

Embedding Built-in Tests in Hot Spots of an Object-Oriented Framework

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Abstract: Object-oriented frameworks require thorough testing as they are intended to be reused repeatedly in developing numerous applications. Moreover, whenever a framework is extended for reuse, it must be revalidated to check for possible regression faults and progressive faults. Frameworks, however, have properties that make it difficult to control and observe the testing of the parts that were modified and extended. This paper describes a scheme of encapsulating test support code as built-in test (BIT) components and embedding them into the framework's hot spots so that defects caused by the modification and extension of the framework can be detected effectively and efficiently through testing. The test components embedded into a framework in this way increase the testability of the framework by making it easy to control and observe the process of framework testing. Using our scheme, test components can be designed and embedded into the hot spots of a framework without incurring changes or intervention to the framework code, and also can be attached and detached dynamically to/from the framework as needed at run-time.

1. Introduction

One of the recent issues in object-oriented technology is to develop software as a framework which can be reused in many application areas[1,2,3]. Since a framework is to be reused repeatedly in many software developments, thorough testing is needed. Furthermore, additional testing is required each time the framework is adapted and extended for reuse. Systematic testing on a framework is therefore crucial for the efficiency and reliability of framework-based software development.

An object-oriented framework provides an architecture which consists of various cooperating abstract and concrete classes[4]. Some of the classes in the framework are designed as hot spots which can be adapted within the limits the architecture permits. The framework is reused in application developments by adapting and extending those hot spots according to the class inheritance and object composition mechanism. The context in which the framework is (re)used can be very complicated[5]. Furthermore, the types of mismatches that can occur when system-level architectures like the framework are reused can be diverse and unpredictable[6]. Consequently, it is not easy to force the classes adapted and composed during framework reuse to satisfy the constraints the framework assumes, or to confirm constraint

violations in advance. Therefore, whenever a framework is adapted or extended, it must be revalidated to check for possible progressive faults and regression faults.

Many test methods on object oriented software have been introduced[7,8]. Most of them can be applied to framework testing. However, an object-oriented framework has many characteristics that make it difficult to test the adapted parts of the framework effectively. Usually, the execution of the extended parts for the framework is controlled by the framework itself, which makes it difficult to set up initial test conditions of the framework and to drive test execution. Since it is not easy to predict the starting point of the execution and to observe the result of the test, it is also difficult to detect occurrences of malfunctions. If changes are made to framework code arbitrarily to intermingle it with test support code to enhance the controllability and observability of framework testing, the reliability of testing cannot be guaranteed.

In order to overcome such problems, this paper proposes a scheme for embedding test support code as BIT(Built-in Test) components into the hot spots of the framework without incurring changes or intervention to the framework code. The test components embedded into the framework make the testing of the adapted framework more controllable and observable, and thereby enable us to effectively detect, through tests, the faults generated during framework adaptation or extension.

This paper is organized as follows. Section 2 provides a brief overview of framework hot spots, framework testability, and the types of test support components we considered for BIT-embedding. Section 3 provides the proposed design scheme for embedding built-in test components in framework hot spots. Section 4 presents an experimental example of applying the design scheme to the testing of a sample framework. Section 5 reviews related work. Section 6 concludes this paper.

2. Hot Spots and Testability of a Framework

2.1 Framework Hot Spot

A framework is composed of frozen spots designed to be shared among applications without modification, and hot spots designed to be adapted/extended according to the application[21,22]. A framework also contains rules of composing and interacting among the system components which must be observed when adapting/extending hot spots. Those rules can be defined precisely using the design by contract principle[18,23,24].

The frozen and hot spots of an object-oriented framework are encapsulated in methods of classes. The method for a frozen spot is called a template method, and the method for a hot spot is called a hook method[21,22]. The class that contains template methods is called a template class, and the class that contains hook methods is called a hook class. The template and hook classes can be of different class or the same class. When they are different, the hook class is adapted and extended by composing an object from a subclass of the hook class into the template class through the instance variable which references the hook class object. When they are same, the hook method is adapted and extended by subclassing the

unified template/hook class.

Pre[3] classified the composition among object-oriented framework components into 7 patterns according to the following two criteria:

- 1) the number of the hook class objects compounded into the template class objects(whether multiple objects are allowed or not)
- 2) whether inheritance exists or not among the compounded template and hook classes.

The object-oriented framework provides its functions through interactions allowable among the template and hook class objects compounded according to the composition patterns. The variable functions implemented through adapting and extending the hook classes, and the interactions among the frozen spots and extended hot spots of the framework must be (re)tested.

2.2 Framework Testability

For effective framework testing, high testability must be maintained when developing, adapting or extending a framework. Software testability, which means ease of revealing software faults through tests[15,16,17], can be affected directly or indirectly by many different factors[15]. In this paper, we focus on the following four factors that have direct influence on framework testability:

- 1) controllability: the ability to set up and control test conditions
- 2) sensitivity: the ability to capture and expose traces of malfunctions in response to tests
- 3) observability: the ability to observe test results externally
- 4) oracle availability: the ability to determine or obtain expected test results

The framework also requires that other important quality factors such as reliability, robustness, flexibility, modularity and performance be maintained at a high level. Usually, testability is complementary to other quality factors, but it may tend to conflict with them. For example, if a framework's test sensitivity gets higher, malfunction by faults could occur more frequently, and consequently, reliability and robustness could be reduced. To take another example, if a framework's controllability and observability get higher, then reliability, flexibility, modularity or performance could be reduced since concealed information could be revealed and components of the framework might be possibly interrupting or interfering with each other.

In order to overcome such difficulties and maintain higher framework testability, we designed a scheme for encapsulating test support codes as a set of tester components separated from the framework under testing and embedding them into the framework with little change to the framework. Since test support codes are embedded as BIT components with little interference to the framework under test, enforcing testability does not sacrifice other quality factors such as reliability and modularity. Furthermore, the tester components are designed to be attached or detached as necessary so that framework testability can be higher during tests and lower in operation in order to avoid performance degradation due to the

overhead incurred by the execution of tester components.

The types of test support components to enforce framework testability presented in this paper are test controllers, test sensitizers, test monitors, test oracles, and test loggers. The test controller increases controllability by setting up and initializing test conditions for framework hot spots. The test sensitizer upgrades sensitivity of the framework by capturing and leaving traces of malfunctions during test execution. The test monitor increases observability by monitoring actual results of test execution and judges pass/fail of the test by comparing actual with expected results. The test oracle helps the monitor judge pass/fail of the test by giving expected pre-conditions, post-conditions and invariants of the test cases. The test result, passed or failed, is sent to the test logger by the monitor. The test logger records and stores the test result according to the current test context.

The pre-, post-conditions, and invariants for the framework hot spots are encapsulated in a suite of assertions that can be inspected by the tester components. The tester components embedded or attached to the framework support the framework test by watching through the assertions to see how the adapted or extended components of the framework observe the required contracts. Much work has been done on the type and grammar of the assertions and where to place them[18,19,20].

3. The Design Scheme of BIT-Embedded Framework Hot Spot

This section describes the proposed design scheme for embedding tester components into the extended hot spots of the framework in order to facilitate testing whether the framework's functional contracts are observed when adapting/extending hot spots. Figure 1 shows a framework hot spot with the composition pattern in which many hook class objects are connected to a template class object. The template class object is composed with the objects that belong to the subclass of the hook class, through an instance variable (represented as hRef in Figure 1)[21].

Figure 2 shows a BIT-embedded composition pattern where the tester components are attached to the framework hot spot, with an extended component of the hook class as a framework CUT (class or component under test). The classes in the shaded area of the figure represent the tester components embedded or attached to the framework hot spot. The TestController and TestLogger are the tester components attached from the outside of the CUT, while the other components are BITs embedded into the CUT. The CutTester is an abstract base class of the BIT components which provides the same interface as the CUT for the template class object through the hook class. The CutSensitizer and CutMonitor are designed as subclasses of the CutTester class, which is a subclass of the hook class. The BITs and the CUT form a chain structure connected through the tCut, which is an instance variable of the CutTester class. The Template object is attached to the CUT through the Hook class interface referenced by the hCut variable. Via a chain of the BIT components in between, the template object is connected to the CUT located at the end of the chain.

When its hMethod is called, each of the tester components embedded into the CUT as elements of the

chain structure performs its own testing function before and after forwarding the hMethod call to the successor component connected through the tCut variable. During the process, however, the functional behavior between the Template object and the CUT is not interfered with by the tester components attached to the CUT. The design pattern of the tester components is similar to the Decorator design pattern[4]. Testing functions on the CUT are divided by the tester components, and the outermost CutMonitor plays the role of a proxy which watches the template object have access to the CUT[4].

The CutSensitizer in Figure 2 captures the clue data critical to the testing of the CUT before and after it calls the hMethod through tCut. For example, the CutSensitizer keeps the state before the CUT is called, so that it is possible to inspect post-conditions and invariants after calling. The CutMonitor checks if the contract is violated by inspecting the pre- and post-conditions and invariants before and after the CUT calls the hook method. The test results are collected and recorded by the TestLogger.

The CutOracle referenced by the CutMonitor calculates the expected result after the CUT executes the hook method. The CutMonitor judges pass or fail of the test by comparing the expected result obtained from the CutOracle with the actual result obtained from the CutSensitizer.

The TestController initializes the other tester components and drives the test execution. Before starting the test execution, it generates an object structure instance of the CUT and BIT components, and embeds the generated BITs in the CUT instance. It then initializes the BIT-embedded CUT and the TestLogger to the condition required by the current test case.

Figure 3 shows an object structure which has a test monitor, sensitizer and oracle between the template object and the CUT object according the BIT-embedded composition pattern in Figure 2. Figure 4 shows a sequence of interactions among the template, CUT and tester objects when the tMethod of the template object is called by the TestController.

Referencing the hCut variable, the tMethod of the template object calls the hMethod of the hook class object. The invocation of the hMethod is forwarded to hMethod of the CUT by way of the CutMonitor and the CutSensitizer. The execution result returns to the tMethod of the template object by way of the CutSensitizer and the CutMonitor. With the help of the CutOracle, the CutMonitor checks the pre-, post-conditions and invariants of the CUT before and after the hMethod of the CutSensitizer is called, and passes the inspection result to the TestLogger. The CutSensitizer captures and stores the states of the CUT before and after the hMethod of the CUT is called. During this process, however, the interaction between the template object and the CUT is not interfered with by the CutMonitor, CutSensitizer and CutOracle.

The object structure of the hot spot in Figures 3 and 4 shows a 1:1 composition of a hook class object and a template class object. The BIT embedding method proposed in this paper supports the framework testing for 1:n composition where a template object is compounded with many hook class objects, as well as for 1:1 composition. For example, in the object structure allowed by Figure 2, where many hook objects are compounded with a template object according to 1:n connection composition pattern, the BIT components are embedded into each of the hook objects. Although this paper exemplifies a case with only

one hook method, testing can be easily extended onto the interactions between a template object and a hook object with many hook methods. In such a case, the BIT-embedding process is defined for each hook method in the same way as the BIT components are embedded in the hMethod in Figure 2.

4. Application Example

4.1 Alarm Monitoring System

The framework exemplified in this chapter is an alarm monitoring framework which we developed for application areas such as process control monitoring systems. The framework can be expanded to an alarm monitoring system[Figure 5] which raises an alarm upon change to an abnormal state.

Figure 6 is the class diagram which shows a part of the composite structure of the alarm monitoring framework classes. The InPoint is the class which directly inputs measured values from the outside. The DerivedPoint class calculates new measured values or state values, using the measured values acquired from other Point class objects. AlarmMonitor, a subclass of the DerivedPoint class, senses state changes, depending on the changes of measured values, and gives an alarm upon change to an abnormal state. AlarmMonitor is a hook class compounded into the Point class, and can be extended to various subclasses depending on the applications. Figure 6 shows the AlarmMonitor class designed according to a state pattern which consists of four state objects[10].

In the example framework, the AlarmMonitor will be the CUT upon which the tester components are attached, and have the object behavior which is specified in the Statechart[25] shown in Figure 7. If the measured values received as parameters when the update operation is called exceed either high or low limits, the AlarmMonitor raises high or low alarm. It also has deadbands to avoid repeating alarms that might occur when the measured values fluctuate between upper or lower boundaries. Figure 8 shows an example of state changes depending on the changes of the measured values, and points of alarms.

Many different alarm monitoring systems can be implemented using the framework in Figure 6. Figure 9 shows an alarm monitoring system which performs independent alarm monitoring upon the measured values coming from two different input sources. Figure 10 illustrates interactions among the objects of the alarm monitoring system when a sequence of measured values comes from a single input source.

4.2 BIT Design and Embedding

Figure 11 shows a class structure in which tester components, as BITs, are embedded into the CUT, AlarmMonitor. The BITs are CutMonitor, CutSensitizer and CutOracle. The CutMonitor and the CutSensitizer are connected to each other through tCut, an instance variable of their superclass, CutTester. The CutSensitizer inspects and captures the internal states of the AlarmMonitor before and after it calls the update function through tCut. The CutOracle is designed to simulate the state behavior in Figure 7. The Cut Monitor is designed to check if the CUT violates the pre-, post-conditions and

invariants, comparing the actual behavior from the CutSensitizer with the expected behavior from the CutOracle. Other tester components, such as a test controller which initializes test conditions and drives the framework testing, or a test logger which collects and records the test results, are also designed to be attached to the framework under test. As test cases, we used sequences of update function calls whose parameters are the measured values. Each of such test cases represents the paths of a state transition spanning tree whose paths are the state transition sequences allowable within the operational mode in the statechart in Figure 7.

At the initial stage of the testing, the test controller instantiates the tester components and embeds them into the CUT. When the test controller attaches AlarmMonitor to the InPoint object, the BITs embedded in the AlarmMonitor are also attached together with the AlarmMonitor. The tester components can be dynamically detached and attached as needed at run-time. The implementation of the tester components and their integration with the framework under testing have been done without incurring changes or intervention to the framework codes.

As shown in Figure 12, the tester component objects, designed as in Figure 11, are embedded into the AlarmMonitor object which is compounded as a hook class object into the InPoint object. Figure 13 shows a possible object structure for the BIT-embedded alarm monitoring system. Upon testing, not only establishing test conditions but also monitoring test results are done transparently without intervening in the alarm monitoring function of the system.

4.3 A Test Scenario

In order to check if the tester components work properly in testing the BIT-embedded alarm monitoring system, we planted some errors in the system that may not be easily detected but cause abnormal state changes, and performed testing with test patterns as explained in the previous section. Two cases of testing have been done : with and without embedding BITs. In the case of tests with BITs, abnormal state changes caused by errors were recorded by the test logger without omission, although not all the known errors were detected. Meanwhile, in the case of tests without BITs, only a subset of the errors that could be detected by the BITs, such as giving a false alarm by misjudging a normal state to be abnormal, were detected by the alarm logger.

We give an example in which a malfunction caused by an error in the alarm monitor is detected by the tester components. Suppose the alarm monitor perceived the current state to be abnormal because a measured value exceeded the high limit, and another measured value below the high limit and within the deadband was input. In this case, the alarm monitor should still regard the current state as abnormal. But, due to an error in the alarm monitor, suppose the alarm monitor regarded the situation as returning to the normal state without considering the deadband. Figure 14 shows the interaction among test controller, InPoint object, BIT-embedded alarm monitor and test logger, under the supposed situation. (In the actual implementation, the caller's reference is passed as a parameter when the Inpoint object calls the update

function. In Figure 14, however, measured values were used here as parameters, as a matter of convenience.) When a normal measured value of 95 which is within the deadband is passed from the inPoint to the alarm monitor, the BITs perceive the alarm monitor misjudge the situation as returning to the normal state. Then, the testLogger logs it as a failed test. Since the alarm monitor gives alarm only when the state changes to abnormal, such a malfunctioning cannot be easily detected without support of the tester components.

5. Related Work

Many testing methods for object-oriented software have been proposed[7,8,9,10,11,12]. For example, ASTOOT[9] offers an algebra-based class test method and support tools, while ClassBench[10] provides a state-based class test method and its support environment. An incremental test for the class hierarchy[11] and object-oriented integration testing methods[12] have been also introduced.

Difficulties in testing adapted frameworks are well-known, and several solutions have been proposed in the literature[5,8,13,14]. Fayad, et al.[14] presented a method in which the test-case generating codes, packaged in Built-in tests(BITs) classes, are embedded into the framework, and reused in framework testing, being inherited and adapted during framework adaptation and extension. Binder[8,15] comprehensively presented test design patterns and methods to construct a test support environment. While all of these approaches and methods are useful for testing frameworks, they do not directly address the testing problems specific to the hot spots of the framework.

6. Conclusion

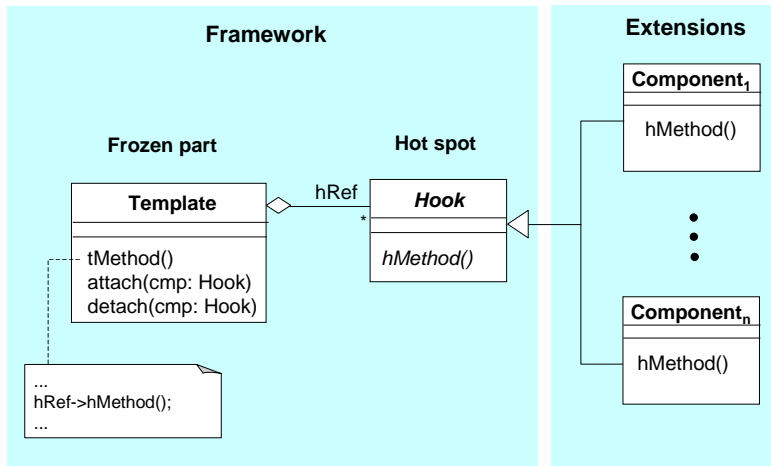
Object-oriented frameworks support efficient software development by providing common, yet flexible architecture composed of classes that are easy to adapt and extend for families of applications. Frameworks, however, have properties that make it difficult to control and observe the process of framework testing needed whenever they are modified and extended for reuse in developing application systems. This paper has described a scheme for encapsulating test support code as built-in test (BIT) components and embedding them into the framework's hot spots so that defects caused by the modification and extension of the framework can be easily detected through testing. Using our scheme, test components can be designed and embedded into a framework to increase the controllability and observability of framework testing without incurring changes to the framework code and without affecting its functional behavior. Finally, the test components can be attached and detached dynamically to/from the framework as needed at run-time.

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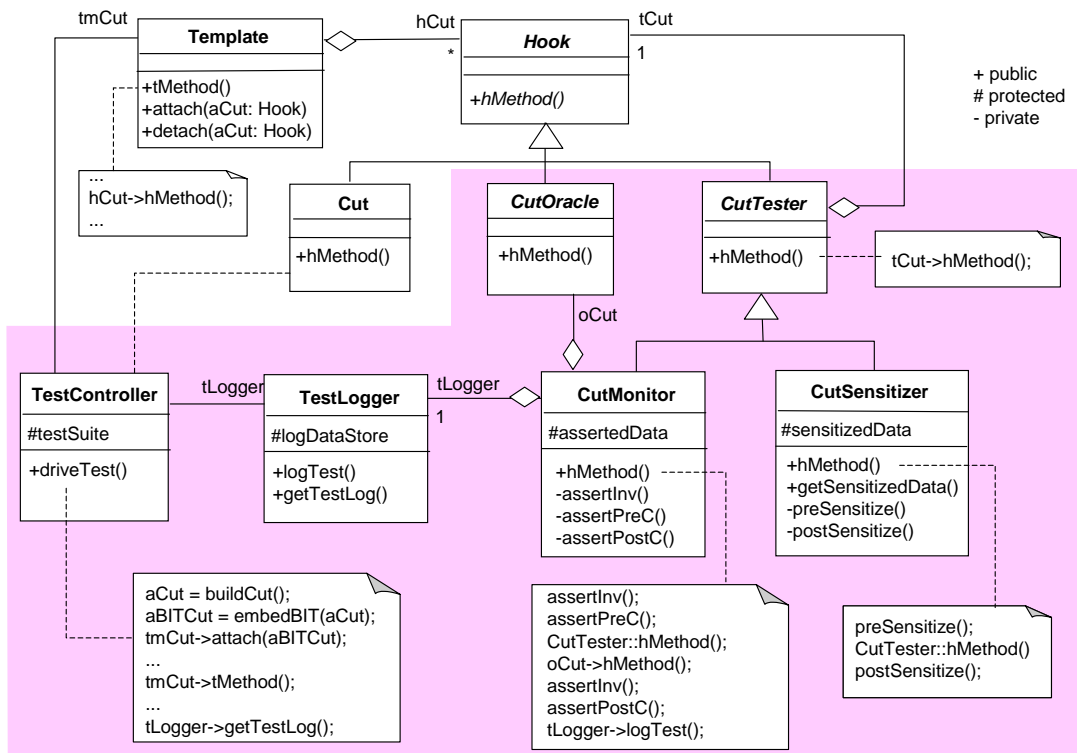
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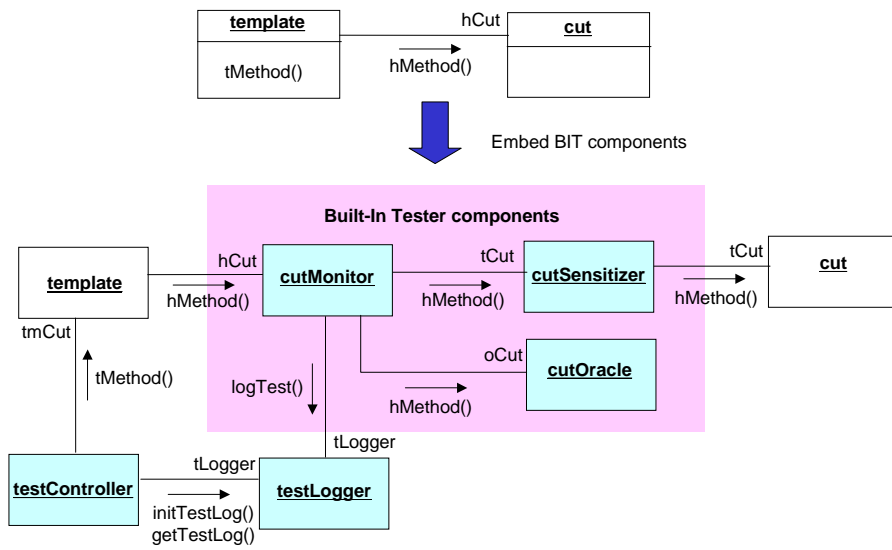
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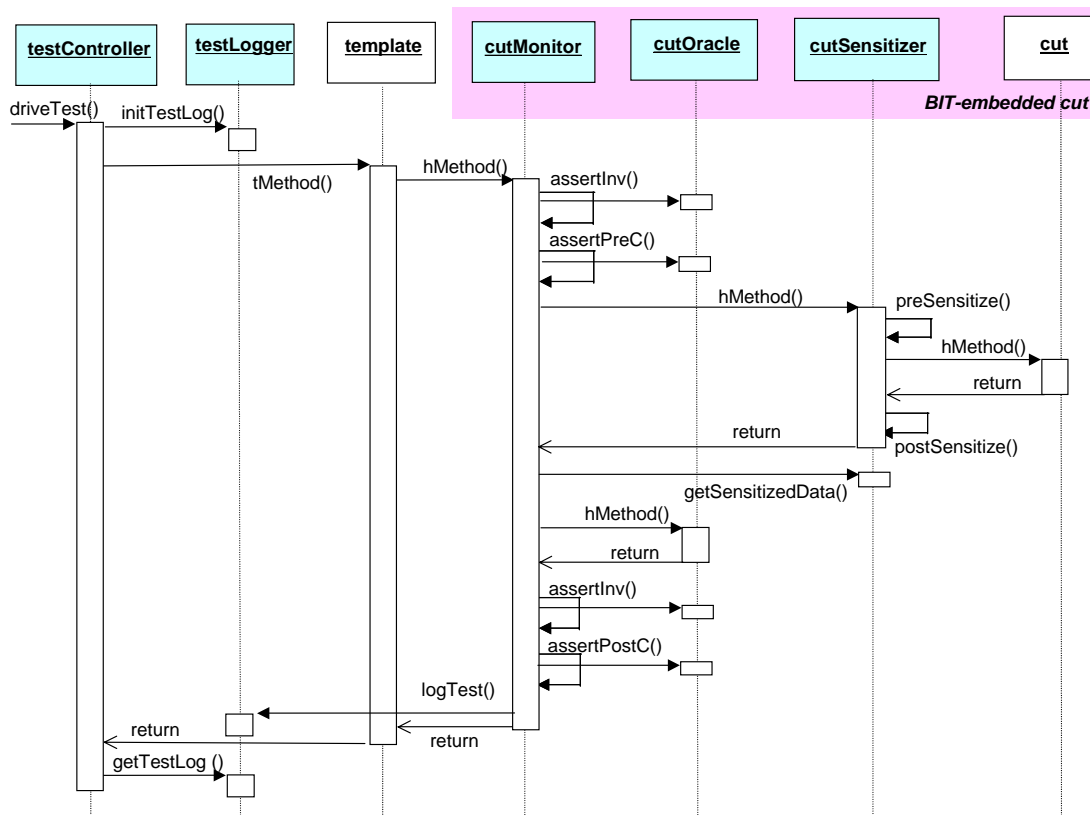
[Figure 1] Framework Hot Spot



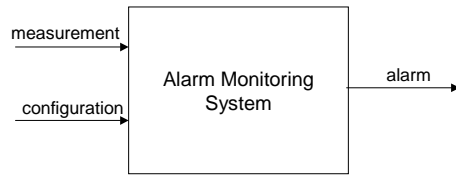
[Figure 2] Class Structure of BIT-Embedded Framework Hot Spot



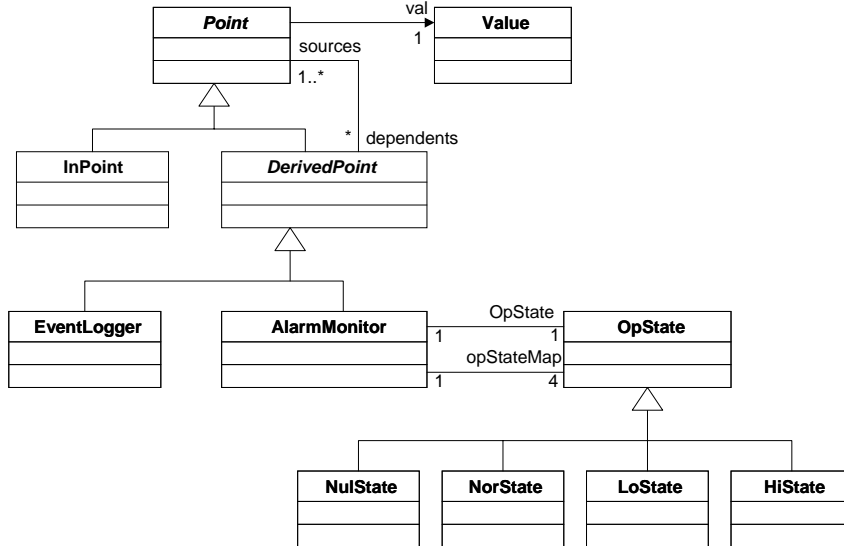
[Figure 3] Object Structure of BIT-Embedded Framework Hot Spot



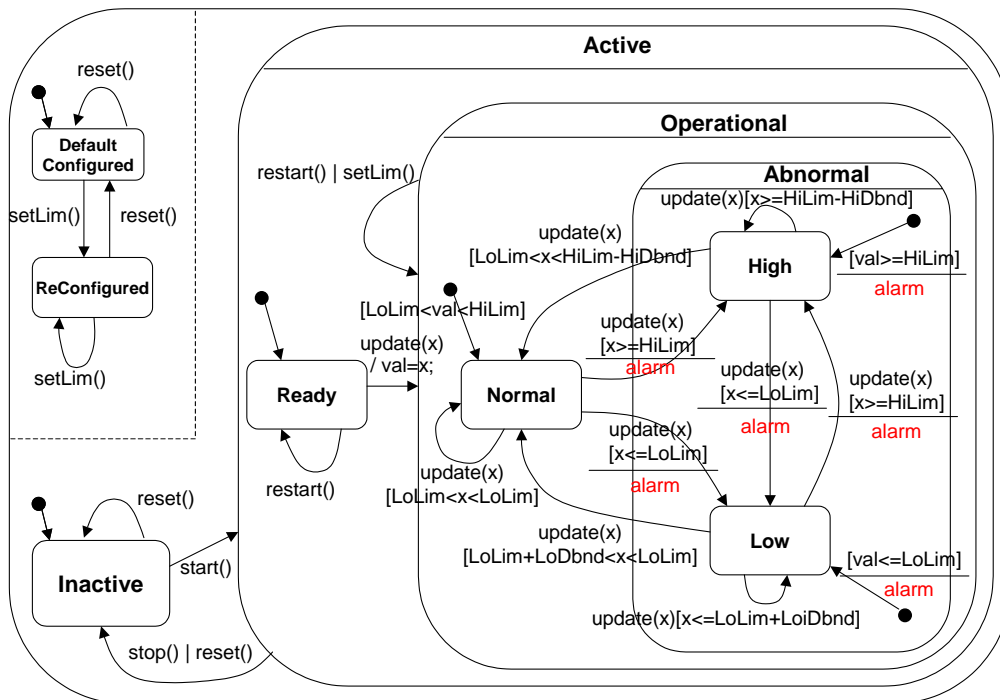
[Figure 4] Sequence Diagram of BIT-Embedded Framework Hot Spot



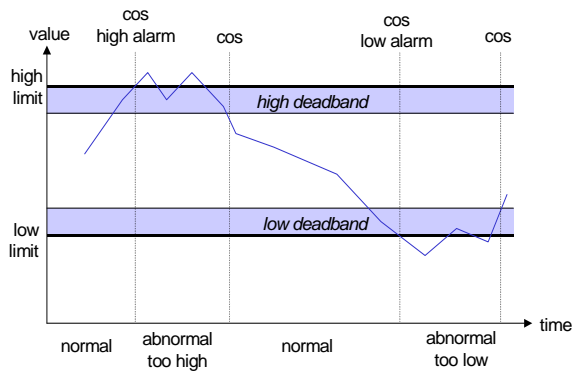
[Figure 5] Alarm Monitoring System



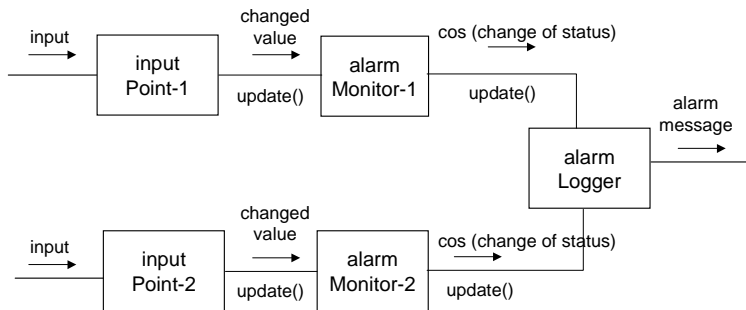
[Figure 6] Partial Class Structure of the Alarm Monitoring Framework



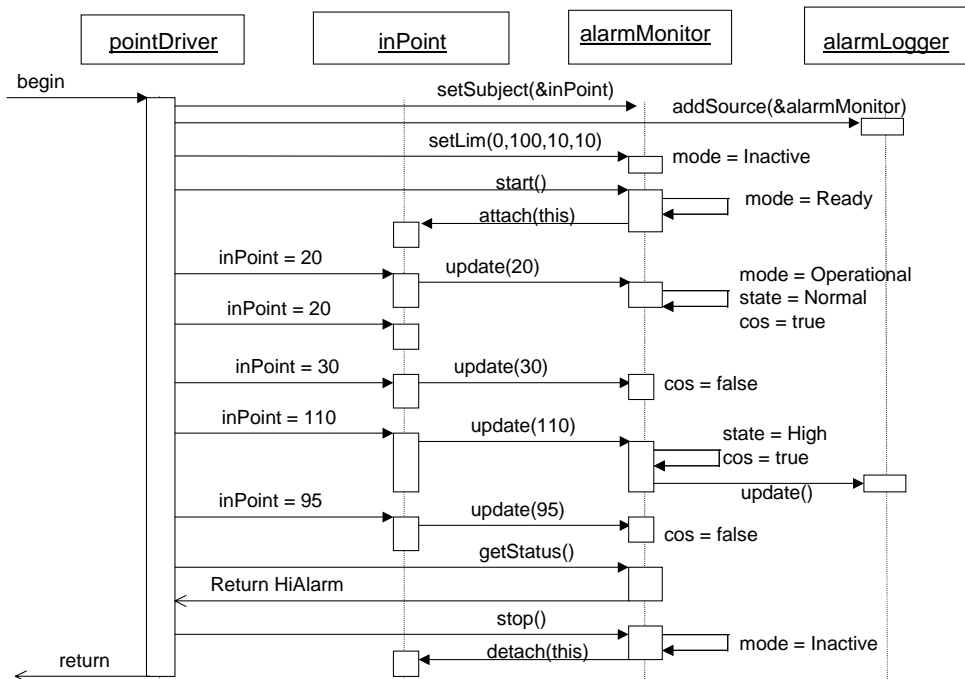
[Figure 7] Statechart Showing the Object Behavior of the AlarmMonitor Class



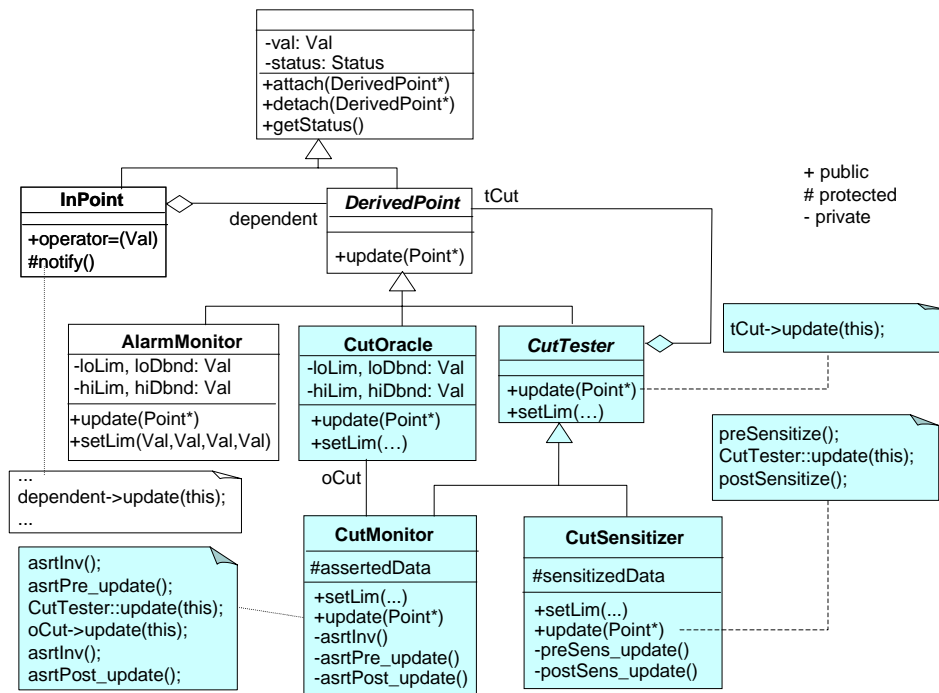
[Figure 8] State Changes as Measured Value Changes



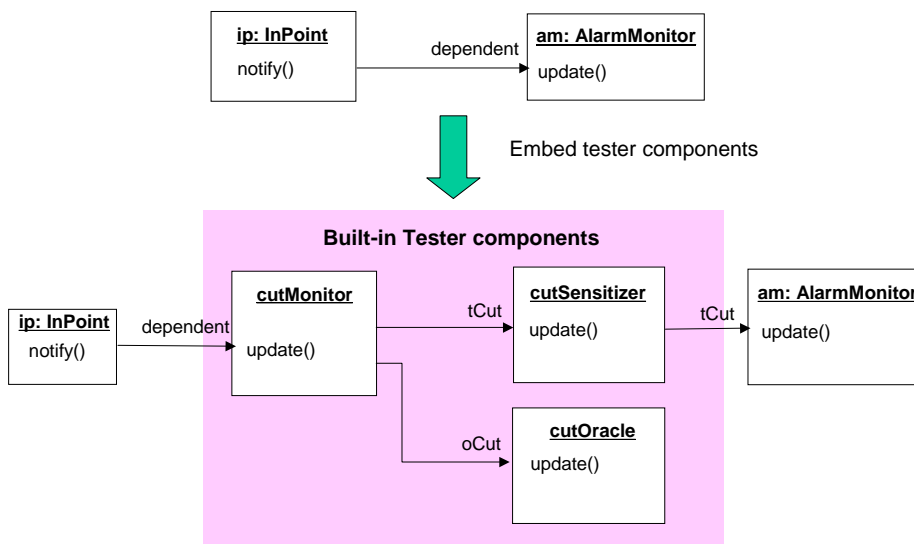
[Figure 9] Object Structure of BIT-Embedded Alarm Monitoring System



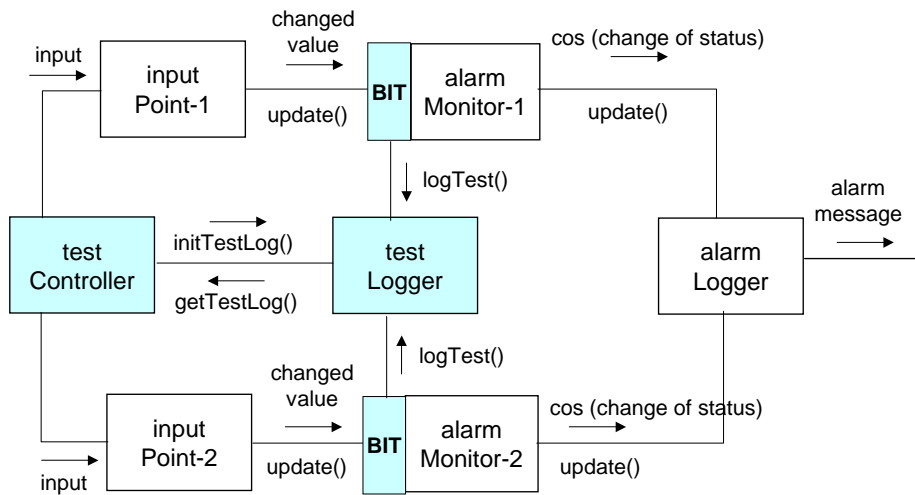
[Figure 10] Sequence Diagram of Alarm Monitoring System



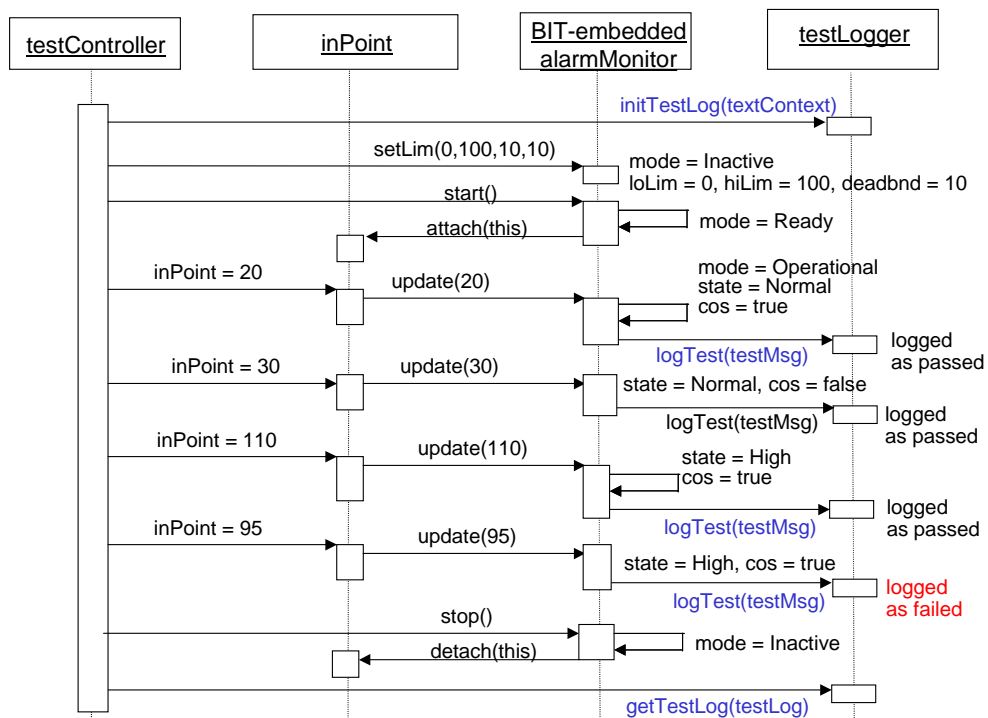
[Figure 11] Class Structure of BIT-Embedded Alarm Monitor



[Figure 12] Embedding BIT Components in an AlarmMonitor



[Figure 13] Possible Object Structure of BIT-Embedded Alarm Monitoring System



[Figure 14] Test Scenario of BIT-Embedded Alarm Monitor