Architectural Prescriptions for Dependable Systems

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Abstract. In today's highly complex software systems it's often impossible to enforce and evaluate dependability requirements unless they are taken into account from the beginning of the development process. Retrofitting it into the system at the code level is not a satisfactory way of solving this problem. Dependability requirements cause transformations to be made to a software system's architecture on various levels. We categorize architectural solutions to non-functional requirements according to the kinds of transformations they cause: additive, separative and integral. The first kind of solution for non-functional requirements just adds new components to the system; the second kind modifies only a subset of the system's architecture; the third kind integrates the effects of the non-functional requirements throughout the entire architecture. The Preskriptor method, which we are developing to transform requirements specifications into architectural prescriptions (i.e. high-level architectural specifications), provides a framework to enforce non-functional (dependability) requirements at the architectural level.

1 Introduction

Experience has shown that, for complex software systems, it's very important to take into account non-functional requirements as early as possible in their design process. The earliest they can be accounted for is the architectural design level. This enables a clear understanding of the implications of non-functional requirements on the high level components and on the topology of such systems.

Dependability requirements are a particular type of non-functional requirements. In this paper we adopt a broad definition of dependability and we intend it to "embrace all those aspects of behavior upon which the user of a system might need to place dependence: it thus includes reliability, safety, availability and security" [1].

Another way that an architectural prescription favors the design of dependable systems is by enabling the reuse of the high level design of systems that, having been already deployed, have demonstrated to be dependable. A prescription allows the architect to reuse all the components and the topology that derive from particular goals (i.e. requirements), including dependability requirements. Generally, a brand new system design has a higher likelihood of failure than a well tested one.

Our approach on solving this issue is based on the properties of goal-oriented requirements and on those of architectural prescriptions. In particular, our approach

takes advantage of the KAOS requirements specification language [3], the architectural prescription language Preskriptor [4].

Before illustrating our approach for dependability enforcement at the architectural level in section 4, we provide an introduction to goal-oriented requirements and to architectural prescriptions in sections 2 and 3 respectively. In section 5 we illustrate our approach with an example, and we summarize our contributions and discuss future work in section 6.

2 Goal Oriented Requirements Specifications and KAOS

Goal oriented requirements specifications are, among all the kinds of requirements specifications, those that are closer to the way humans think [2] and hence the easiest to be understood by all the stakeholders of the system's development process. KAOS is the goal oriented specification language, introduced by A. van Lamsweerde [3], which we used in our methodology.

The KAOS' ontology is composed of objects, operations and goals. Objects can be agents (active objects), entities (passive objects), events (instantaneous objects), or relationships (objects depending on other objects). Operations are performed by an agent, and they change the state of one or more objects. Operations are characterized by pre-, post- and trigger- conditions. Goals are the objectives that the system has to achieve. In general, a goal can be AND/OR refined till we obtain a set of achievable sub-goals. The goal refinement process generates a goal refinement tree. All the nodes of the tree represent goals. The leaves of the tree may also be called requisites. The requisites that are assigned to the software system are called requirements; those assigned to the interacting environment are called assumptions. Here is an example of goal declaration in KAOS:

```
Goal Maintain[AuthorizedAccessesOnly]
InstanceOf SecurityGoal
Concerns StockValues, BankerActor
ReducedTo
    ConfidentialityOfAccessPassword,
    ConfidentialityOfTransmittedStockValues
InformalDef
      Access passwords must remain confidential.  Stock
    values information has to be released only to those
    providing the correct passwords.
```

Fig 1. Goal specification in KAOS

The keyword *Goal* denotes the name of the goal; *InstanceOf* declares the type of the goal; *Concerns* indicates the objects involved in the achievement of the goal; *ReducedTo* contains the names of the sub-goals into which the goal is refined. Finally, there is *InformalDef*: the informal definition of the goal. There can also be an optional attribute *FormalDef*, which contains a formal definition of the goal (which can be expressed in any formal notation such as linear temporal logic).

3 Architectural Prescriptions and Preskriptor

An architectural prescription [4] lays out the space for the system structure by selecting the architectural components (processes, data, and connectors), their relationships (interactions) and their constraints. In a prescription, the fundamental characterization of components is given by the goals they are responsible for (that are their constraints). Components are further characterized by their type, which can be processing, data or connecting. The processing components, or processors, are those that provide the transformation on the data components. The data components contain the information to be used and transformed. The connecting components, or connectors, can be either implemented by data components, processing components or a by combination of both. They are the glue that holds all the pieces of the system together. The interactions of the components among each other, together with the restriction of their possible number of instances characterize the topology of the system.

Fig. 2 contains the architectural prescription of a data component specified in Preskriptor. Preskriptor is our architectural prescription language, whose process takes KAOS requirements specifications as starting point.

```
Component StockValues [1, 1]
Type Data
Constraints Maintain[LatestStockValuesInfo], …
Composed of DB [1,1], Server [1,1]
Uses MarketConnect to interact with
    StockMarket
```

Fig. 2. A component's specification in Preskriptor

The field *Component* denotes the name of the component. *Type* specifies the type of the component. *Constraints* is the most important attribute of a component. It denotes the requirements that the component is responsible for. We use here the term constraint to denote both functional and non-functional constraints (which correspond to requirements of the system). *Composed of* identifies the subcomponents that implement the component. The last attribute, *Uses*, indicates what are the components used by the component. Since interactions can only happen through a connector, the *Uses* attribute has the additional keyword *to interact with* that indicates which components the component interacts with using a particular connector.

Without going into the details of how to get a prescription from the requirements [4], it's important to know that at the beginning some candidate components for the architecture are proposed, then the functional goals first, and non-functional goals later, are assigned, one at a time, to a subset of the potential components. The potential components which do not contribute to the achievement of any goal are discarded from the system. The next section explains in some detail how to account for non-functional requirements in an architectural prescription.

4 Non-Functional Requirements in Prescription Design

Taking into account Non-Functional Requirements (NFRs) while designing an architectural prescription has, in the most general case, three kinds of effects on the already designed prescription of a system:

1) The introduction of new components.
2) The transformation of the system's topology, i.e. a change on the relationships among the system's components.
3) The further constraining of already existing components.

Some non-functional requirements allow for separations of concerns among the architectural components; other requirements, instead, are spread throughout the code: they reach every component of the system like blood vessels reach every cell of our body.

We denote those NFRs that enable separation of concerns with respect to an architecture as *Separative Non-Functional Requirements* (SNFRs). SNFRs are those requirements that can be achieved by further constraining, adding new components and/or by transforming the topology of only a precisely identifiable subset in strict sense of the architecture's components. By "precisely identifiable" subsystem we mean that the subsystem can be characterized by a property. By subsystem "in strict sense" we exclude the complete system, case in which we don't achieve separation of concerns. A precisely identifiable subsystem in strict sense is, for example, a single component of the system. This happens in the case of a performance goal if a single component is the bottleneck for computation. Another example of a precisely identifiable subset in strict sense can be the set including all the connectors from a particular component, and the component itself, like in the fault tolerance example that we will illustrate in next section.

The simplest SNFRs are those that, given a particular architecture, can be achieved by only adding to the system new components and the relationships of those new components with other components, i.e. by composing some existing components with new ones without changing the constraints of any of the old components. We denote this kind of NFRs as *Additive Non-Functional Requirements* (ANFRs).

Those NFRs that are not SNFRs are denoted as Integral Non-Functional Requirements (INFRs). These requirements affect the entire system or a subset of the system for which no characterizing property can be found, i.e. the system is not precisely identifiable. A way to achieve this other kind of requirements is by making all the components conform to a particular style. An example of INFR is the goal for a system is to be composed by only components that conform to CORBA. No matter what, this requirement has to be added as a constraint to all the system's components.

In general, whether an NFR is integral, separative, or additive depends on the architecture on which we want to achieve it. It also may depend on the level of refinement of the architecture. In fact, what at a finer resolution of an architecture is a clearly identifiable subset in strict sense may become the whole set of the system's components at a coarser refinement.

5 Enforcing Dependability at the Architectural Level

Let's see, with the aid of an example, how a dependability requirement, in this case fault tolerance, can be handled by the Preskriptor process.

Any computer network can have, even in absence of catastrophic events (such us power failures, earthquakes, etc.) a certain number of machines that crash or become inaccessible. Let's consider the case of a distributed system, which runs on a distributed network, and which contains a data component whose accessibility, at any time, is vital. This data component can contain, for example, the value of the stocks managed by an investment bank. It's vital for the bankers to be able to access at any time the current value of a stock. Not being possible to do so could cost to the bank thousands of dollars, perhaps millions!

This kind of fault tolerance problem has been widely studied in the distributed systems community and a standard solution it's the following. Suppose that in a network with x nodes containing the data object StockValues there can be at most t (with $t < x$) of the x nodes that can fail at the same time. We can achieve a fault-tolerant real-time access to the vital data object StockValues, by having, at least, t+1 copies of the object stored in t+1 different nodes. To guarantee the fault tolerance we also need some protocol that manages the access to the object from outside the network, and which updates the copies of the object in the different nodes to achieve consistency among them.

Fig. 3 contains the prescription of a simple distributed system. This is the prescription of the system before we take into account the fault tolerance goal.

```
Component StockValues [1, 1]
Type Data
Constraints Maintain[LatestStockValuesInfo], …
Composed of DB[1,1], Server[1,1]
Uses MarketConnect to interact with StockMarket

Component BankerClient [0, n]
Type Processing
Constraints …
Uses
    StockValuesAccess to interact with StockValues
    BankerUserInterface to interact with BankerActor

Component StockValuesAccess [0, n]
Type Connecting
Constraints Maintain[AuthorizedAccessesOnly]
```

Fig. 3. Prescription for a stock values information system

In the prescription of Fig. 3 we have only one copy of the data component *StockValues*, the component storing the latest values of the stocks belonging to different markets that is updated by using *MarketConnect* connecting it to the stock markets. The prescription allows any number n of components *BankerClient* to be instantiated. *BankerClient* is the piece of software running on the bankers' machines.

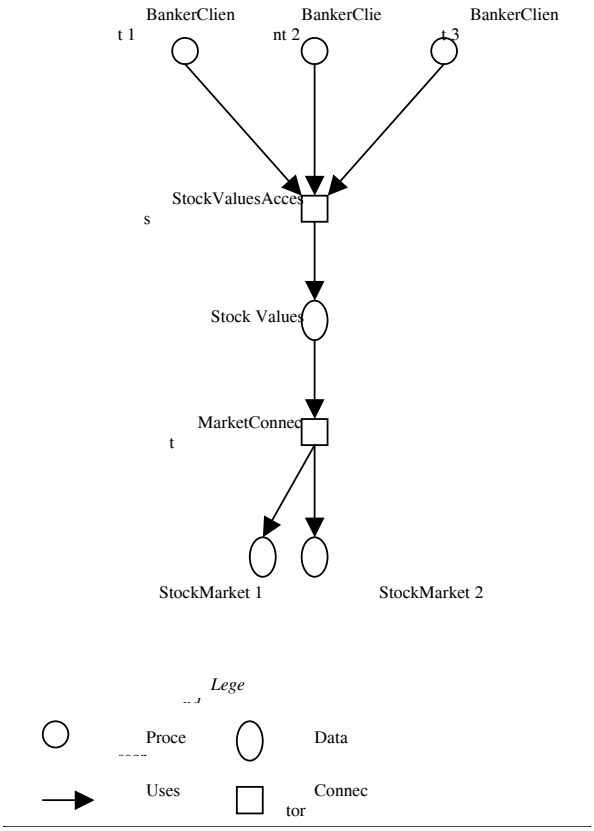

Fig. 4. Topology graph of the prescription in Fig. 3

The prescription requires the system to have communication between *BankerClient* and *StockValues* through connector *StockValuesAccess*, that has to achieve the security goal *Maintain[AuhorizesAccessesOnly]* (defined in Example 1.) together with other goals (such as mutual exclusion) not included here for simplicity. Given a particular choice of implementation of connector *StockValuesAccess*, the low level design may instantiate the connector only once for all the n *BankerClients*, instantiate it n times, or any other number of times between 0 and n.

Fig. 4 contains the graphical representation of the topology of an instantiation of the same prescription. It's the topology of an *instantiation* of the prescription because for each component a particular number of instances has been chosen. For example, there are only three clients rather than an indefinite number; and there is only one instance of connector *StockValuesAccess* for the interaction of all the clients with *StockValues,* rather than an indefinite number of connectors that is at most equal to the number of *BankerClient* components. Graphical representations are useful to

better understand the topology, which is implicit in every textual specification of a prescription.

In a prescription graph, the arrow representing the *Uses* attribute goes from the component C1, which needs some information from the interaction, to the connector CN that makes the interaction possible, and from the connector CN to component C2 that provides the information needed by C1.

Fig. 5 shows the same prescription after it has been transformed to account for the non-functional goal of fault tolerance for the component StockValues.

```
Component StockValues [t+1, n]
Type Data
Constraints Maintain[LatestStockValuesInfo], …
Composed of DB[1,1], Server[1,1]
Uses
      MarketConnect to interact with StockMarket
      InterCopyCoordinator to interact with
          StockValues

Component InterCopyCoordinator [1, n]
Type Connecting
Constraints Maintain[FaultTolerance]

Component StockValuesAccess [0, n]
Type Connecting
Constraints Maintain[AuthorizedAccessesOnly]

Component StockValueFTAccess [1,n]
Type Connecting
Constraints
    Maintain[FaultTolerance],
    Maintain[AuthorizedAccessesOnly]
Composed of
      IntercopyCoordinator   [1,n],   StockValuesAccess
    [0,n]

Component BankerClient [0, n]
Type Processing
Constraints …
Uses
     StockValuesFTAccess to interact with
          StockValues
      BankerUserInterface to interact with
          BankerActor
```

Fig. 5. Prescription for a stock values information system with fault tolerance

Like many dependability requirements, the non-functional fault tolerance requirement given the previous prescription is an ANFR. It's an ANFR because it can be assigned as a constraint only to the new connector *InterCopyCoordinator,* which coordinates the now multiple copies of component *StockValues*. This is an example of achieving an ANFR via connectors; another such example can be found in a system developed by the DSSA group [5], case in which the NFR is performance.

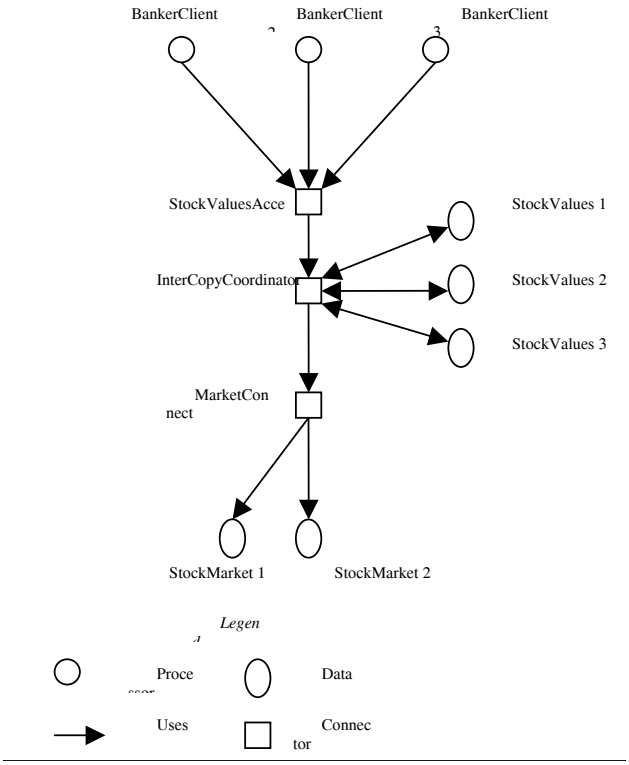

Fig. 6. Topology graph of the prescription in Fig. 5

The system specified by the new version of the prescription has to have at least t+1 (t being the maximum number of faults) copies of component *StockValues*, rather than only one like its pre-fault tolerance prescription. *StockValues* is now using the newly added connector *InterCopyCoordinator*. To achieve the fault tolerance goal, among the other things, this connector will have to make it sure that, at any time, there are at least t+1 copies of *StockValues*. Also, it has to assure that the different copies are, somehow, kept consistent at least from the perspective of the rest of the software system. The *BankerClients* interacting with component *StockValues* must always get the latest updated value of the stocks. The access to *StockValues* by two or more clients at the same time has to abide to the same mutual exclusion policies that held when only one instance of *StockValues* was in the system. We designed the prescription so that *InterCopyCoordinator* keeps the topological transformations transparent to *BankerClient*. The only change in *BankerClient*'s specification is that now this component uses connector *StockValuesFTAccess* (resulting from the composition of *InterCopyCoordinator* and *StockValuesAccess*) to interact with *StockValues*, rather than using *StockValuesAccess*. It's the *InterCopyCoordinator*'s

subcomponent of *StockFTValuesAccess* that hooks into *StockValues* to guarantee that *BankerClient* always gets the updated values of the stocks.

In a particular implementation of the prescription in a latter phase of the development process, *InterCopyCoordinator* may take care of the creation of t+1 copies at start-up, as well as creating new copies, moving the existing ones, or remove copies whenever some node fails or to save on communication costs like in illustrated in [6].

The effects of the topological transformation are evident if we have a look the topology graph of the new prescription in Fig. 6. There, the graph is the same than the one of figure 4., apart from having substituted the single component *StockValues* with a more complex component, composed by the different *StockValues* instances (three in the example) and the *IntercopyCoordinator* used by them. The double edged arrows are a syntactic shortcut to make the graph more elegant: they represent at the same time the arrow that go from component A to B and the one from component B to component A.

6 Conclusion

Dependability requirements are a subset of non-functional requirements. To better achieve them and manage their changes they should be taken into account already at the architectural design level. We provided an overview of our methodology to design an architectural prescription given a set of goal oriented requirements specifications.

The requirements can either be functional or non-functional. Separative Non-Functional Requirements (SNFRs) enable separation of concerns in achieving them. Their effects are limited to a subset of the system identifiable by a property (like the set of connectors outgoing from a particular component). In particular, we illustrated with an example how a fault tolerance requirement for an object in a computer network (which is an ANFR, an easier case of SNFR) can be achieved on a given architecture. This was done by introducing in the architecture a new connector and by modifying the topology of the system locally to one of its components. Many other dependability requirements, including security, performance and other kinds of fault tolerance can be ANFRs with respect to architectures.

Our future work will be aimed at finding out domain independent ways to compositionally transform the prescription of a system to account for ANFRs and at developing a tool to do so automatically as well as investigating how to achieve the other, more complex kinds of non-functional requirements.

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