in the plant. A jump transition is illustrated in Figure 3b.

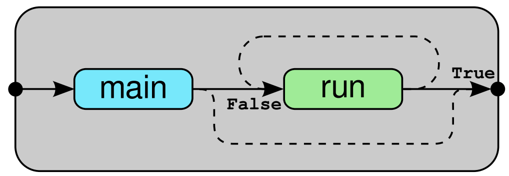
Guardian has three operating modes that determine how the system graph is traversed:

auto mode: Graph traversal follows the shortest path to the requested state. After jump transitions the system attempts to automatically recover back to the requested state by following the path from the jump target to the previous requested state.

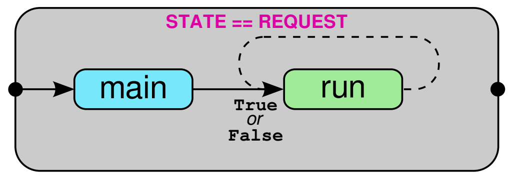
managed mode: Graph traversal follows the shortest path to the requested state, as in auto mode. After jump transitions, however, the system "stalls" at the jump target and does not transition away from the jump target until a new request is issued. This mode is used when the node is being managed by another node, since it gives the managing node the opportunity to identify that the subordinate has jumped and redirect the subordinate to a different request state if needed.

manual mode: The graph as a whole is ignored and the system immediately transitions between requested states. This mode is useful only for commissioning and debugging.

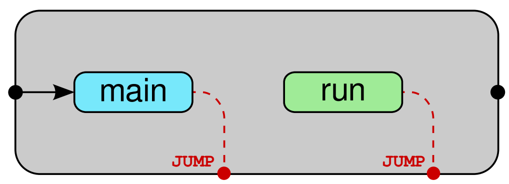
The default mode of operation is auto mode, and nodes are automatically put into managed mode when they are assigned a managing node.



(a) Basic operation, where a return value of `True` from either method causes the state to exit, and a return value of `False` causes the `run()` method to be executed again.



(b) If the current state equals the requested state the `run()` method is executed again regardless of whether the method returns `True` or `False`.



(c) If either method returns a `str` state name a jump transition to that state occurs immediately.

FIG. 4: Guardian state process flow, showing execution logic of the two state methods: `main()` and `run()`.

B. State code programming and execution

Each Guardian state is a Python class definition that inherits from a `GuardState` base class. The `GuardState` class has two methods: `main()` and `run()`. The `main()` method is executed once upon entering the state, after which the `run()` method is executed in a loop. The `main()` method is typically used for executing primary plant changes, while the `run()` method is typically used to watch for state exit conditions. Both state methods have three return type options:

- `False` or `None`: This indicates that the state is not complete and that the current state's `run()` method should be executed again.
- `True`: This indicates that the state is complete. If the current state is not the target state, e.g. there are more states in the path, a transition is made to the next state in the path. If the current state *is* the target state the current state's `run()` method is executed again.
- `str`: If the return value is a string it is assumed to be the name of a state in the graph. The named state is set to be the new target state and an immediate transition to that state is initiated (*jump transition*).

Figure 4 shows diagrams for the state method execution logic under various conditions.

Figure 5 shows an example Guardian user code module and the resulting state graph. The primary activity in each state consists of monitoring the plant via EPICS readback channels and controlling the plant by writing to plant settings channels. A special EPICS client interface object (`ezca`) provides methods specifically designed to deal with the Advanced LIGO front end system.

C. Process architecture

Guardian utilizes a soft real-time model for user code execution that is similar in some respects to programmable logic controllers (PLCs). The execution/scan loop is nominally 16 Hz, but each state method is allowed to take as long as it needs to complete. Once a method returns, the next method execution occurs on the next 1/16 second boundary. Only one method is executed per cycle.

In order to handle user code execution in a fully controlled environment, the `guardian` program is designed around a daemon/worker subprocess architecture (see

```python
from guardian import GuardState

class SAFE(GuardState):
    def main(self):
        ezca['SP0'] = 0
        ezca['SP1'] = 0
        self.t = ezca['T']

class DAMPED(GuardState):
    def main(self):
        ezca['SP0'] = 2
        ezca['SP1'] = 3

    def run(self):
        if ezca['RB0'] <= self.t:
            return True

edges = [
    ('SAFE', 'DAMPED'),
]
```

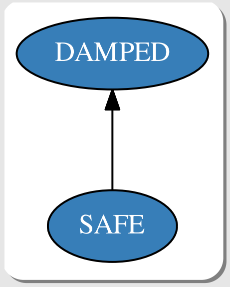


FIG. 5: Example Guardian user code module defining two states, SAFE and DAMPED, and one edge connecting the SAFE state to the DAMPED state. The global `ezca` object is the specially designed LIGO EPICS client interface. Class attributes can be used to pass variables between method calls. The resulting system graph for this module is shown in the inset.

Figure 6). The main daemon process handles operator interaction via a built-in EPICS server control interface, and determination of the appropriate state and state method to be executed. The worker subprocess handles all user code execution. The daemon and worker process communicate via a shared memory interface. This subprocess architecture allows the main daemon process to terminate user code execution at any time by simply terminating the worker subprocess.

The daemon's EPICS server provides a standard interface through which operators or other managing guardian nodes can request states in the graph, request reload of the user code, and monitor state execution. When instructed from the operator, the daemon loads the user code, constructs the state graph, and launches the worker subprocess if it's not already running. Through the shared memory interface the daemon tells the worker process which state object to instantiate and which state method to execute. The worker then executes the method, waits for it to return, and reports the return value to the daemon. The daemon then calculates the next state/method to be executed and the process continues. User code errors and exceptions are captured by the worker process and reported to the daemon, which halts further execution until the error condition is acknowledged and cleared by the operator.

The `ezca` EPICS client interface used in the worker process keeps track of all active EPICS channel subscriptions. Channel connectivity issues are reported to the daemon and user code can be suspended until all connections errors have cleared. The values of all EPICS channel writes are recorded in the `ezca` object and a set point monitor can be used to check settings during each execution cycle. This allows for tracking of set points and notifications if any set point has been changed externally.

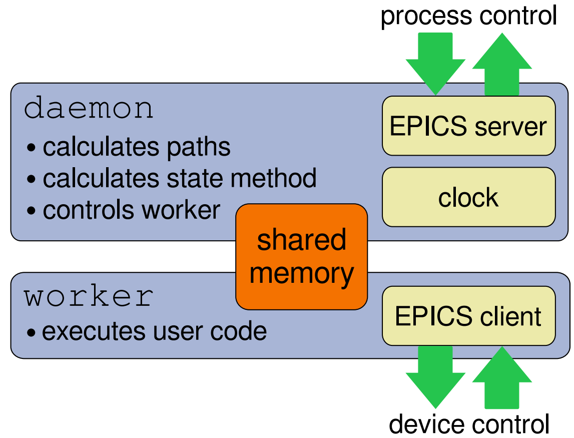


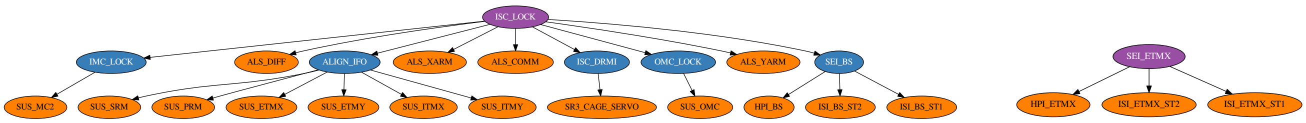
FIG. 6: Architecture of the core `guardian` program. The main daemon process loads the system graph, calculates state/method logic, and handles user interaction via a built-in EPICS control server. The daemon spawns the worker subprocess to execute all user code state methods. All communication between daemon and worker is handled via a shared memory interface.

D. Inter-node management

A special `NodeManager` interface is provided to facilitate inter-node control. Manager nodes list their subordinate nodes in the `NodeManager` object. Once the subordinate nodes are "acquired" the `NodeManager` object sets the subordinate nodes to be in managed mode and starts tracking their state and status channels. Via the interface, manager nodes can request states of their subordinates and inspect their state and status in an idiomatic way.

E. State tracking and validation

Instrument state tracking is critical for scientific applications where instrument validation needs to be well documented during an experiment, and there are a couple of key benefits of the state machine approach that make it particularly well suited for this task. First, at any given time the system can be in only a single well-defined state, which helps eliminate ambiguities. Second, since there are no persistent variables between states, all process variables of the system must be external to the state



(a) ISC_LOCK node hierarchy

(b) SEI nodes

FIG. 7: Guardian node hierarchy for various Advanced LIGO subsystems. (a) node hierarchy below the ISC_LOCK node that handles the interferometer lock acquisition process. (b) An SEI node hierarchy (for SEI_ETMX specifically) for which there are 11 similar in the full interferometer control. The top node for this system is known as the "chamber manager".

machine itself. In the case of Guardian this is achieved by having all process variables be EPICS records that are archived by the data acquisition system. Since Guardian node states and status are also broadcast over EPICS and recorded by the data acquisition system, the complete state of the instrument at any given point in time can be reconstructed completely from data on disk.

Guardian has additional features to facilitate instrument validation during operation. A *nominal* state can be defined for each Guardian node indicating the state the system is expected to be in during nominal operation. Each Guardian node can then broadcast the overall status of the system via a single binary status channel. The conditions that are checked are: a) the requested state is equal to the nominal state, b) the current state is equal to the nominal state, c) the node is in execution mode (not paused or stopped), and d) there are no error conditions present. If all of those conditions are met, the node returns an overall status of "OK" to indicate that the system is ready for operation.

F. User interface features

All user code can be reloaded on the fly on a live system, even while in the middle of state execution. A snapshot of all user code at time of load is committed into per-node user code git archives, which allows for inspecting the exact code that was running on any node at any point in time.

A notification system provides a way for state code to push important notifications to the operator. Verbose logs are archived by a logging infrastructure that provides full access to all node logs over time.

A supporting suite of utilities is available to draw state graphs, analyze and validate code, etc. Further details, installation and usage instructions, and a description of code syntax can be found in the LIGO document control center[34].

subsystem	number of units	nodes per unit	total nodes
ISC	1	9	9
SUS	26	1	26
SEI	10	4/3	35
TCS	2	2	4
DIAG	4	1	4

TABLE I: Advanced LIGO Guardian node breakdown among subsystems. ISC: interferometer sensing and control; SUS: suspensions; SEI: seismic isolation; TCS: thermal compensation; DIAG: diagnostics.

IV. GUARDIAN SUPERVISION OF ADVANCED LIGO

Advanced LIGO employs roughly 100 Guardian nodes in the full control of each detector (a number that continues to increase as new subsystems and functionality are commissioned). Table I shows the breakdown of nodes among the various subsystem components. Figure 7 shows graphs of the node hierarchies for the ISC and SEI BSC subsystems.

A. Subsystem control

The Advanced LIGO Guardian implementation takes advantage of standardization in subsystem hardware and the accompanying real-time controls code to create a highly modular and distributed automation infrastructure.

The suspension subsystem defines a single Guardian module to describe automation for all suspension systems in the interferometer. A common suspension class object abstracts various suspension readout and control functions depending on the suspension type. The Guardian code for each individual suspension system merely specifies the suspension type, and an appropriate EPICS channel access prefix, then loads the common suspension state graph. All suspension systems in Guardian therefore present an identical state graph interface to the rest of the system.

The seismic isolation subsystem further modularizes its code among the different types of control loops employed by the various ISI and HEPI devices. Sub-packages define functions, states and sub-graphs separately for damping and isolation control, as well as for system initialization and watchdog handling. The full system graph for each SEI component is then assembled from the necessary components. Additionally, due to the complexity of interaction between the various isolation stacks on a given chamber, multiple Guardian nodes are used to cover the SEI systems for a single chamber. For the larger BSC chambers that house the beam splitter and core test mass optics, one node handles the HEPI system, two nodes handle the two stages of the ISI system, and a "chamber manager" is used to orchestrate their actions. This hierarchy can be seen in Figure 7b. The smaller HAM chambers that house auxiliary optics use a similar hierarchy except with only a single ISI node for the single stage ISI system.

The SUS and SEI Guardian systems constantly monitor the state of their plant watchdogs. If a watchdog trip occurs, the systems will immediately jump to special states that reset all control loops and wait for the operator to reset the watchdogs. Once the watchdogs are reset, Guardian automatically brings all systems back to their previously requested states.

Overall interferometer lock acquisition is handled by the hierarchy of nodes shown in Figure 7a. Separate nodes handle locking the IMC, OMC, and ALS systems, and the overall DC alignment of the various suspension controllers. The full lock acquisition process[23] is orchestrated by the ISC_LOCK node.

B. System diagnostics and system validation

A set of specialized diagnostic (DIAG) nodes are employed to monitor aspects of the instrument that are not directly handled by the primary automation and subsystem nodes. These look at things like laser status, light levels on various detectors, the states of various electronics modules, the state of the Beckhoff system, etc.

At the top of the instrument node hierarchy is an "IFO top node" whose job is to monitor the status of all other nodes in the system. This node provides a single channel that reports on the status of the entire system as a whole, which is critical in determining if the observatory is ready to begin observation or not.

The status reporting of the Guardian system is also used extensively for detector characterization and validation purposes. Downstream detector characterization processes use individual subsystem status reporting during analysis of subsystem behavior.

C. Performance

The first operational demonstration of the full Guardian deployment in LIGO was the first Advanced LIGO observing run from September 2015 to January 2016, during which LIGO made the first ever direct detection of gravitational waves. The system performed robustly with no issues of note, and was used to aid in validation of the first gravitational wave event candidates.

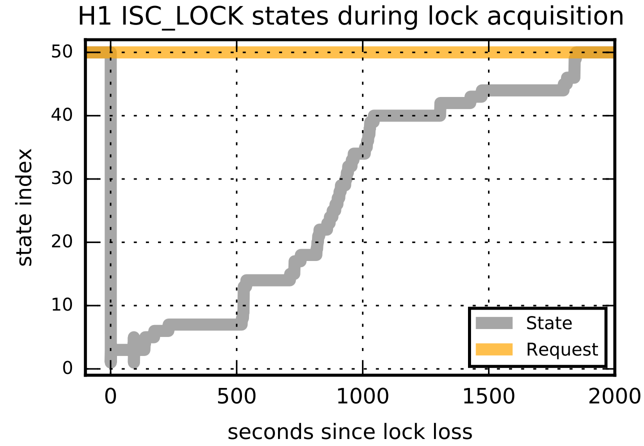


FIG. 8: An example of the ISC_LOCK Guardian node at the H1 detector autonomously recovering the interferometer to full low-noise lock after an unintended lock loss. The y-axis shows arbitrary state indices for the node. Before $t = 0$ the system is in the nominal locked state, corresponding to the orange "Request" state. At $t = 0$ the system loses lock and the system transitions to a "DOWN" state that resets all control loops in preparation for re-acquisition. At the end, the system has recovered the initial nominal lock state. In this particular instance, there is at no point any human intervention. The recovery time in this case is roughly 30 minutes.

The fully commissioned lock acquisition process takes about 30 minutes, with some variability between the two LIGO detectors. Figure 8 shows the primary lock acquisition node (ISC_LOCK, top node in Figure 7a) at the Hanford "H1" detector as it progresses through the states in the lock acquisition sequence during a fully autonomous lock loss recovery. The limiting factors in the recovery time are generally the physical responses of the various interferometer subsystems during the engagement of various control loops and not by anything inherent to the Guardian system itself. Lock acquisition time will likely be improved with further commissioning.

Figure 9 shows the progression of states for the hierarchy of nodes controlling the seismic isolation system in a BSC chamber during autonomous recovery from a watchdog trip. During normal operation, these types of trips are usually the result of earthquakes. The nodes involved are the same as those shown in the hierarchy in Figure 7b. The chamber manager node coordinates the activity of three subordinate nodes by issuing state requests. The watchdog recovery time is less than 15 minutes. The distributed nature of Guardian allows all suspension and seismic systems to recover in parallel if multiple trips occur simultaneously, thereby significantly reducing overall recovery time.

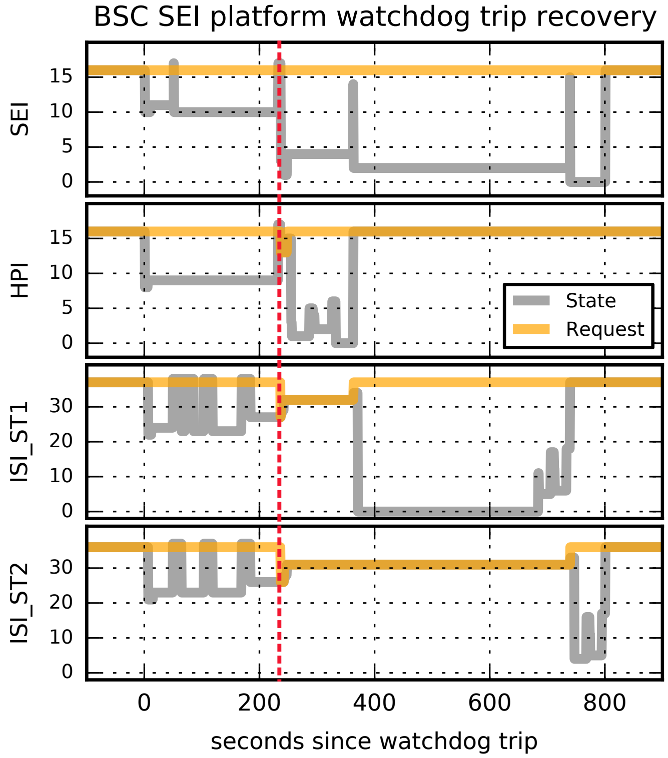


FIG. 9: An example of automated Guardian watchdog recovery of a BSC seismic system (see Figure 1). The y-axis shows arbitrary state indices for each node. The top row is the SEI "chamber manager" node which manages the actions of the following nodes shown in the lower three plots: HPI, for the BSC HEPI system; ISI_ST1, for the first stage of the BSC ISI system; ISI_ST2, for the second stage of the BSC ISI system. The red dashed line at 232 seconds indicates when the watchdogs were cleared by the operator and the full Guardian recovery began. The recovery procedure is described in Section II B. The full recovery time is less than 10 minutes.

V. CONCLUSION AND OUTLOOK

Guardian has proven to be a powerful tool for commissioning the Advanced LIGO detectors and has demonstrated robustness in the operation of both detectors during the first Advanced LIGO observing run. Many future runs are planned and continual improvement will be made to the user code logic during commissioning breaks. Additionally, short term detector improvements will involve new automation challenges. In particular, plans are being made to increase laser power in the interferometers, which will increase the complexity of the lock acquisition process and require full commissioning of the thermal compensation system, as well as potentially introducing additional nodes to handle issues such as parametric instabilities[35]. Longer term plans involve even more substantial upgrades that will introduce new subsystems with their own automation requirements, such as squeezed light systems to reduce quantum noise[36].

While the Guardian platform itself is now stable, many new features are planned for future releases. Further integration of the user code archive will facilitate detailed inspection of the historical data for detector characterization purposes. User interface improvements are planned that will integrate system graphs directly into the control UI. Node management interfaces will be streamlined.

Success in LIGO is also leading to the adoption of Guardian by other long-baseline gravitational wave detectors. Guardian is being used by the Japanese 3 km-baseline, cryogenic gravitational-wave detector KAGRA[37], and may be used by Advanced Virgo. Plans are also afoot to install a third LIGO detector in India.

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