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Composition and Testing of Connection Fault Handling Behaviors in Programs with AND/OR Graph

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To programs running on components in a distributed system, both network and component failures manifest as connection faults that are represented by exceptions. Although many strategies are available for handling connection faults, it is often necessary to compose multiple strategies in such programs, especially in Internet of Things systems and cyber-physical systems. Moreover, it should be possible to specify a program's connection fault handling behaviors prior to implementation. Having observed the lack of appropriate design-level constructs, we propose an extended AND/OR graph for modeling composite connection fault handling behaviors in programs. The extended AND/OR graph enables succinct representations of complex fault handling behaviors by composing the constituent strategies of retrying, communicating failure, and ignoring failure. Furthermore, we develop a model-based testing framework that accepts the extended AND/OR graph specification as input and generates tests for checking the connection fault handling behaviors of a program constructed from the specification. The proposed method is illustrated with a Java program to detect and report failure of a device. In particular, the AND/OR graph specification stipulates that the program handles connection faults covering network failures by composing retrying strategy. From this specification, tests are generated by finding all solution trees of the AND/OR graph subject to the number of retries to cover all the paths that lead to the program's normal and exceptional exits, respectively. The extended AND/OR graph and the model-based testing framework contribute to the means for specifying and testing connection fault handling behaviors of programs that are crucial to the success of Internet of Things systems and cyber-physical systems.

Keywords: connection fault, exception handling, AND/OR graph, model-based testing, aspect-oriented programming

1. INTRODUCTION

A program running on a computer solves a problem by being *connected*, through the execution environment provisioned by the computer, to the context where the problem is located. Through the connection, relevant *phenomena* – events and states – are shared between the program and the problem context [1]. The efficacy of the program depends on the quality of the connection and the correctness of the phenomena shared through the connection: a failed connection could isolate the program from its context and corrupted shared phenomena could prevent it from computing the correct result.

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Failed connections and corrupted shared phenomena are aspects of availability and robustness of software [2] that become pervasive in Internet of Things (IoT) applications [3, 4, 5] and cyber-physical systems (CPS) [6]. A typical IoT application can easily comprise thousands of nodes interconnected through networks of varying degree of reliability. Battery-powered nodes that die or network transmissions that fail are common failures. Programs that run on these constituent nodes should be built to handle unreliable connections and corrupted sensory data and to withstand node and subsystem failures [4, 7]. Thus, regardless of the role a node plays in a system – as a server, a hub controller, or a sink node directly connected to sensors and actuators – a node's capability to cope with failed connection and corrupted shared phenomena is critical to its success in the system [5, 8].

In this research, we shall focus on tolerating connections faults through exception handling [2, 9]. As long as a program connects to the problem context to share phenomena, connection faults beyond the program's control will always be present. Between being completely robust and being totally broken, a connection can be intermittent due to certain transient conditions [10]; while a connection is in good order most of the time, it could appear broken when needed. Here are two examples.

- Consider a mobile application that uses a LTE or WiFi connection to access remote services where the acquired connection is intermittent due to terrains or weak wireless airwaves; a required database retrieval could not be completed through the acquired connection because of heavy network traffic bounded for the database server; and so on. Such transient conditions are instances of active connection faults.

- Consider the use of a smart phone as the edge sink/controller in a smart home application that contacts sensors and appliances deployed in a living room through Bluetooth, NFC, or WiFi [5]. Obviously, it is highly desirable for the application to use the best connection. However, when the best connection is not available, it should automatically switch to an alternative connection with a negligible delay.

A program that easily fails on transient connection faults is fragile and not suitable for distributed, mobile, and IoT applications. Usually, connection faults can be tolerated by retrying the failed operation, possibly after a small length of time of waiting. Since retry incurs minimal overhead, accepting failure or attempting some other more expensive strategies (*e.g.*, retrying with an alternative connection) become justified alternative options only after a reasonable number of consecutive retries have failed [11].

Indeed, the need to tolerate transient faults has been well recognized by the development community. In addition to the exception handling constructs of most programming languages, many widely used application programming interfaces (APIs) are available to developers in composing programs that handle connection faults [12, 13, 14]. For example, the Microsoft Enterprise Library provides fault detection strategies and backoff strategies (*i.e.*, number of retries to attempt in case of failure and the length of time to wait between two retries), the selections of which are wrapped in an object called the *transient fault handling application block*, which provides a surrogate around the method to be retried to ride out a transient fault [12].

Both the use of exception handling constructs and the use of APIs can be viewed as implementation-level means for handling connection faults. As pointed out in [2], this often has a consequence that program-level availability is inadequately planned and the resulting program is insufficiently tested [15].

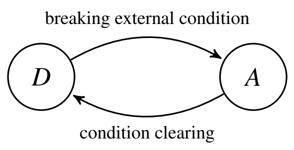
To make connection fault handling a part of the specification of the program under development, a more abstract way above the level of language features or APIs is needed. In particular, the abstraction should be able to express the composition of exception handling operations for implementing the exception handling strategies - including retrying, state restoration, and error reporting [11] – once the situation of the applicable strategy has been determined [16]. Further, the abstraction should also serve as a foundation to automate the subsequent technical tasks, including generating the tests to check an implementation's conformance to the specification [17].

In this paper, we extend the AND/OR graph for structured programming [18] to compose the connection fault handling behaviors of a program. A node in the extended AND/OR graph is called an *operation*, which extends an *action* in AND/OR programming [18] or a *statement* in structured programming [19], *that terminates with or without an exception*. To the collection of basic operations available in the AND/OR programming, we propose to add two additional *exception handling operations* derived from the *try-catch-finally* construct that are available in most programming languages. With the extended collection of operations, operations that tolerate connection faults are constructed through the AND and OR compositions [18]. With the extended AND/OR graph, we make two contributions. First, as an artifact that focuses on specifying the connection fault handling behaviors of programs, the extended AND/OR graph complements the existing design artifacts such as sequence diagrams and communication diagrams [20], which focus on specifying the normal behaviors of programs. Second, we demonstrate that the extended AND/OR graph can be used as a model in *model-based testing* (MBT) [17]. In so doing, we have developed a framework to generate unit tests from the AND/OR graph specification, where both the specification and AND/OR graph search algorithm are implemented with the Prolog programming language [21]. The generated tests, each of which corresponds to a solution tree of the AND/OR graph traversed by the search algorithm, make use of aspect-oriented programming [22] to inject active connection faults as described by the solution tree during testing. A failing unit test indicates that the specification has not been implemented correctly for the particular sequence of connection faults encountered.

The rest of this paper is organized as follows. In Section 2, the state model of an operation facing connection faults is defined, followed by the definitions of the basic operations and the exception handling operations. Section 3 shows how common strategies for handling connection faults are constructed with the extended AND/OR graph. In Section 4, a working example in composing the connection fault handling behaviors of detecting a device failure function is detailed to illustrate the use of the extended AND/OR graph. In Section 5, we develop a model-based testing framework that generates tests for checking a program's conformance to its connection fault handling AND/OR graph specification using a detecting a device failure as an illustrating example. A review of some related work is found in Section 6. Finally, we offer our conclusion in Section 7.

2. THE EXTENDED AND/OR GRAPH FOR CONNECTION FAULT HANDLING

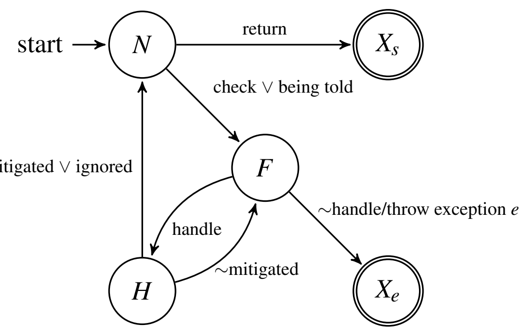
Our objective is to extend the AND/OR graph formalism to represent a composite operation with the specified connection fault handling behaviors [18]. In order to do this, Section 2.1 defines the connection fault-operation relation and the fault handling behaviors of an operation in response to a connection fault. The basic operations and the proposed extensions of the AND/OR graph for exception handling are detailed in Section 2.2.



Legends

D	connection fault is dormant
A	connection fault is active

Fig. 1. State model of a connection fault



Legends

N	normal
F	faulting
H	handling
X_s	normal exiting
X_e	erroneous exiting
$\sim$	logical negation
$\vee$	logical disjunction
a/b	on a, do b

Fig. 2. State model of an operation *op* regarding connection fault.

2.1 Connection Fault, Operation, and Their Relationship

First, we shall define the effects of a connection fault on an operation *op*. A connection fault is either *dormant* or *active* [9] as shown in Fig. 1. A dormant connection fault becomes an active connection fault when an external condition breaks the connection (*e.g.*, network is disconnected); an active connection fault turns dormant when the condition that breaks the connection clears (*e.g.*, network is reconnected). A dormant connection fault is *benign* to operation *op*. That is, it does not affect operation *op*'s behavior in exchanging information with the external entities. Further, an active connection fault is benign to operation *op* if the connection with the ongoing active fault is not being used by operation *op*.

The tolerance of a connection fault by an operation is *to ensure that only benign connections are used when the operation communicates with the external entities*. Accordingly, an active connection fault causes operation *op* to exhibit an *error* if (1) the connection is being used by operation *op* when the fault becomes active *and* (2) operation *op* does nothing to handle or fails to handle the active connection fault.

For the purpose of tolerating connection faults, the behavior of an operation *op* regarding connection fault can be modeled by the state diagram in Fig. 2. Operation *op* enters its *normal* state N upon invocation. Regardless of its functionality, operation *op* exits normally by leaving the state N and entering the normal accepting state X_s when all the connections actually used during its execution are benign. When operation *op* uses a connection with an ongoing active connection fault (state A in Fig. 1), it leaves the normal state N and enters the *faulting* state F either by detecting it (*e.g.*, operation *op* times out in getting data through the connection) or by being informed about it (*e.g.*, operation *op* throws an exception when establishing the connection). From the faulting state F, operation *op* either enters the *handling* state H to mitigate the active connection fault (Section 3), or enters the accepting *erroneous* state X_e after throwing an exception e. Depending on whether the active connection fault is mitigated (or can be safely ignored) or not, operation *op* returns to the normal state N or the faulting state F.

There are two noteworthy points about the state model of Fig. 2. First, the state model says nothing about the correctness of operation *op* when it exits normally in entering X_s;

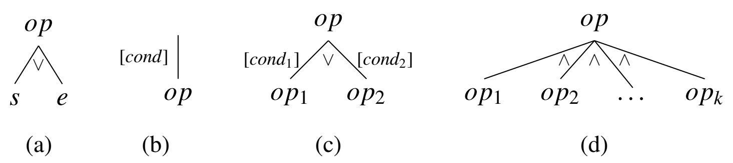


Fig. 3. Operations: (a) an OR-node to model an operation that can terminate with success *s* or with failure conveyed by exception *e*; (b) a guarded operation $cond|op$ where the operation *op* is executed only if the specified condition *cond* holds; (c) a conditional operation op_{cond} can be constructed by forming an OR-node with a number of guarded operations as its branches, where the conditions are evaluated from the left-most branch to the right-most branch; (d) an exception-stopping AND-node to compose an operation consisting of *k* constituent operations $op_1, op_2, \cdots, op_k$.

it singularly focuses on modeling the connection fault handling behaviors of operation *op*. Second, the non-presence of an unconditional transition from state *F* to state *N* or state X_s in Fig. 2 requires operation *op not* to ignore an active connection fault it has encountered. This requirement ensures that operation *op* is free of the *internal fault*, or *bug*, of ignoring an encountered active connection fault without checking (Section 3.4). In other words, an operation with behaviors described by the state model in Fig. 2 always throws an exception when an encountered active connection fault is not handled.

2.2 Operations and the AND/OR Composition

With the state models of Figs. 1 and 2 in place, we are ready to define the basic operations and exception handling operation of the AND/OR graph for composing connection fault handling behaviors of an operation.

2.2.1 Basic operations

According to the state model of Fig. 2, an operation *op* can terminate normally without raising an exception *or* it can terminate erroneously with an exception raised. This is denoted as $Result(op) \in \{s, e\}$, where *s* denotes normal exit (entering state X_s) without an exception and *e* denotes erroneous exit (entering state X_e). For example, an action of a client sending a message to a server can terminate erroneously if the network is intermittent. Operation *op* is modeled as an *OR-node* as shown in Fig. 3 (a). The nodes *s* and *e* are instances of a *terminal node* that represents an operation where no further expansion is possible. By this definition, an operation that does not raise an exception always terminates with the node *s*; for brevity, such an operation is represented as a terminal node by omitting the node *s*.

A *guarded operation* is an operation that is executed only when the specified condition is satisfied [18, 23]. In Fig. 3 (b), a guarded operation is denoted by $cond|op$, where operation *op* is executed only if condition *cond* specified at the inbound edge evaluates to $true$. The guarded operation and the OR-composition are combined to express a conditional statement as shown in the conditional operation *op* in Fig. 3 (c), where $cond_1$ is evaluated before $cond_2$ and $cond_2$ is evaluated only if $cond_1$ evaluates to false. Note that $cond_1$ and $cond_2$ need not be mutually exclusive. For a conditional operation *op* with *k* ($k \geq 1$) guarded operations $cond_i|op_i$ ($1 \leq i \leq k$), $Result(op) = Result(op_j)$ if there exists a $j, 1 \leq j \leq k$, $cond_j = true$ and $cond_1 \vee \ldots \vee cond_{j-1} = false$; otherwise, $Result(op) = s$.

An operation *op* consisting of a sequence of *k* ($k \geq 1$) operations op_1, op_2, $\cdots$, op_k is modeled as an *exception-stopping AND-node* as shown in Fig. 3 (d). The constituent operations op_1, op_2, $\cdots$, op_k are executed sequentially; that is, operation op_i is executed before operation op_j if $i < j, 1 \leq i \leq k-1$. Note that the *AND-node* can represent a parallel construct and a sequential construct [18]. In this paper, the *AND-node* is restricted to be a sequential execution of the constituent operations from left to right. $Result(op) = s$ if all constituent operations $op_i, i = 1, \cdots, k$ end in s; $Result(op) = e$ if all operations before operation op_j end in s and operation $op_j (j \geq 1)$ ends in e, upon which operations $op_i, i = j+1, \cdots, k$ are not executed. Skipping the latter constituent operations explains why the node of operation *op* of Fig. 3 (d) is called an *exception-stopping* AND-node: it terminates the normal execution and propagates to its caller the exception thrown by the failing constituent operation. The exception-stopping AND-node is consistent with the *termination model* of the continuation of control flow upon exception [24], which is adopted by all of the programming languages analyzed in [25], including C++ and Java. An exception-stopping AND-node degenerates into a regular AND-node if none of its constituent operations throws an exception. Where no confusion is possible, the term AND-node will be used for brevity.

2.2.2 Exception handling operations

The try-statement that is available in most languages is modeled as a composite operation. Since the semantics of the try-statements cannot be expressed by the basic operations of Fig. 3, two new types of operations are introduced: the *try-catch* operation and the *try-finally* operation.

Operations corresponding to the three variants of the try-statement are depicted in Fig. 4. Fig. 4 (a) denotes the *try-catch* operation *op*, which is stereotyped with the symbol ≪t-c≫. Operation *op* is composed of the normal operation op_t reached through the branch labeled `try` and the conditional operation op_c reached through the branch labeled `catch` for exception handling, respectively. Operation op_t is executed unconditionally. Operation op_c is executed only if operation op_t throws an exception e that matches any conditions in the ordered list $e = e_1, e = e_2, \ldots, e = e_k$ of operation op_c.

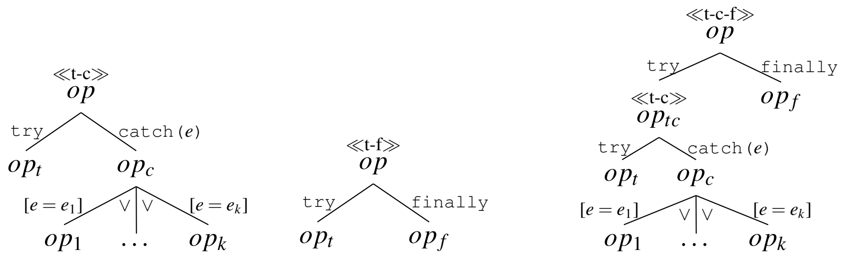
We assume that op_t and op_c behave according to the state model of Fig. 2. The result of executing operation *op*, $Result(op)$, is determined in three different cases according to Fig. 2:

- If operation op_t exits normally, $Result(op) = Result(op_t) = s$. In this case, operation op_t – and therefore operation *op* – makes the transition from state N to state X_s in Fig. 2; or

- operation op_t terminates in error raisng an exception $e \neq e_j$ $(j \in \{1, \cdots, k\})$. Operation *op* propagates exception e and $Result(op) = Result(op_t) = e$. In this case, operation op_t – and therefore operation *op* – makes the transition from state F to state X_e in Fig. 2; or else

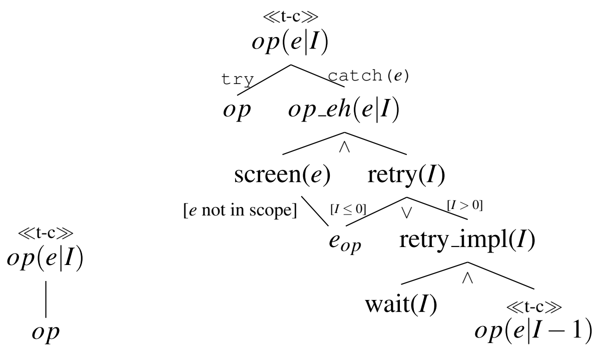
- operation op_t terminates in error with an exception $e = e_j$ raised for some $j \in \{1, \cdots, k\}$. The first matching operation op_j of operation op_c is executed and $Result(op) = Result(op_c) = Result(op_j)$. In this case, operation op_t makes the transition from state F to state X_e, causing operation *op* to make the transition from state F to state H to invoke the operation op_c in Fig. 2 to handle exception e.

The *try-finally* operation *op* is modeled as in Fig. 4 (b), where the node is stereotyped with the symbol ≪t-f≫. The operation op_t is executed unconditionally. Then, the *cleanup* operation op_f of the `finally` branch is always executed regardless of the result of executing operation op_t of the `try` branch. The *try-finally* operation *op* has the result of $Result(op_f)$ if $Result(op_f) \neq s$; otherwise, it has the result of $Result(op_t)$. Note that



(a) try-catch (b) try-finally (c) try-catch-finally

Fig. 4. Exception handling operations based on try-statement.



(a) (b)

Fig. 5. Retrying with the original; (a) Making operation op tolerate transient faults represented by exception e by retrying it at most I times with the surrogate operation $op(e|I)$; (b) a possible implementation expansion of operation $op(e|I)$.

the *try-finally* operation op does not enter the state H of Fig. 2; that is, it does not handle any exception thrown by operation op_t.

The *try-catch-finally* operation can be constructed by plugging in the *try-catch* operation into the `try` branch of the *try-finally* operation and is stereotyped with the symbol ≪t-c-f≫; see Fig. 4 (c).

3. MODELING THE COMMON CONNECTION FAULT HANDLING STRATEGIES

An operation op selects from three strategies for handling an active connection fault: *retrying*, *communicating failure*, and *ignoring failure* [11, 26, 27]. For retrying, there are two options: *retrying with the original* and *retrying with an alternative* [28]. If the failure is caused by a bug or by an incorrect action of the user, *retrying with the original* does not help at all. The strategy *retrying with an alternative* is applicable to both connection faults and bugs provided that the alternative operation is bug-free. Finally, if the failure is caused by the user, the proper strategy is to involve the user to fix the cause after *communicating failure* [27].

3.1 Retrying With the Original

The strategy *retrying with the original* is implemented with a surrogate that controls the repeated calls to the original operation. As depicted in Fig. 5 (a), operation *op* is made to tolerate connection faults represented by exception *e* by inserting the try-catch node $op(e|I)$ above it, where the notation $e|I$ means that at most $I (I \geq 0)$ retries are attempted for a caught exception of type *e*.[1]

While Fig. 5 (a) is appropriate as a design level notation for operation $op(e|I)$, during implementation time, it can be expanded to show further details, including the screening operation for excluding exceptions from retry and the backoff strategies before retry. Fig. 5 (b) shows a possible expansion of node $op(e|I)$. In the expansion, the try-catch node $op(e|I)$ is composed of the try operation *op* and the catch operation $op\_eh(e|I)$. The AND-node $op\_eh(e|I)$ is sequentially composed of operation screen(*e*) and operation retry(*I*). Operation screen(*e*) terminates by throwing exception e_{op} (with exception *e* as its cause) if exception *e* thrown by operation *op* is *not in scope* for *retrying with the original*. By being not in scope, we mean that the exception is not appropriate to handle with retrying, *e.g.*, when the exception is caused by an error committed by the user. Ideally, such a user error should be represented by an exception other than *e*. In practice, however, the same exception type is often used for both connection fault and user error. The exception used in such a practice is called a *homogeneous exception* [29]. Thus, operation screen(*e*) is employed to further check for exceptions representing non-connection faults. Section 4 gives an example of how the screening operation deals with a homogeneous exception.

When screen(*e*) exits without throwing an exception, exception *e* is appropriate to handle with *retrying with the original*. This is implemented with retry(*I*), which ends either with *op* exiting in success or in failure by throwing exception e_{op} when the number of retries *I* has been exhausted. Note that a retry is attempted after a waiting period determined by wait(*I*), which could implement an appropriate backoff strategy such as exponential backoff [14].

3.2 Retrying With an Alternative

Let *op* be an operation called by operation op_a as depicted in Fig. 6 (a). The operation op_a is made to tolerate failure of operation *op* by inserting a surrogate try-catch operation *opReAlt* between operation op_a and operation *op* and providing an alternative operation *opAlt* that is different from but functionally the same as operation *op*. The alternative operation *opAlt* is executed when operation *op* raises exception e_{op}; see Fig. 6 (b). For example, if a SQL command fails against the primary database, it can be alternatively executed against the backup database.

3.3 Communicating Failure

When it is appropriate for operation op_a to allow the failure of *op* to become its own failure, this strategy is modeled with the exception-stopping AND-node and make operation *op* a child of operation op_a (Fig. 3 (d)). That is, *i.e.*, both operations *op* and op_a make the transition from state *F* to state X_e in Fig. 2.

3.4 Ignoring Failure

Sometimes it is necessary to ignore a connection failure. An implementation of *ignoring failure* is shown in Fig. 7 (a). The surrogate operation $op(\bar{e})$ catches the active

[1] In general, the surrogate operation could be written as $op_b([e_i|I_i]), i = 1, \ldots, k$, if there are *k* exceptions for which the strategy *retrying with the original* is applicable.

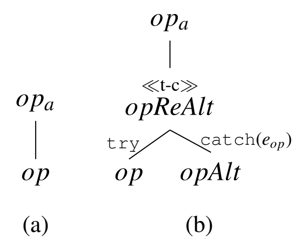


Fig. 6. Retrying with an alternative; (a) Operation op_a calls operation op; (b) tolerating failure of operation op represented by exception e_{op} with an alternative operation $opAlt$ through the surrogate operation $opReAlt$.

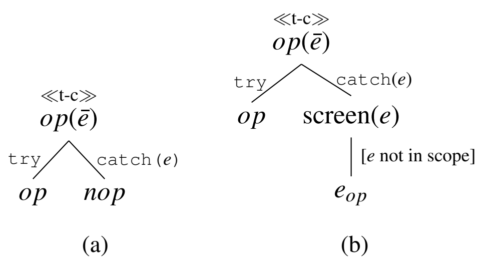


Fig. 7. Ignoring an exception e, where nop stands for no operation.

connection fault conveyed by exception e but does nothing to fix it (represented by nop - no operation, which always has the result of success s.) as indicated by the bar notation over the exception e. Note that, however, it may be necessary to screen for exceptions that should not be ignored when the homogeneous exception is used, in which case the expansion in Fig. 7 (b) is used. Strategy *ignoring failure* is applicable, for example, when closing a database connection fails after successfully accessing the database. In this case, it is reasonable for the access operation to ignore the failure (probably after logging) and terminate normally [27], *i.e.*, taking the transition from state H to state N in Fig. 2.

4. AN ILLUSTRATING EXAMPLE WITH DETECTING AND REPORTING FAILURE OF AN ANALOG DEVICE

In this section, we illustrate the use of the extended AND/OR graph to compose the connection fault handling behaviors of an operation. The illustrating example is adapted

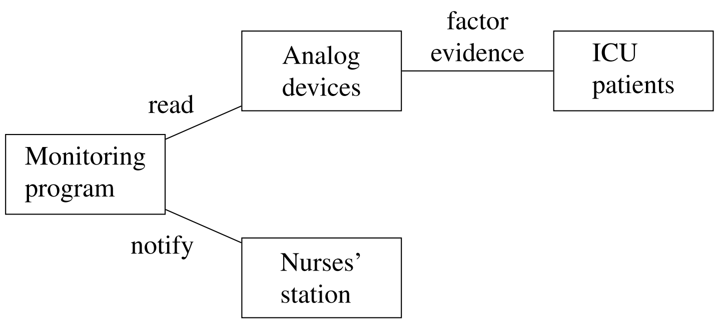


Fig. 8. Detecting and reporting failure of analog devices.

from the *Patient Monitoring* problem [1]. Our focus is on detecting failures of the analog device.

A patient-monitoring program is required for the intensive care unit (ICU) in a hospital. Each patient is monitored by an attached analog device which periodically measures factors such as pulse, temperature, blood pressure, and skin resistance. The monitoring program reads these factors on a periodic basis. If an analog device fails, the nurses' station is notified by the monitoring program. In the event that notification fails, an SMS message is sent to the phone of the medical staff on duty.

Fig. 8 shows the context diagram of the sub-problem of detecting and notifying failure of analog devices. We are going to assume that the analog device is implemented with a network-capable embedded system such as Arduino [30] or Raspberry Pi [31], which allows the monitoring program to read the vital factors through a RESTful API [32], (*e.g.*, using the library [33] on Arduino.)

An analog device failure can come from three sources:

- The network connection between the monitoring program and the analog device is experiencing a breakage.
- The analog device is broken and exhibits a reading out of the normal range; *e.g.*, a temperature reading that is out of range of living human body temperature ($88^\circ \sim 100^\circ$ F).
- A sensor is detached from the patient and exhibits a reading out of the normal range.

Of the three sources, only the first source is related to connection fault handling; the other two sources are domain errors whose detection requires building a domain model of the analog device. For the first source, we shall apply the strategy of retrying with the original to ride out the transient connection fault. For the the the domain error, we shall apply the strategy of error reporting.

Since these faults can occur during the read operation performed by the monitoring program, we are going to compose the two strategies in the operation `read`. In Java, the signature of read is

`void read() throws` f_{ad},

where f_{ad}[2] is an exception representing an analog device failure. Likewise, the operation `notify` has the signature

`void notify() throws` f_{ns},

where f_{ns}[3] is an exception representing failure to notify the nurse station, which is appropriate since either the network connection to the nurse station or the nurse station itself could be down.

The operations are composed into the operation `readOrNotify` with a signature as follows:

`void readOrNotify() throws` f_{ns}.

Finally, to satisfy the requirement, the operation `monitor` is composed as in Fig. 9. In a nutshell, in the event that both analog device and the nurse station fail, an SMS message is sent through the phone network to the medical staff in charge.

[2]Implemented as exception `ADFailureException` in Java in Section 5.

[3]Implemented as exception `NotifyNSFailureException` in Java in Section 5.

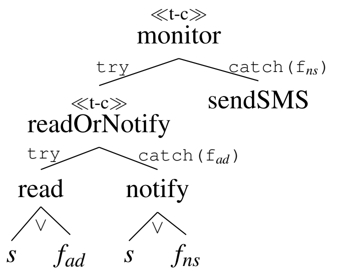


Fig. 9. Operation `monitor` is the top level operation that composes `read` and `notify`.

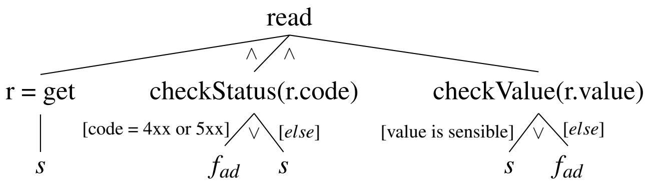


Fig. 10. Expanded operation `read` reads a measurement and checks whether it has a failure.

4.1 Implementing the Strategies of Communicating Failure and Retrying With the Original

With the top level operation `monitor` specified as in Fig. 9, we can go a step further to consider the fault handling strategies applicable operation `read`. Fig. 10 shows the expanded tree of subtree rooted at operation `read` in Fig. 9. The operation `read` is composed of the operations `get`, `checkStatus`, and `checkValue`. Specifically, operation `get` reads a measurement from an analog device and returns the standard HTTP status code used by the RESTful API [32]. The status code is a 3-digit integer where the first digit defines a class of response: a 2 indicates the request has succeeded, a 4 indicates the client error, and a 5 indicates the server error [34]. Operation `checkStatus` checks for connection fault and throws an instance of exception f_{ad} if a client error (return code = 4xx) or a server error (return code = 5xx) is detected, *e.g.*, code 408 for timeout and code 503 for an overloaded device. Finally, operation `checkValue` checks for domain error and throws an instance of exception f_{ad} if the reading has a value that is nonsensical. Note that in either case, the cause is recorded in a data field of exception f_{ad}.

Operation `read` has the semantics of *communicating failure*, *i.e.*, it deals with both connection fault and domain error by throwing the exception f_{ad}. The use of homogeneous exception f_{ad} is a common practice for exception handling design [29] [35] [36].

While operation `read` satisfies the requirement, an intermittent network connection can send an alarm to nurse station. By the time the medical staff on duty reaches the alleged failed analog device, it could happen that no failure has found. This is clearly undesirable and should be further improved.

In Fig. 11 operation `read(`f_{ad}`|I)` is introduced as a surrogate around operation `read` to ride out transient connection faults by applying strategy of *retrying with the original.*

The original operation `read` throws a homogeneous exception f_{ad} for both a domain error and a connection fault. Operation `screen` is introduced to single connection faults for the application of the strategy of *retrying with the original.* In this case, operation `retry` is attempted at most I times ($I \geq 0$). In each attempt, an appropriate backoff strat-

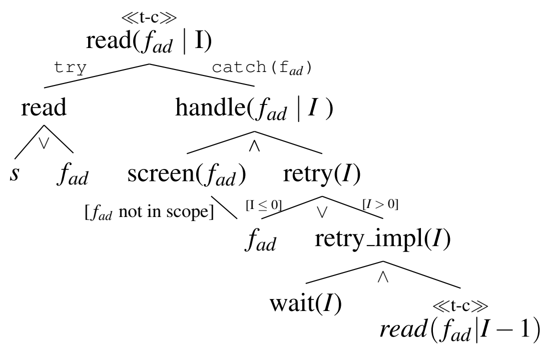


Fig. 11. Surrogate operation `read(`f_{ad}`|I)` implementing the strategy of *retrying with the original.*

egy `wait(`I`)` is applied. After exhausting the allowed number of retries without success, the failure is communicated by raising exception f_{ad} to signify failure of operation `read` (Fig. 11).

5. SPECIFICATION-BASED TESTING

The connection fault handling behavior composition graph can serve as a specification for constructing the connection fault handling behaviors of an operation. In particular, the extended AND/OR graph representation of an operation can be easily represented with a rule-based program for generating various artifacts that describe an operation's connection fault handling behaviors, including code and tests.

In this section, we shall focus on generating tests for checking the connection fault handling behaviors of an operation from the specification. Using terms of AND/OR graph searching [21], a node is said to be *solved* when it exits either normally or erroneously. A *solution tree* is a sub-graph of the AND/OR graph where the result of executing the *root node*, which is the top-level operation whose connection fault handling behavior is being modeled, is known.

Using the example of Section 4, we assume that code of the operation `read(`f_{ad}`|I)` to detect failure of an analog device has been manually constructed according to the AND/OR graph of Fig. 11. We want to know if the implementation conforms to the specification through tests generated from the solution trees obtained by searching the AND/OR graph. Used in this way, the AND/OR specification is a model for generating tests in *model-based testing* (MBT) [17].

5.1 System Model

Fig. 12 shows a system that uses an AND/OR specification to generate and run tests for checking the connection fault handling behaviors. We shall assume that the Java environment is used. The system makes use of *aspect oriented programming* (AOP) with AspectJ [22] and *unit testing* with JUnit [37].

In Fig. 12, the system consists of the following components. *Test Generator* creates a collection of tests based on a given *Specification*, which is an instance of the extended AND/OR graph. A generated *Test* contains code for invoking *Operation Under Test* as well as *Directives* to be consulted by *Advice* on deciding what to insert at a joint point (*i.e.*, a specific invocation of a constituent operation) of *Operation Under Test*, *e.g.*, whether to

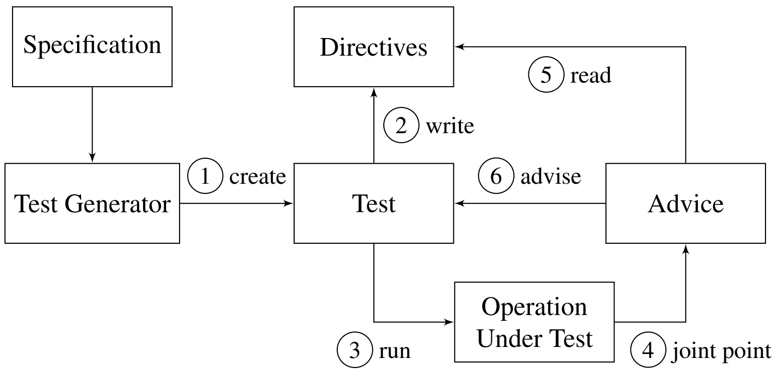


Fig. 12. Generating and executing tests from an AND/OR graph specification: a test carries information for directing what an advice should do when an operation is called during the execution of the test.

```
1   :-  op( 100, xfx, >>).
2   :-  op( 500, xfx, :).
3   :-  op( 600, xfx, ---> ).
4   read*I/R--->try_catch:(read/Rt,
5                                 (eh*I)*Rt/Rc).
6   read/R--->or:[s, f(ad)].
7   (eh*I)*Rt/R--->and:[screen(Rt)/R1, ['=',Rt,f(ad)]>>(retry*I)/R2].
8   (retry*I)/R--->or:[['=<',I,0]>>throw(f(ad))/R, ['>',I,0]>>(read*J)/R]
9       :- J is I-1.
10  screen(Rt)/R--->or:[s].
11  throw(F)/R--->or:[F].
```

Fig. 13. An extended AND/OR specification of the *Operation Under Test* `read(`f_{ad}`|I)` in Prolog.

let the constituent operation go through normally or to inject an exception to emulate an active connection fault.

The interaction between components are labeled with numbers to be read in increasing order. *Tests* are first generated by *Test Generator* (step 1) according to the AND/OR graph specification of connection fault handling behaviors for the *Operation Under Test*. A *Test* is run by going through steps 2 to 6. First, *Directives* to be consulted by *Advice* are written by the *Test* (step 2). As the execution continues, *Operation Under Test* is invoked (step 3) with *Advice* inserted before specific constituent operations specified by a joint point and then executed (step 4). *Advice* then reads the previously written *Directives* (step 5), and performs the required action (step 6), *i.e.*, to continue normally or to throw a designated exception.

5.2 The AND/OR Graph in Prolog

The AND/OR graph specification of operation `read(`f_{ad}`|I)` in Fig. 11 has been translated into the equivalent specification in Prolog in Fig. 13. The AND/OR graph is an extension of the implementation of [21].

We now briefly describe the notational conventions in the following user-defined operators. In lines 1-3, the three operators '`>>`', '`:`', and '`--->`' are infix, right-associative operators of precedences 100, 500, and 600, respectively, with smaller precedence value binding more strongly. Operator '`--->`' is a relation from a node to its successors. Operator '`:`' marks the node type (and, or, try-catch and try-finally) in its first argument and the successor nodes as a list in its second argument. For example, node `a` with two OR successors `b` and `c` is represented by the clause:

```
a ---> or:[b,c].
```

The operator '>>' binds the guard condition to a node. In the following clause, node `a*I` has the successor `b` if `I=<0` and the successor `c` if `I>0`, where '`*`' is a built-in operator of precedence 400 that binds node `a` with the variable `I`:

```
a*I ---> or:[I =< 0 >> b, I > 0 >> c].
```
[4]

Lastly, we use the binary operator / to bind a node and the result `R` of evaluating the node. Thus, the node

```
read*I/R
```

denotes that operation `read` is attempted at most `I` times with `R` as the result.

With the operators defined and the notational convention out of the way, we are ready to explain the conversion of the AND/OR graph of operation `read(`$f_{ad}|$`I)` in Fig. 11 into the Prolog code of Fig. 13. In lines 4-5, the node `read*I/R` is a *try-catch* node with node `read/Rt` at the *try*-branch and node `(eh*I)*Rt/Rc` at the *catch*-branch. The node `read*I/R` stipulates that operation `read` will be attempted at most `I` times, at the end of which the result `R` is obtained. The node `read/Rt` is always executed with `Rt` being equal to `s` for success, `f(ad)` for a connection fault while detecting an analog device; see line 6. At the catch branch the AND-node `(eh*I)*Rt/Rc` comprises operation `screen(Rt)/R1` (which always exits successfully with `s` for simplicity in line 10) and the guarded retry operation `(retry*I)/R2` (line 7) that is expanded only if the exception is f_{ad}. The clause in lines 8-9 stipulates that exception `f(ad)` is thrown (line 11) if all allowed retries have been exhausted; otherwise, operation `(read*(I-1))/R` is executed. For simplicity, the wait operation of Fig. 11 is omitted.

5.3 The AND/OR Graph Search Algorithm

Fig. 14 shows the key clauses of the Prolog procedure

```
compose(Node/R, Node/R--->Tree)
```

for exploring an AND/OR graph using depth-first search, where `Node/R--->Tree` is a solution tree with result `R`. The rule for processing an OR-node with guarded branches of Fig. 3 (c) is found in lines 1-6. Line 2 expands a node that matches with an OR-node. In line 3, operator >> separates the condition (which is the list `CondList`) from the guarded operation (which is the term `Node1/R`). Line 4 assembles the list `CondList` into a term, and line 5 calls the assembled term as a goal. For example, in line 4 of Fig. 13, the condition list `['=',Rt, f(ad)]` is assembled into the term `Rt = f(ad)`, which is then executed as a goal by the built-in predicate `call`. In line 6, the node `Node1/R` is executed if the condition `Cond` in line 4 evaluates to true.

We summarize the rest of the Prolog program in Fig. 14 without going into detail. The clause at lines 8-11 explores the OR-node of Fig. 3 (a). The clause at lines 13-15 explores the AND-node of Fig. 3 (d). The clause at lines 17-20 explores a node that corresponds to a `try_catch` node where the try clause succeeds without an exception. The clause at lines 22-29 explores a node that corresponds to a `try_catch` node where the try clause throws an exception that is not caught by any of catch clauses. Lastly, the clause at lines 31-37 explores a node that corresponds to a `try_catch` node where the try clause throws an exception that is caught by a matching catch clause.

After loading the programs of Figs. 13 and 14, the Prolog query

```
?- compose(read*1/R,T).
```

generates all of the possible results `R` with solution trees `T` for tolerating at most one active connection fault encountered by operation `read`. Fig. 15 shows the solution tree `T` where

[4]In Prolog, the condition `Cond` is constructed from a list `CondList` with the built-in operator '`=..`' in the clause `Cond =..CondList`. Thus, the condition `I =< 0` is written as `['=<', I, 0]`.

```
compose( Node/R, Node/R--->Tree)  :-
  Node/R--->or:Nodes,               % OR-node
  member( CondList>>Node1/R, Nodes),% Select a branch if Cond
  Cond =.. CondList,
  call(Cond), !,
  compose( Node1/R, Tree).

compose( Node/R, Node/R--->Tree)  :-
  Node/R--->or:Nodes,               % OR-node
  member( Node1, Nodes),            % Select a branch
  compose( Node1/R, Tree).

compose( Node/R, Node/R--->and:Trees) :-
  Node/R ---> and:Nodes,             % AND-node
  composeall( Nodes, Trees, R).      % Solve all Node's successors

% try catch - try success
compose( Node/s, Node/s--->try_catch:TreeT) :-
  Node/s ---> try_catch:(Try/s,Catch),
  compose(Try/s,TreeT).

% try - catch: try throws exception uncaught by Catch
compose( Node/R, Node/R--->try_catch:TreeT) :-
  Node/R ---> try_catch:(Try/R,Catch*R1/RC),
  getLeavesOrNode(Catch*R1/RC,Catches),
  failureCaught(Catches,FC),
  EFC = [s|FC],                         % extend the failure list by s
  compose(Try/R,TreeT),
  \+ member(R,EFC).

% try - catch: try throws exception caught by Catch
compose( Node/R, Node/R--->try_catch:TreeT+TreeC) :-
  Node/R ---> try_catch:(Try/R1,Catch*R1/RC),
  compose(Try/R1,TreeT),
  R1 \= s,
  compose(Catch*R1/RC,TreeC),
  R = RC.
```

Fig. 14. The key clauses of a depth-first AND/OR graph search algorithm in Prolog.

the surrogate operation `read*1` ends with `R=s` after the surrogated operation `read` first encountered a f_{ad} (when `I=1`) and then exited with success (when `I=0`).

5.4 Generated Tests

Fig. 16 shows three of the JUnit tests generated by *Test Generator* with the Prolog specification in Fig. 13 translated from the extended AND/OR graph of Fig. 11 with the Prolog query

```
?- compose(read*1/R,T).
```

In what follows, we shall explain in detail the test from at lines 1-14 in Fig. 16 corresponding to the solution tree in Fig. 15.

The intent and result of a test are succinctly summarized in the name of the test (line 2). In this case, the test checks that operation `read(1)` indeed terminates in success as indicated by the suffix '`_ts`' in the method name, where '`t`' and '`s`' denote that the surrogated operation `read` first encounters a transient connection fault (when `I=1`) and a success (when `I=0`), respectively.

Line 3 stipulates to tolerate at most one transient fault. Lines 4-7 are the directives written by the test for an advice to consult (see Fig. 12 and Section 5.5) and consist of injecting one `ADFailureException` (implementation of terminal node f_{ad}) followed by '`s`' for the execution of operation `read`. As a result, the call `monitoring.read(I)` is expected to complete without throwing an exception; see lines 8 - 13.

An implementation of the surrogate operation `read(I)` with `I=1` that passes the

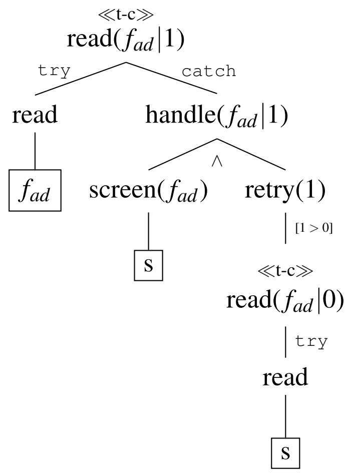


Fig. 15. Solution tree of the AND/OR graph of Fig. 11 where operation `read` first exits with a f_{ad} (when `I=1`) and then exits with success (when `I=0`). The rectangular nodes are terminal.

three tests in Fig. 16 conforms to the specification that it retries at most once for the connection fault, and terminates successfully or throws an exception as required by the connection fault handling specification in Figs. 11 and 13 and the state model in Fig. 2. Tests of operation `read(I)` with `I` greater than 1 are similar to tests of operation `read(I)` with `I=1`. Since the total number of tests generated exceeds 5,000, for brevity, Fig. 16 only shows the three tests of `read(I)` with `I=1`.

5.5 Advice

An *Advice* can be seen as a test stub which provides an indirect input (to raise an exception or not) to control the flow of *Operation Under Test* [38]. Fig. 17 shows the partial AspectJ implementation of *Advice* [22]. The pointcut looks for invocations of `Monitoring.read()` (line 2). The `before` advice stipulates that before an instance of `Monitoring.read()` is executed, one of the two alternative actions is taken. Depending on the instruction read from *Directives* (line 6) set by the test, it allows the invocation to go through (lines 7-8); replaces it with a mocked `ADFailureException` with a HTTP status code 408 (*Request Timeout*) (lines 9-10).

6. RELATED WORK

The present work is based on the previous results in fault handling [39, 40, 41, 42, 25], although with a much narrower scope of modeling and testing connection fault handling behaviors. In what follows, we shall relate the present work to the various techniques used, including AND/OR graph, aspect-oriented programming, and software testing.

AND/OR graphs model problems that are solved by decomposition in artificial intelligence, *e.g.*, in symbolic integration [43], game-playing, theorem proving, and many other problems [44, 45]. The use of AND/OR graph to represent a program was proposed in [18]. Indeed, an AND-node subsumes sequential and parallel composition and an OR-node subsumes non-determinism and conditionals; thus, it can be used for structured programming. The extended AND/OR graph proposed in this paper can be seen as parallel to the AND/OR program of [18] by including exception handling operations, but

```java
@Test
public void test_read_x1_success_after_0_transients_ts(){
    int I = 1;
    repo.initResponse();
    repo.addResponse("read/f(ad)");
    repo.addResponse("read/s");
    repo.toBeforeFirstResponse();
    try {
        monitoring.read(I);
    }
    catch(Exception e){
        fail("Exception thrown");
    }
}
@Test
public void test_read_x1_success_after_0_transients_s(){
    int I = 1;
    repo.initResponse();
    repo.addResponse("read/s");
    repo.toBeforeFirstResponse();
    try {
        monitoring.read(I);
    }
    catch(Exception e){
        fail("Exception thrown");
    }
}
@Test
public void test_read_x1_Fad_after_0_transients_tt(){
    int I = 1;
    repo.initResponse();
    repo.addResponse("read/f(ad)");
    repo.addResponse("read/f(ad)");
    repo.toBeforeFirstResponse();
    try {
        monitoring.read(I);
        fail("Exception not thrown");
    }
    catch(ADFailureException e){
        assertEquals("Analog device fails", e.getMessage());
    }
}
```

Fig. 16. JUnit tests of the operation `read(`f_{ad}`|1)` generated by the *Test Generator*.

is simplified to solely focus on the specification of connection fault handling behaviors. It should be noted that the extension can be achieved with *monads* to extend the normal operation to account for exceptions as is used in functional programming [46].

Model-based testing has been proposed for testing standard specification conformance [47]. Basically, standard specification written in a natural language is first translated into a finite state machine description, which is then used to generate tests for testing conformance. It has been found that the tests generated from model were able to exceed the test suites directly crafted from the natural language specification. The AND/OR graph formalism proposed for modeling connection fault handling behaviors and for generating test cases is an instance along the line of MBT research [17]. In particular, the MBT technique implemented in this paper achieves redundancy in generating tests from the AND/OR graphs for checking the conformance of an implemented program to the specification.

In this research, we use aspect oriented programming (AOP) as part of the testing framework to inject exceptions and share states between test cases and the operation under test. It is interesting to note that AOP has been used in extracting exception handling behaviors to aspects so that normal behaviors and exceptional behaviors are separated [48]. The AND/OR graph composition of connection fault handling behaviors could,

```
public aspect AspectConnection {
 public pointcut read() : call( * Monitoring.read() );

 OpRespRepo repo = OpRespRepo.getRepo();
 before() throws ADFailureException : read() {
  String OpRes[] = repo.emitNext();
  if (OpRes[1].equals("s")) {
   // do nothing, call original or provide a viable replacement
  } else if (OpRes[1].equals("f(ad)")) {
   throw new ADFailureException("Analog device fails", 408);
  }
 }
}
```

Fig. 17. An *Advice* in AspectJ.

in principle, be implemented as aspects to be weaved into the join points identified by point cuts. The main benefit is the potential of reusing the exception handling aspects, especially if only generic and homogeneous handling such as logging and reporting is involved. However, there are limitations when the handler's behavior depends on the exceptional context [49]. For example, the *retrying with the original* strategy of Fig. 11 uses a local variable *I* in the faulting method to control the number of retries to attempt, which is not available to the extracted aspect. Although this can be fixed by making the control variable *I* a field of the object that owns the faulting method and by making the object an argument passed to the pointcut and associated advices, the need to specify the object's class in the parameter declaration limits the aspect's reuse. One way to get around the limitation is to have the object owning the faulting method implement an interface created solely for the purpose of accessing the control variable. Therefore, it seems unlikely that reuse of aspects is possible without some consideration given to the design of exception handling. In either way, it seems inevitable that endowing an object with connection fault handling behaviors will unavoidably tangle normal and exceptional behaviors.

Numerous researches for exception handling testing based on static analysis of program code have been published [50, 51]. In contrast, the proposed method is based on specification and testing. In software development life cycle, static analysis, specification, and testing techniques complement each other for software quality assurance. For example, during requirement analysis and development, the proposed method for AND/OR composition of connection fault handling can be used for specification and testing, while static analysis techniques such as control-flow or data-flow analyses can be applied afterwards to check for further exception handling defects.

7. CONCLUSION

We have presented the extended AND/OR graph for composing connection fault handling behaviors in programs. The extended AND/OR graph not only enables the description of specification to be followed by developers in building programs with the required connection fault handling behaviors, but can also be used to generate tests for checking a program's conformance to the specification. The extended AND/OR graph and the model-based testing framework are illustrated with the implementation and testing of a program to detect and report failure of an analog device. The extended AND/OR graphs are easily converted into Prolog programs. Solution trees obtained by searching the AND/OR graph are used to generate tests. Although the AND/OR graph formalism requires more effort from the developers, it can be seen as a reasonable price to pay for better robustness in handling connection faults.

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