Error Modeling in Dependable Component-based Systems*

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Abstract

Component-Based Development (CBD) of software, with its successes in enterprise computing, has the promise of being a good development model due to its cost effectiveness and potential for achieving high quality of components by virtue of reuse. However, for systems with dependability concerns, such as real-time systems, a major challenge in using CBD consists of predicting dependability attributes, or providing dependability assertions, based on the individual component properties and architectural aspects. In this paper, we propose a framework which aims to address this challenge. Specifically, we present a revised error classification together with error propagation aspects, and briefly sketch how to compose error models within the context of Component-Based Systems (CBS). The ultimate goal is to perform the analysis on a given CBS, in order to find bottlenecks in achieving dependability requirements and to provide guidelines to the designer on the usage of appropriate error detection and fault tolerance mechanisms.

1. Introduction

The main advantages of CBD approach are the ability to manage complexity and the possibility to select the most suitable component among the ones that provide same functionality. However, the latter can be best achieved only if the design step incorporates rigorous analysis for this specific need. This issue becomes all the more relevant when CBD is used for developing dependable systems, since one has to analyze multiple extra-functional properties as well.

Our main goal is development of a framework based on well-founded theories, while keeping industrial realities in focus, which will provide meaningful reasoning about dependability attributes in CBS based on the characteristics of the component model, properties of individual components and component connection scheme in a given design. Since errors are one of the main impediments for achieving dependability, this paper particularly focuses on modeling the error behavior of components and error propagation aspects in order to reason about the dependability attributes of the composed system and its failure modes. We use an in-house developed component model (SaveCCM) [2] to illustrate how a specific component model can influence the error propagation aspects.

In a recent work, Elmqvist and Nadjm-Tehrani [7] addressed formal modeling of safety interfaces and provided compositional reasoning about safety properties of composed systems. Our focus is more on reliability and timing aspects and on analytical approaches. Grunske and Neumann [9] have proposed an approach to model error behavior of composed systems by using the Failure Propagation and Transformation Notation (FPTN) for each architectural element and to construct the composed systems' Component Fault Trees (CFT) from the FPTN models to perform safety analysis. Rugina et al. [14] proposed a framework where the Architecture Analysis and Design Language (AADL) with the features of Error Model Annex is used to create models of composed systems' error behavior. Then, these models are converted to Generalised Stochastic Petri Nets (GSPNs) or Markov Chains to be analyzed by existing tools. More recently, Joshi et al. [11] have proposed an approach to convert error models, generated using AADL with Error Model Annex, to Fault Trees to perform further analysis.

A substantial amount of research has been conducted on reliability modeling of composed systems based on individual component reliabilities, with a recent focus on architecture based models. Most of these works assume the existence of known probabilities for error state transitions, and only a few address the error propagation aspects. On the other hand, research on dependable systems has been focussing more on fundamental system level models of errors, and mechanisms for tolerating those error modes, with arguably less interest on how these models are linked to the reliability prediction models. In our view, the links between these two research directions are loosely coupled and less explored. Specifically in CBD, architectural decisions and specific aspects of the component model will influence the

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dependability evaluations. Our aim is to enable end-to-end linking from system level dependability requirements (normally specified in terms of diverse qualitative/quantitaive terms), to models for dependability evaluation and predictions of composed systems. We envision our research to provide substantial clarity and simplifications needed for CBD of applications with dependability concerns.

The rest of the paper is organized as follows: in Section 2 we state the challenges in system level modeling of error behavior, and present the principal parts of our proposed framework. Section 3 presents our revised error classification from a CBS perspective. Section 4 discusses error propagation and composition aspects, which are further exemplified in SaveCCM, and Section 5 presents conclusions and ongoing research.

2. Outline of the proposed framework

The major challenges in realization of a generalized framework for dependability evaluation of CBS are:

- diversity of dependability requirements specification
- different dependability attributes require different analysis techniques and approaches
- limited information on component properties
- lack of techniques for performing analysis with partial or evolving information
- relating usage profiles of components to target system contexts
- non-scalability of most of the formal analysis techniques to industrial-size systems

In order to enable modeling and analysis of system-level dependability behavior, the framework must include dependability requirements specification, component-level error modeling, and system-level dependability analysis, which are briefly mentioned in following subsections.

2.1 Dependability requirement specifications

At this step, the system designer has to specify the dependability requirements for the target system. Due to the diversity of the dependability attributes, as well as the varied industrial priorities and practices, this step is critical as it has a considerable impact on the subsequent analysis (including the choice of techniques). For instance, the reliability requirements of systems are usually defined in diverse terms, ranging from qualitative to quantitative ones. A typical requirement specification can be 'System reliability should exceed 0.99999' or 'System should not have any timing failures even under a hardware node failure'. The framework must have means to accurately capture and formally specify a wide variety of such requirements, which the subsequent analysis techniques need to address.

While designing a dependable system, the goal is typically to achieve fail-controllability [3], i.e., to introduce a certain degree of restrictions on how the system can fail. The level and type of such restrictions are usually dependent on the application domain, criticality of the system, and the dependability attributes that are considered. Typical failure modes include fail-operational, fail-safe, fail-soft, fail-silent, fail-stop, crash and Byzantine (arbitrary) failures [3]. Failure mode requirements can effectively be used for generating subsystem-level requirements in a hierarchical way and can help in performing localized analysis.

2.2 Component-level error modeling

Typically, this step involves modeling error behavior of individual software components, as well as other system elements, such as component connectors, hardware nodes, middleware, and communication media. Our plan is to use probabilistic automata with timing, where nodes of the automata represent error states, and edges denote transition probabilities. An approach based on AADL [14] can be suitable for this step, with proper extensions on the error modeling aspects. Our integrated development environment for CBS is being designed to specify and include information about component error behaviors with varying levels of details, based on the available specifications. The level of details in component-level error models, as well as the dependability requirement specifications of the system, will decide the choice of analysis technique to be performed.

2.3 System-level dependability analysis

The analysis to be performed at this step depends on the dependability specifications and the component-level error models. Our aim is to get the basic structure in place so that multiple analysis techniques can be easily integrated to our framework. A challenging issue is how to compose error models to obtain a system-level error behavior. Error propagation can occur between two components, between a component and another system element, or between two system elements. The architecture of the system will serve as an input to this step, where both impact and criticality analysis will be performed. Ideally, by looking at the error model of the composed system, one should be able to observe whether the system can possibly fail in a certain mode that is not allowed. If this is the case, the framework should further enable the identification of the critical paths

in the architecture, and provide guidelines for efficient detection/recovery/correction strategies along with appropriate location for incorporating them, so that the resulting system meets the original dependability requirements as specified by the system designer.

Figure 1 illustrates the skeleton of our proposed methodology for composing error information to perform a system-level error analysis. The methodology consists of critical path identification followed by propagation analysis performed on each identified path where the type of analysis depends on the specific failure mode requirement. Though components are usually considered as black boxes, we assume traceability of a critical parameter evaluation through the component chain. If, on the other hand, this is not possible, we may have to consider all possible scenarios.

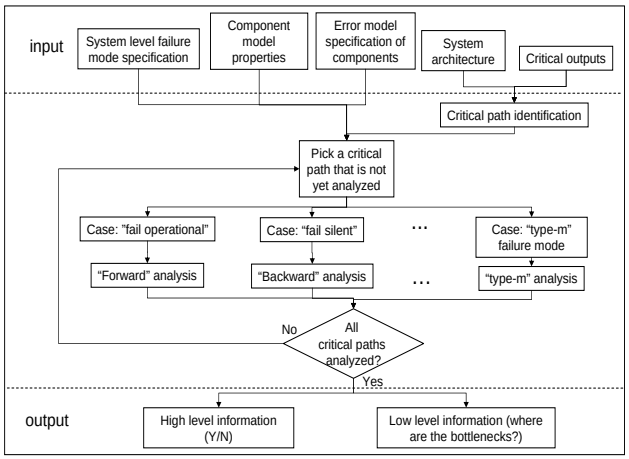

Figure 1. System-level error analysis

3. Error classification - revised

The error characteristics presented in this section are based on a synthesized view of several works [3, 13, 4, 10, 6]. We follow the basic classification of Avizienis et. al. [3] while extending it into details with other works, most of which address narrower areas but with finer details. It also presents various aspects of errors in two categories based on their influence on the error handling mechanisms. These categories essentially determine 'which mechanisms' and 'how much' are needed for adequate error handling. The various aspects considered are domain, consistency, detectability, impact, criticality, and persistence of errors. The domain and consistency determine what kind of error handling mechanisms are appropriate while the rest determine the amount of error handling needed.

3.1 Domain

In component based systems, outputs generated by components can be specified by two domain parameters, viz., value and time [3, 4, 13]. Our hypothesis is that tolerating value and timing errors at component-level, requires different approaches with significantly different associated costs. Hence, separation of value and time domains will enable the use of dedicated fault tolerance mechanisms for each type, as well as aid in achieving better error coverage with minimum cost. In this paper, we define the specified output generated by a component as a tuple based on these domain parameters:

$$\text{Specified Output (SO)} = < v^*, V, T, \Delta_1, \Delta_2 >$$

where the v^* is the exact desired value, V is the set of acceptable values, T is the exact desired point in time when the output should be delivered and $[T - \Delta_1, T + \Delta_2]$ is the acceptable time range for the output delivery.

The output generated by a component is denoted as:

$$\text{Generated Output (GO)} = < v, t >$$

where v is the value and the t is the time point when the output is actually delivered.

The GO is considered to be correct if:

$$v \in V \text{ and } T - \Delta_1 \leq t \leq T + \Delta_2$$

Value errors: The output generated by a component is erroneous in value domain (e_v) if $v \notin V$, where V is the set of acceptable values. We first classify errors in value domain as ***subtle*** (e_v^s), and ***coarse*** (e_v^c) based on our knowledge about the set of reasonable values for the output and the syntax that should be followed as in [4, 13].

- *Inexact value* errors $(e_v^{\overline{e}})$

  $v \notin V$, where $V = \{v^*\}$

- *Unacceptable distinct value* errors $(e_v^{\overline{d}})$

  $v \notin V$, where $V = \{v^*, v_1, v_2, ..., v_n\}$, v^* is the ideal value and $v_1, v_2, ..., v_n$ are the other acceptable values

- *Inaccurate value* errors $(e_v^{\overline{a}})$

  $v \notin V$, where $V = \{v^* - \Delta_1^v, ..., v^* - 1, v^*, v^* + 1, ..., v^* + \Delta_2^v\}$ and $[v^* - \Delta_1^v, v^* + \Delta_2^v]$ is the range of acceptable values

A value error is a combination of the above classifications, i.e., e_v^{xy}, where $x \in \{c, s\}$ and $y \in \{\overline{a}, \overline{d}, \overline{e}\}$.

Timing errors: In [4, 13, 6] and in our classification, errors in time domain are classified into *early, late* and *infinitely late(omission)* timing errors.

- *early* timing errors (e_t^e): $t < T - \Delta_1$
- *late* timing errors (e_t^l): $t > T + \Delta_2$
- *omission* timing errors (e_t^o): $t = \infty$

Additional classes [13] are, bounded, omission, and permanent omission (crash or permanent halt) errors. paragraph Errors in both time and value domain: Component outputs under this category are erroneous in both value and time domain simultaneously, i.e., $e_{v,t}^{a,b}$, where $a \in \{c\overline{e}, c\overline{d}, c\overline{a}, s\overline{e}, s\overline{d}, s\overline{a}\}$ and $b \in \{e, l, o\}$ if:

$$v \notin V \text{ and } (t < T - \Delta_1 \text{ or } t > T + \Delta_2)$$

3.2 Consistency

If a component provides replicas of an output to several components, consistency issues may arise. In this case, the errors are considered consistent if all receivers get identical errors. In [13], multi-user service errors are classified into consistent value errors, consistent timing errors, consistent value and timing errors, and semi-consistent value errors. In semi-consistent value errors, some output replicas have unreasonable, or out-of-syntax values, while the rest have identically incorrect values. In [4], non-homogeneous output replicas are defined to be erroneous. A non-homogeneous value (or timing) error occurs if the values (or times) of received outputs are not close enough to each other. Closeness is specified by using threshold values. In our classification, we use both consistency and homogeneity concepts.

- *Consistent* errors: Replicas of the output from a component are consistently erroneous if they belong to the same error category, e.g., both have coarse value errors or late timing errors.

  We further classify these errors as:

  - *Precise*: The values or generation times of replicas are consistently erroneous as well as both are within a precision range or identical.
  - *Imprecise*: The values or timing of replicas are consistently erroneous. However either values or generation times (depending on the error type) are outside the specified precision range.

- *Semi-consistent* errors: Replicas of an output are defined as semi-consistently erroneous if all users receive erroneous outputs while at least one of them belongs to a different error category than the others.

- *Inconsistent* errors: Replicas of an output are defined as inconsistent if there are both correct and incorrect replicas.

The characteristics presented so far define our error classification and will be used in both propagation analysis and composition of component error models. Furthermore the classification will be used to determine which error handling mechanisms are adequate to control the error behavior during composition.

4. Error propagation in CBS

Errors in a component based system can occur in software components, middleware, or hardware platform, and can propagate up to a system interface causing a system failure with a certain probability. This probability is, in its turn, dependent on the probability of error occurrences, the isolation between different system elements, existing error detection and handling mechanisms, as well as the type of errors. The research effort is currently increasing for finding ways to get these probabilities, and to use them appropriately [10, 8, 12, 1, 5].

We define the set of errors E, which includes instantiations of error types discussed in the previous section. We also define the following subsets of E as follows:

- E_i^{in} is the set of errors that are *propagated into* component C_i
- E_i^{gen} is the set of errors that are *internally generated* by component C_i and *propagated out* without any changes
- E_i^{pass} is the set of errors *propagated into* C_i that are *propagated out* without any changes
- E_i^{mod} is the is the subset of E_i^{in} that are *transformed* to another error type, masked or corrected
- E_i^{trans} is the set of errors that were originally belonging to E_i^{mod} or *internally generated* errors and *transformed* into the members forming this set
- E_i^{out} is the set of errors that are *propagated from* component C_i

$$\begin{aligned} E_i^{in} &= E_i^{mod} \cup E_i^{pass} \\ E_i^{out} &= E_i^{gen} \cup E_i^{pass} \cup E_i^{trans} \end{aligned}$$

Errors can be transformed into E_i^{trans} by either C_i's normal execution or by error handling mechanisms. These mechanisms can be implemented within components at component design stage, at the component interfaces at the

architectural design, or at integration stages of CBD. Various mechanisms for different types of errors and their effects on error propagation are discussed in the following paragraphs.

Transformation of value errors: The possible ways of error transformations in value domain are shown in Table 1.

Cause	Initial error	Final error
Error detection	e_v	e_v (transformation in time domain)
Error masking	e_v	no error
Error correction	e_v	no error
Component operation	e_v e_v^s e_v^c	no error e_v^c e_v^s

Table 1. Transformations of value errors

One way to detect coarse value errors is using reasonableness checks. Implementing reasonableness checks necessitates having knowledge about the behavior of the producer, for example, a range checking mechanism marks the temperature reading of a room as erroneous if the value read is $-200°$C based on our knowledge about the reasonable boundaries for that output. Coding checks are used to detect non-code value errors which is a specific type of coarse value errors (parity-check is an example for this type of check). Obviously, if more advanced error detection mechanisms are used, which can identify more complex erroneous behaviors, the coverage of detectable errors is increased. Detecting subtle value errors is performed by more expensive error detection mechanisms, such as replica checking at a voter element. Propagation of value errors can be blocked after detection, by simply not allowing the erroneous output to be delivered to the next component. In this case a value error is transformed into an omission timing error.

Certain means allow masking of value errors, such as N-modular redundancy techniques, while some others can *correct* value errors by using, e.g., error correction codes. Both masking and correction techniques enable continuation of correct functioning upon errors.

Transformation of timing errors: Errors in time domain can be transformed according to the following order:

$$e_t^e \rightarrow \textit{no error} \rightarrow e_t^l \rightarrow e_t^o$$

Timing checks and watchdog timers can be used to detect timing errors produced by components. Early timing errors can be corrected by introducing delays. Propagation of early or late timing errors can be blocked by not transmitting them, if there are no means to correct them. In such cases, these errors are transformed into omission errors. When a value error is detected and omitted, as described previously, the output is actually transformed from having no timing error to an omission error.

For *errors regarding consistency*, similar checks can be used and inconsistent errors can be transformed into consistent errors in both value and timing domains.

To illustrate how a specific component model can influence the error propagation aspects, we have considered the in-house developed SaveComp Component Model (SaveCCM) [2] and propagation between components through connectors.

4.1 SaveCCM component model

SaveCCM was developed under the SAVE project and was intended for use in automotive applications. In SaveCCM, systems are built by composing entities which belong to one of three main categories, namely components, switches and assemblies, via well-defined interfaces.

Components are basic entities in SaveCCM that follow strict read-execute-write semantics. A component is initially in an inactive state. Once *all* input trigger ports are activated, input data ports are read and the component starts executing. When the execution is completed, results are written to output data ports, input data ports are reset, and all output trigger ports are activated. Then the component returns to the idle or inactive state. *Switches* are lightweight components that allow changing the interconnections of components either statically, for offline configuration, or dynamically at run-time. Switches are not triggered and only perform routing of incoming data to output ports according to the connection pattern guards. Finally, *assemblies* are encapsulated subsystems whose internal structures may (or may not) be visible from the rest of the system.

Interfaces between SaveCCM entities consist of input and output ports. They are further classified into data ports, trigger ports, and both data and trigger ports. Connections between components consist of *immediate* or *complex connections*, where immediate connections are assumed to behave as ideal connections which take place instantly without any loss of information. Complex connections, on the other hand, are used to model more realistic connection scenarios, e.g., with certain delays and possible loss of information.

4.2 Error propagation in SaveCCM

In this section, we first investigate which error types can be propagated from one entity to another through different SaveCCM ports (Table 2). If two SaveCCM entities are connected by a *trigger* port, then the preceding entity can propagate only timing errors by triggering (therefore activating) the following entity at an incorrect time. If the con-

	Value Errors	Timing Errors
Data ports	✓	✓
Trigger ports	-	✓
Data and trigger ports	✓	✓

Table 2. Error propagation through SaveCCM

nection is implemented with a *data and trigger* port, both value and timing errors can be propagated. This is also the case for connections implemented with a *data* port, since the time when the data is written to the port will determine if there is a timing error. Hence, SaveCCM entities can be classified with respect to error generation and propagation as follows:

- SaveCCM entities that can generate value errors: These are the entities that have *output data* or *output data and trigger* ports.
- SaveCCM entities that can propagate value errors: Entities in this group have *input data* or *input data and trigger* ports to receive a value error from a preceding entity. Furthermore they must have *output data* or *output data and trigger* ports in order to propagate the error to the following entity.
- SaveCCM entities that can generate timing errors: Any entity that has output ports can generate timing errors.
- SaveCCM entities that can propagate timing errors: Similarly any SaveCCM entity can propagate timing errors provided that there exists at least one input and one output port.

As different component models have different levels of impact on the error propagations, similar detailed analysis, in the context of the given component model, is essential for an accurate and computationally feasible system level error behavior prediction.

5. Summary and Ongoing Work

In this paper, we have proposed a framework to enable compositional reasoning of error models. We have surveyed various error classifications and failure modes in the literature with the aim of identifying their relations/contrasts as well as in arriving at an 'all-encompassing compilation of classifications'. We have investigated the error propagation in CBS and discussed the effects of error handling mechanisms on error propagation, exemplifying it on SaveCCM component model. Our ongoing research aims to: a) add formalizations of component error models, error propagation models and error handling mechanisms (including probabilistic variants of them), b) provide links to architectural reliability prediction models together with new theories on dependability reasoning of multi-level compositions, as well as c) instantiate our framework on the SaveCCM successor, i.e., *ProComp*, currently under development.

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