

# Automating Middleware Specializations for Fault Tolerance

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## Abstract

*General-purpose middleware solutions, by definition, cannot readily support domain-specific semantics without significant manual efforts in specializing the middleware. This paper presents GRAFT (GeneRative Aspects for Fault Tolerance), which is a model-driven, generative, and aspects-based approach to specialize general-purpose middleware with failure handling and recovery semantics imposed by a domain. Model-driven techniques are used to specify the special fault tolerance requirements, which are then transformed into middleware-level code artifacts using generative programming. Since the resulting fault tolerance semantics often crosscut the middleware architecture, GRAFT uses aspect-oriented programming to weave them into the original fabric of the general-purpose middleware. We evaluate the capabilities of GRAFT using a representative case study.*

**Keywords:** Fault tolerance, middleware specialization, generative programming, aspects, model-based.

## 1 Introduction

Research in middleware over the past decade has significantly advanced the quality and feature-richness of contemporary general-purpose middleware, such as CORBA, J2EE and .NET. Support for different non-functional properties, such as fault tolerance, real-time, transactions and security are now readily available within the middleware and its services. Application domains as diverse as industrial automation and business processing use these middleware for reliable and robust coordination and communication between software components.

Despite these advances, general purpose middleware have limitations in how many *domain-specific* semantics can they readily support *out-of-the-box*. For example, fault tolerant CORBA (FT-CORBA) defines the infrastructure- and application-controlled styles of

consistency management. In the former, the middleware provides consistency to the applications; however, without knowing the semantics of the data, this style of consistency management can at best be coarse grained. On the other hand, in the application-controlled consistency management style, the applications must provide all these capabilities thereby incurring additional development efforts and maintenance costs. Often it is desirable for applications to provide the semantics of their data to the middleware while delegating all consistency management to the middleware.

Supporting such domain-specific semantics using general-purpose middleware is challenging because these semantics are often not supported by the general-purpose middleware. Since different application domains may impose different variations in fault tolerance (or for that matter, other forms of quality of service) requirements, these semantics cannot be supported out-of-the-box in general-purpose middleware since they are developed with an aim to be broadly applicable to a wide range of domains. Developing a proprietary middleware solution for the application domain is not a viable solution either due to the high development and maintenance costs.

Resolving this tension requires answering two important questions. First, how can solutions to domain-specific fault tolerance requirements be made part of general-purpose middleware without permanently modifying the latter? An approach based on aspect-oriented programming (AOP) [10] can be used to modularize the domain-specific semantics as *aspects*, which can then be woven into general-purpose middleware using aspect compilers. This creates *specialized* forms of general-purpose middleware that support the domain-imposed properties.

Many solutions to specializing middleware exist [9, 12], however, these solutions are often handcrafted, which require a thorough understanding of the middleware design and implementation. The second question therefore is how can these specializations be automated to overcome the tedious, error-prone, and expensive manual approaches? *Generative programming* [4] of

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fers a promising choice to address this question.

In this paper we present GRAFT (*GeneRative Aspects for Fault-Tolerance*), which incorporates these solutions to specialize general-purpose middleware with domain-specific fault tolerance semantics. GRAFT uses domain-specific modeling and model-driven engineering (MDE) [3,16] techniques due to their ability to intuitively capture and modularize domain-specific requirements, and their inherent support for generative programming.

GRAFT uses a two stage process. In the first stage, fault tolerance requirements of the domain are modularized as first class modeling artifacts using our domain-specific modeling language called the Component Availability Modeling Language (CAML). CAML uses these modularized units to annotate the models of application structure, which in our case are component assemblies.

Aspect-oriented model weaving [6] is used to automatically transform the original structural models into refinements that incorporate the fault tolerance requirements captured using CAML. In the second stage, generators associated with CAML synthesize aspect code that captures the runtime fault tolerance behavior, which is then woven into the middleware code using an aspect compiler.

We show the feasibility of our approach in the context of a representative case study taken from a warehouse material handling system that uses the Component-Integrated ACE ORB (CIAO) – a C++ implementation of Lightweight CORBA Component Model (LwCCM) [13] – for implementing the software components that control conveyor belt motors. Our empirical studies focus on measuring the savings in efforts to specialize general-purpose middleware.

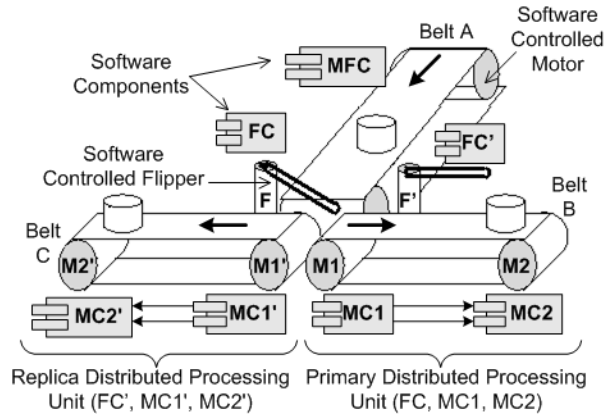
## 2 Motivational Case Study

To better present our GRAFT solution, we illustrate a case study that benefits from GRAFT to realize its fault tolerance requirements. Our case study is a warehouse *material handling system* (MHS). A MHS automates the monitoring, management, and control of storage and flow of goods and assets within a warehouse. A MHS represents a class of conveyor systems used by couriers (*e.g.*, UPS, DHL, and Fedex), airport baggage handling, retailers (*e.g.*, Walmart and Target), food processing and bottling.

**Architecture.** The software components in the MHS architecture can be classified as (1) *management components*, which make decisions such as where to store incoming goods, (2) *material flow control components* (*MFC*), which provide support for warehouse man-

agement components by determining the routes the goods have to traverse, and (3) *hardware interface layer (HIL) components*, which control MHS hardware, such as conveyor belts and flippers.

Figure 1 shows a subset of the MHS operations, where a *MFC* component directs goods within the warehouse using the route BELT A→BELT B or the route BELT A→BELT C. Flippers *F* and *F'* assist in directing goods from BELT A to BELT B and BELT C, respectively. Further, as shown in Figure 1, *HIL* components, such as Motor Controllers (*MC1*, *MC2*) and the Flipper Controller (*FC*), control the belt motors and flippers, respectively. The *MFC* component instructs the Flipper Controller component to flip, which in turn instructs the Motor Controller components to start the motors and begin transporting goods.



**Figure 1.** A Distributed Processing Unit Controlling Conveyor Belts

**Domain-specific Fault Model.** As goods are transported using the different conveyor belts, faults could occur. Two broad kinds of faults are possible in the MHS system: (1) hardware faults, (*e.g.*, jamming of the flipper) and (2) software faults, (*e.g.*, MC or FC component crashes). Both these faults affect the reliable and correct operation of the MHS system, and are classified as *catastrophic* faults.

Hardware catastrophic faults in the MHS system are detected by their associated *HIL* components and communicated using application-specific software exceptions. Software faults, such as software component crashes, are detected by the clients of those components using system-level software exceptions generated by the underlying middleware.

**Domain-specific Failure Handling and Recovery Semantics.** When catastrophic faults are detected in a MHS, the desired system response is to shutdown the affected hardware assembly and activate a backup

hardware assembly automatically. For example, when one of the motors of BELT B or flipper F fails, the MFC component should stop using the BELT B and route the packages via BELT C instead. The consequence of such a decision means that the HIL components associated with BELT B should be deactivated and those with BELT C as well as flipper F' need to be activated.

The MHS thus imposes a *group*-based fault tolerance semantics on the software components controlling the physical hardware. If any one component of the group fails, the failure prevents the whole group from functioning and warrants a failover to another group. We call this group of components as a distributed processing unit (DPU) – in this case MC1, MC2 and FC for BELT B. Further, the clients of a DPU (*e.g.*, the MFC component) must failover to an alternative DPU if any of the component in the primary DPU fails.

### System Design and Implementation Challenges.

The software components of MHS are implemented using the Component-Integrated ACE ORB (CIAO), which is a C++ implementation of Lightweight CORBA Component Model (LwCCM) [13]. Designing and implementing systems that support DPU group failure recovery semantics of a MHS using general-purpose middleware, such as LwCCM and its support for fault tolerance via FT-CORBA, is challenging because it lacks out-of-the-box support for (1) grouping multiple and distributed HIL components and treating them as a single unit of failure, (2) recovering a collection of HIL components together based on the group recovery semantics and redirecting all client MFC components to a replica group of HIL components. The remainder of the paper describes how GRAFT automates such domain-specific fault tolerance semantics within general-purpose middleware.

## 3 GRAFT Process for Middleware Specialization

This section describes the desired properties of a middleware specialization process, and shows how GRAFT meets these requirements.

### 3.1 Overview of GRAFT

Redundancy in the form of replicating application functionality provides the primary means to obtaining fault tolerance across a number of application domains. Redundancy, however, requires maintaining state consistency among the replicas for stateful applications. In addition to supporting these properties, special forms of replication and fault recovery, such as the DPU semantics described in Section 2, must be made available

in general-purpose middleware for the correct operation of the systems.

In component-based systems, such as our case study, realizing these capabilities impacts the entire lifecycle phases of the application. First, application developers must modify their interface descriptions specified in IDL files to specify new types of exceptions, which indicate domain-specific fault conditions. Only then can the IDL compiler provided by the middleware generate stubs that can recognize the additional exceptions. Naturally, with changes in the interfaces and the generated stubs, application developers must reprogram their application to conform to the modified interfaces.

Modifying application source code to support application-specific failure handling semantics is not scalable as multiple components need to be modified to react to failures and provision failure recovery behavior. Further, such an approach results in crosscutting of failure handling code with that of the normal behavior across several component implementation modules.

Second, replication requires new instances of application components to be specified, created and deployed. The middleware must then be able to recognize fault conditions and enforce failover by accounting for semantics, such as the DPU failover. The middleware must also support the right state consistency management for the enhanced fault tolerance requirements.

One approach to realizing this capability is to manually modify the general-purpose middleware. Such modifications, however, are seldom restricted to a small portion of the middleware. Instead they tend to impact multiple different parts of the middleware. For example, the replication semantics from our case study requires changes to (a) the generated stubs, (b) functionality to maintain group semantics and coordination among group members, (c) connection management among group components, replicas and clients, and (d) client-side perception of the failover target which now is a group rather than a single component.

In other words, these modifications crosscut a large portion of the middleware architecture. Naturally, a manual approach consumes significant development efforts and requires invasive and permanent changes to the middleware. Crosscutting of failure handling hinders program comprehensibility and maintainability as the number of functions or modules where failure handling code crosscuts increases.

Overcoming these challenges requires an approach that automates middleware specialization and relieves applications from having to incur extra development effort. In particular, the following properties are desired of the proposed approach:

- **Property 1:** Application developers must not in-

cur extra effort at design/development-time, *e.g.*, no changes to IDL and existing system models that describe how application components are assembled and deployed should be required. Moreover, any approach to capture the domain-specific requirements must be modularized to avoid scattering.

- **Property 2:** No manual efforts should be expended to incorporate the crosscutting changes to middleware while ensuring that no permanent changes are made to existing middleware. In other words, the domain-specific changes should remain decoupled from the original middleware, yet they must be made available at runtime to the application via the middleware.

The rest of this section presents our two stage GRAFT process to specialize middleware for domain-specific fault tolerance properties, while meeting these requirements. Stage 1 in GRAFT leverages existing structural models of applications modeled as component assemblies, and annotates them with domain-specific fault tolerance requirements using our CAML language. The C-SAW [18] aspect-oriented model weaver is then used to transform the base models into those comprising new structural elements corresponding to the fault tolerance requirements.

In stage 2, the refined structural models and their deployment decisions are used to carry out specialization to the middleware that hosts these application components. GRAFT uses the AspectC++ [19] aspect compiler to weave in the generated specialized code into the CIAO middleware. The entire GRAFT process is orchestrated within our CoSMIC [5] MDE framework.

### 3.2 Stage 1: Design-time Support for Specialization

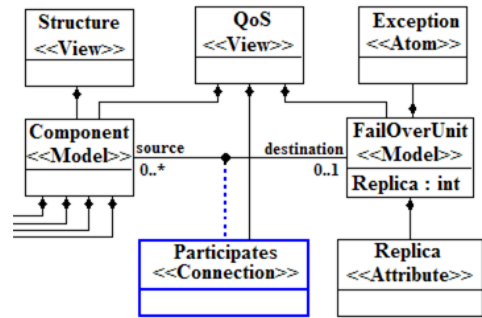
Specializing middleware for fault tolerance properties imposed by a domain requires a means to specify these requirements from which the middleware can be specialized. The level of IDL, application logic or middleware code to specify these requirements is not the right level of abstraction since all these approaches are crosscutting and invasive, which require significant modifications to and maintenance of different artifacts. Satisfying Property 1 from Section 3.1 requires that the application design and its structure (*i.e.*, the composition of its components) be shielded from the domain-imposed fault tolerance capabilities that are desired within the general-purpose middleware.

Thus, it is desirable to specify these requirements using approaches that are intuitive, non invasive, and which promote automation. Model-driven engineering (MDE) [16], which uses domain-specific modeling languages (DSML) [7], provides the right level of abstraction

at which such domain-specific requirements can be captured. MDE can enable a clean separation of application structural models from domain-specific fault tolerance requirements by leveraging the language composition property [11] supported in MDE. Moreover, since MDE is a widely used approach to designing large-scale applications, it becomes the natural choice to specify these domain-specific requirements.

**I. Specifying requirements using MDE:** GRAFT provides a DSML called the Component Availability Modeling Language (CAML), which provides capabilities to annotate application structural models with domain-specific fault tolerance requirements. CAML is developed using the Generic Modeling Environment (GME) [2], which provides a meta-programmable design environment for developing domain-specific graphical modeling languages. CAML leverages the DSML composition property of GME to compose itself on an existing DSML that supports structural modeling.

This property ensures that any domain-specific annotations of fault tolerance requirements to application structural models are realized as superimposition or an overlay, which preserves the original design and structure of the application. CAML also leverages the “separation of concerns” capability provided by GME wherein the modeling environment can provide different views or projections of the overall system to the application developer. To that end, CAML’s fault tolerance requirements are separated from the application’s structural models by projecting them only in the *QoS view* but not in the *structural view*.



**Figure 2.** Composing Availability Annotation Meta-model of CAML

To capture the DPU semantics of our case study from Section 2, we developed an annotation meta-model in CAML that is composed with a base language as shown in Figure 2. To modularize the DPU fault-tolerance requirements at the modeling level, CAML provides a key modeling abstraction called *FailOverUnit* that supports group recovery semantics

for the components associated with the relation *Participates*. One or more components can be grouped together and treated as a DPU when they are associated with a single FailOverUnit.

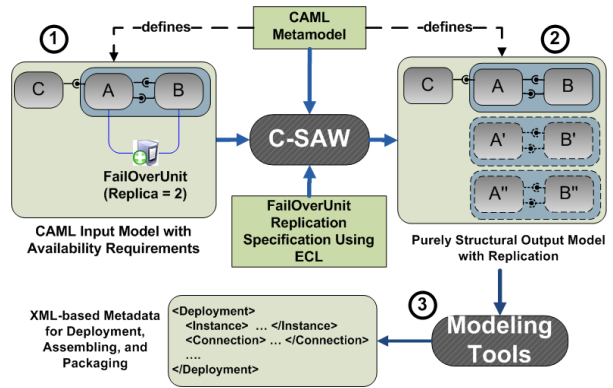
It also captures the degree of replication of a DPU as a unit using an integer attribute called *Replica*. Finally, the FailOverUnit also provides support for modeling system level and application-specific catastrophic exceptions because group recovery semantics are critically dependent on such observable exceptions. Notice how CAML ensures that the FailOverUnit is projected only within the *QoS view* while the *structural view* continues to be part of the base language.

**II. Automating structural changes based on modularized requirements:** Note that middleware specializations are required for all component instances in the system including replicas. Although CAML modularizes the domain-specific fault tolerance requirements by providing the annotation capabilities, these annotations by themselves do not produce extra component instances for the replicas in the structural model of the application. Without these, the model interpreters associated with the base language, which do not understand the annotations, cannot synthesize deployment and configuration metadata for the new components. Thus the original structural models of the application must be transformed using these annotated requirements, however, without the developer expending any effort.

In our case study, such a transformation requires several steps including (1) duplicating models of the primary components participating in a FailOverUnit, and (2) duplicating their interconnections so that the necessary connections can be established at deployment time for the replica DPU.

GRAFT uses aspect-oriented model weaving [6] support provided by the Constraint-Specification Aspect Weaver (C-SAW) [18] tool to transform the original structural models with the annotated requirements. The C-SAW weaver is a generalized model-to-model transformation engine for manipulating domain-specific models. C-SAW uses a built-in language called Embedded Constraint Language (ECL) to specify transformations.

As shown in Figure 3, we developed a model-to-model transformation using C-SAW that takes a CAML model having a clear separation of structural design and the fault tolerance requirements as an input model, and generates a structural output model in response to the fault tolerance requirements. The new structural model is then traversed by existing interpreters of the base language to produce metadata for packaging, assembling, deployment and configuration.



**Figure 3.** Automated Model Weaving Using C-SAW and FailOverUnit Replication Specification Using ECL

Step 1 in Figure 3 represents a CAML model, which has fault-tolerance requirements modeled along with the application’s structure. Step 2 in Figure 3 shows how a CAML model is automatically enriched using a transformation written using ECL. The transformation specification is parameterized and accepts the number of desired replicas as a parameter, which is specified as an integer attribute of a FailOverUnit in Step 1. Step 3 then uses existing model interpreters of the base language and operates on the transformed models.

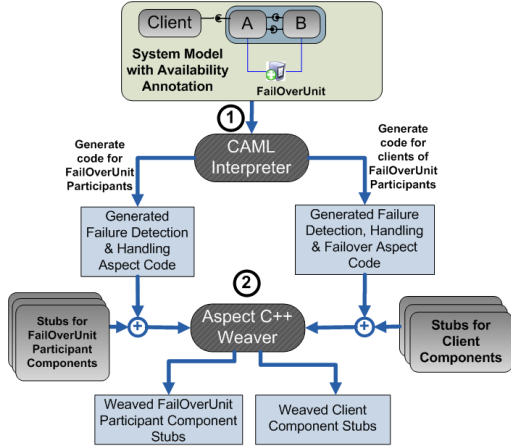
The transformation is divided into multiple ECL strategies that perform two important steps. First, it creates clones of the participant components of a FailOverUnit. Second, it replicates the interconnections between the primary components into replica components. The result of these two steps is that structurally identical copies of the primary component models are created. This is necessary because the deployment and configuration tools do not distinguish between the primary components and the replica components.

### 3.3 Stage 2: Runtime Support for Specialization

The MDE tools deploy the entire system and configure the middleware, however, they do not specialize the middleware. It is necessary for the middleware to be specialized using the the domain-specific fault tolerant semantics specified in the MDE tools, without expending any manual effort. To address this challenge, GRAFT uses a deployment-time *generative* approach that augments general-purpose middleware with the desired *specializations*.

For our case study, GRAFT specializes the client-side middleware stubs. Client-side middleware stubs

are used to communicate the exceptions raised at the server-side middleware so that applications can adapt to exceptional behavior. GRAFT augments the *behavior* of the middleware-generated stubs at deployment-time to catch failure exceptions, and initiate domain-specific failure recovery actions.



**Figure 4.** Automated Generation of Failure Detection and Handling Code

GRAFT provides a model interpreter, which (1) traverses the CAML model, (2) identifies the components that participate in FailOverUnits, (3) identifies the components that are clients of the FailOverUnit participant components, and (4) generates modularized source code that provides failure detection and recovery as shown by Step 1 in Figure 4. Depending upon the role of the component, two different types of behaviors are generated by the interpreter.

We have identified two different roles of components with respect to a DPU: (1) a participant of a DPU (*e.g.*, FC component) or (2) an external client of a component in a DPU but not a participant of the DPU (*e.g.*, MFC component). The participants of a DPU do not failover, however, clients of a DPU fail over to a replica DPU. To allow this difference in the behavior, failover code is generated only for the client components whereas the code for FailOverUnit participant components do not perform failover; instead they trigger fail over in the client components of the FailOverUnit.

To modularize and transparently weave the failure detection and recovery functionality within the stubs, GRAFT leverages Aspect-oriented Programming (AOP) [10] support provided by the AspectC++ [19] compiler. The CAML model interpreter generates AspectC++ code,<sup>1</sup> which is then woven by

<sup>1</sup>Due to space restrictions we are not showing the generated

the AspectC++ compiler into stubs at the client side producing specialized stub implementations as shown by Step 2 in Figure 4. Finally, the specialized source code of the stubs are compiled using a traditional C++ compiler.

## 4 Evaluation of GRAFT

We evaluate GRAFT by measuring the efforts saved to specialize middleware in the context of the MHS case study of Section 2. Additionally we also qualitatively validate the runtime behavior of the specialized middleware in meeting the fault tolerance requirements of the MHS case study.

**Evaluating savings in effort to specialize middleware:** Table 1 shows the manual efforts saved by adopting GRAFT’s approach in designing and developing the MHS case study described in Section 2. The table shows that there is reduction in the efforts of modeling replica components and connections for all the four components. The declarative nature of the CAML’s FailOverUnit annotations and the automated model-to-model transformation thereafter, obviates the need for modeling the replica components and connections explicitly resulting in a modular design of the MHS system.

A significant reduction in programming efforts is achieved due to automatic generation of code that handles failure conditions at runtime in the MHS system. The generated code for each component is different depending upon the number of remote interfaces used by a component, the number of methods in each remote interface, and the types of exceptions raised by the methods. The number of `try` blocks in Table 1 corresponds to the number of methods whereas the number of `catch` blocks correspond to the number of exceptions.

For example, when MFC component invokes the `flip()` method of the FC component, 45 lines of aspect code is generated to handle group recovery semantics for that one function call alone. GRAFT’s approach yields higher savings in modeling and programming efforts for larger, more complex systems, which may have hundreds of components with tens of them requiring fault-tolerance capabilities.

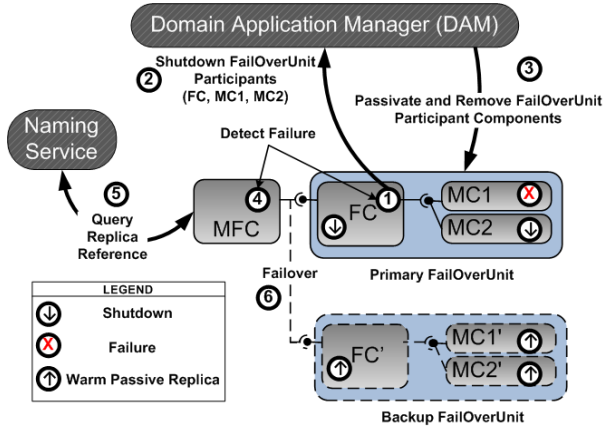
**Qualitative validation of runtime behavior:** Figure 5 shows how the specialized stubs generated by GRAFT react to failures at runtime and provide group recovery semantics. To control the lifecycle of the components, the aspect code communicates with domain application manager (DAM), which is a standard de-

aspect code.

Component Name	Fault-tolerance Modeling Efforts			Fault-tolerance Programming Efforts		
	# of original connections	# of replica components	# of replica connections	# of try blocks	# of catch blocks	Total # of lines
Material Flow Control	1 / 1	0 / 0	2 / 0	1 / 0	3 / 0	45 / 0
Flipper Controller	2 / 2	2 / 0	4 / 0	2 / 0	6 / 0	90 / 0
Motor Controller 1	1 / 1	2 / 0	2 / 0	0 / 0	0 / 0	0 / 0
Motor Controller 2	2 / 1	2 / 0	2 / 0	0 / 0	0 / 0	0 / 0

**Table 1.** Manual Efforts in Developing ITS Casestudy Without/With GRAFT

ployment and configuration infrastructure service defined in LwCCM. It provides high-level application programming interface (API) to manage lifecycle of application components. Below, we describe the steps taken by GRAFT when a catastrophic exception is raised.



**Figure 5.** Runtime Steps Showing Group Recovery Using GRAFT

1. When FC makes a call on MC1, MC1 detects a motor failure and raises *MotorFailureException*, which is caught by the generated aspect code in FC.
2. The specialized stubs in FC, initiate shutdown of the primary DPU by instructing the DAM to remove participating components of the primary DPU (FC, MC1, and MC2), including itself.
3. DAM contacts application servers hosting the primary DPU components (FC, MC1, and MC2) and instructs them to passivate and remove the components.
4. Removal of FC component triggers a system-level exception at the MFC component, which is again caught by the specialized stub at MFC-side.
5. The specialized stubs for MFC fetch a reference of FC' from the naming service. The naming service is assumed to be pre-configured at deployment-

time with lookup information for all the components in the system.

6. MFC successfully fails over to the replica DPU (FC', MC1', and MC2') and resumes the earlier incomplete remote function call. Finally, FC' communicates with MC1' and MC2' to drive the belt motors of the backup BELT C and continues the operation of MHS system without interruption.

## 5 Related Work

Polze *et. al.*, [14], use AOP techniques to describe fault-tolerance as a non-functional component property and focus on the automatic generation and replication of protected components and fault tolerant middleware services based on aspect information and demonstrate service configuration through a graphical user-interface. GRAFT's approach overlaps significantly with this approach, however, GRAFT provides automatic support for domain-specific failure handling semantics to applications as opposed to common middleware services.

ACT [15] enables runtime adaptation by transparently weaving adaptive code in the ORBs at runtime, which intercepts and adapts the requests, replies and exceptions that pass through the ORBs. ACT uses a runtime approach, which is based on portable interceptors. Although ACT's generic and rule-based interceptor capabilities could be used to provide various failure management semantics at runtime, it provides no support for capturing design-, deployment-time domain-specific fault-tolerance requirements.

Sevilla *et. al.*, [17] describe an automatic code generation approach for distribution, fault tolerance and load balancing aspects of component based systems. GRAFT on the other hand provides mechanisms that specifically support group failover failure semantics based on the model- as well as code-based weaving of component-based systems along with runtime monitoring infrastructure support.

Afonso *et. al.*, [1] propose a manual AOP-based approach for modularizing existing fault tolerance code

from the legacy threaded applications. But the modularization and weaving must be done manually at application level whereas GRAFT automatically weaves the domain-specific failure handling code in general purpose middleware to provide transparent recovery though client-side failover.

JReplika [8] attempts to modularize the replication aspect of fault tolerance using AOP. JReplika extends UML with a replication language to define replication policies at a finer domain-independent granularity whereas GRAFT supports domain-specific failure semantics such as group failover. However JReplika does not provide the middleware implementation for fault recovery whereas GRAFT automatically generates and weaves the necessary failure recovery code transparently in the middleware. A common feature between JReplika and GRAFT is that they both ensure that only the required method invocation paths are intercepted.

## 6 Conclusion

This paper presented GRAFT, which is a two stage generative approach to specialize general purpose middleware with domain-specific fault tolerance semantics. General purpose middleware are designed to support a wide range of application domains and can only provide generic solutions for non-functional properties, such as fault tolerance. When the domain imposes a rich set of fault tolerance requirements, GRAFT's approach is to automatically specialize the middleware using contemporary aspect-oriented languages to provide the desired failure recovery semantics without any modifications to the applications.

The capabilities of GRAFT were demonstrated in the context of an automated warehouse inventory tracking system (ITS) case study for group-wide failure recovery semantics. The MDE capabilities of GRAFT including CAML are available in open source as part of our CoSMIC toolsuite at [www.dre.vanderbilt.edu/cosmic](http://www.dre.vanderbilt.edu/cosmic).

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