

$\mathcal{R}\mathcal{E}\mathcal{L}$: A Fault Tolerance Linguistic Structure for Distributed Applications

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Abstract

The embedding of fault tolerance provisions into the application layer of a programming language is a non-trivial task that has not found a satisfactory solution yet. Such a solution is very important, and the lack of a simple, coherent and effective structuring technique for fault tolerance has been termed by researchers in this field as the “software bottleneck of system development”. The aim of this paper is to report on the current status of a novel fault tolerance linguistic structure for distributed applications characterized by soft real-time requirements. A compliant prototype architecture is also described. The key aspect of this structure is that it allows to decompose the target fault-tolerant application into three distinct components, respectively responsible for (1) the functional service, (2) the management of the fault tolerance provisions, and (3) the adaptation to the current environmental conditions. The paper also briefly mentions a few case studies and preliminary results obtained exercising the prototype.

1. Introduction

Structuring techniques provide means to control complexity, the latter being a relevant factor for preventing the introduction of design faults. This fact and the ever increasing complexity of today’s distributed software justify the need for simple, coherent, and effective structures for the expression of fault tolerance in the application software. This paper describes the “recovery language approach” ($\mathcal{R}\mathcal{E}\mathcal{L}$), i.e., a structuring technique for the expression of the fault tolerance design aspects in the applications characterized by soft real-time requirements. The $\mathcal{R}\mathcal{E}\mathcal{L}$ technique in particular addresses three requirements of fault-tolerant software design:

- R1** Separation of the functional and fault tolerance design aspects, such that the two design concerns do not conflict with each other.
- R2** Dynamic adaptability to varying environmental conditions, obtained through a sort of dynamic linking of the fault tolerance executable code.
- R3** A syntactical structure capable of hosting a wide class of fault tolerance (FT) provisions¹.

The above requirements are met by exploiting $\mathcal{R}\mathcal{E}\mathcal{L}$ ’s capability to partition the design complexity of a distributed application into three components:

1. An application-specific component realizing the functional specification.
2. A special-purpose component dealing with the management of the FT provisions.
3. A special-purpose component responsible for the run-time adaptation of the FT provisions to the current environmental conditions.

The structure of this paper is as follows: Section 2 introduces the elements of our approach. Section 3 describes a $\mathcal{R}\mathcal{E}\mathcal{L}$ -compliant prototype software architecture that has been developed in the framework of the two ESPRIT projects EFTOS (“embedded fault-tolerant supercomputing”) [15] and TIRAN (“tailorable fault tolerance frameworks for embedded applications”) [2]. That architecture focuses on component 2. Section 3 also mentions a few case studies where $\mathcal{R}\mathcal{E}\mathcal{L}$ is proving its effectiveness. The paper is concluded by Sect. 4, which also provides the reader with

¹By “FT provision” we mean any strategy (e.g. recovery blocks), or mechanism (such as watchdog timers), that can be used to introduce FT aspects into an application.

the elements of a new $\mathcal{R}\mathcal{E}\mathcal{L}$ -compliant architecture. Such architecture, which is being developed in the framework of the IST-2000-25434 project DepAuDE (“*Dependability for embedded Automation systems in Dynamic Environments with intra-site and inter-site distribution aspects*”), is to fully exploit the capabilities of $\mathcal{R}\mathcal{E}\mathcal{L}$. The key goal of this architecture is to realize all the special-purpose components of a fully $\mathcal{R}\mathcal{E}\mathcal{L}$ -compliant distributed architecture, leaving to the user the sole management of the service specification.

2. The Recovery Language Approach

This section describes $\mathcal{R}\mathcal{E}\mathcal{L}$, a FT linguistic structuring technique for distributed applications with soft real-time constraints. By structuring technique we mean a set of methods by means of which it is possible to **express** and to **manage** some FT provision. In the following, we will characterize both the above “methods”—expressing and managing a FT provision. Furthermore, in order to characterize our technique with respect to the existing ones, we will make use, informally, of a “base” of structural properties, namely

SC: separation of design concerns,

A: adaptability to a varying environment, and

SA: syntactical adequacy, i.e., the adequacy of the technique at hosting a FT provision, averaged on the set of possible FT provisions.

Clearly the above properties respectively match requirement **R1**, **R2** and **R3**. In what follows we will show that $\mathcal{R}\mathcal{E}\mathcal{L}$ is a simple, coherent, and effective FT linguistic structure that provides satisfactory values of the three structural properties (SC, A, SA) in the domain of soft real-time, distributed applications.

In $\mathcal{R}\mathcal{E}\mathcal{L}$ two distinct programming languages are available to the programmer: a service language, i.e., the programming language addressing the functional design concerns, and a special-purpose linguistic structure (called “recovery language”) for the expression of error recovery and reconfiguration tasks. This recovery language comes into play either asynchronously, as soon as an error is detected by an underlying error detection layer, or when some erroneous condition is signaled by the application processes. Error recovery and reconfiguration are specified as a set of *guarded actions*, i.e., actions that require a pre-condition to be fulfilled in order to be executed. Recovery actions deal with coarse-grained entities of the application and the system, and pre-conditions query the current state of those entities. An example of a recovery action is the following one:

if a transient faults affects “task 10” :
restart task 10

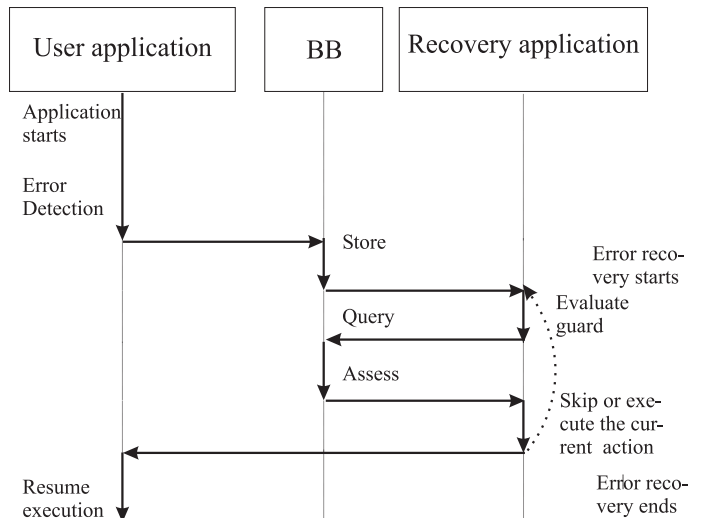


Figure 1. Scheme of execution of a $\mathcal{R}\mathcal{E}\mathcal{L}$ -compliant application: together with the application, two special-purpose tasks are running—a system-wide database management system (we call it the “backbone”), which stores error detection notifications sent by a periphery of detection tools, and a “recovery application”, i.e., a task responsible for the execution of the recovery actions. The diagram describes the execution of the user-specified recovery actions. The dotted line represents a jump to the execution of the next guarded action, if any. Error recovery ends when the last guarded action is evaluated.

notify the group of tasks to which task 10 belongs
end

A larger example of guards and actions can be seen in Sect. 3, where a prototype $\mathcal{R}\mathcal{E}\mathcal{L}$ -compliant architecture is described.

An important added value of $\mathcal{R}\mathcal{E}\mathcal{L}$ is that it allows for the **expression** of the recovery actions to be done in a design and programming context other than the one in which the expression of the functional service takes place. This minimizes non-functional code intrusion and hence enhances property SC.

The execution of the recovery actions is done via a fixed (i.e., special-purpose) scheme, portrayed in the sequence diagram of Fig. 1: as soon as an error is detected, a notification describing that event is sent to a distributed entity responsible for the collection and the management of these notifications. Let us call such entity the “backbone” (BB). Immediately after storing each notification, the guards of the recovery actions are evaluated. Guards evaluation is done by querying the BB. When a guard is found to be true, its corresponding actions are executed, otherwise they are

skipped.

The just sketched strategy represents the way $\mathcal{R}\mathcal{E}\mathcal{L}$ performs its **management** of the FT provisions to be embedded in the target application. An important consequence of the adoption of this strategy is that the functional executable code and the non-functional executable code are *distinct*: the former implements the user tasks, while the latter is given by a proper coding of the recovery actions. This allows to decompose the design process into two distinct phases. When the interface between the two “aspects” is simple and well-defined, this provides a way to control the design complexity, which decreases development times and costs. In the current implementation, described in Sect. 3, the recovery actions are translated into a “recovery pseudo-code” (we call it *r-code*) that is interpreted by an *r-code* virtual machine. Currently, the *r-code* can either be read from a file or “hardwired” in the *r-code* virtual machine. The separability of the *r-code* from the functional code provides the elements for the approach described in Sect. 4, which focuses on adaptability and FT software reuse.

The above strategy clearly focuses on the *error recovery* step of FT. In order to minimize the code intrusion due to *error detection* and *fault masking*, we envisaged a **configuration language** that allows the user to set up ready-to-use instances of provisions selected from a custom library of single-version FT mechanisms, including, e.g., a watchdog timer or a voting tool. These instances are also instrumented in such a way as to forward transparently their notifications to the BB. Notifications include, e.g., a watchdog timer’s alarm, or a caught division-by-zero exception, or a minority input value to a voting tool. An example of configuration language can be seen in Sect. 3. The same translator that turns the recovery actions into the *r-code* is used in that case to write the source files with the configured instances.

2.1. System and Application Models

The target system for $\mathcal{R}\mathcal{E}\mathcal{L}$ is assumed to be a distributed or parallel system. Basic components are nodes, tasks, and the network. A node can be, e.g., a workstation in a networked cluster or a processor in a MIMD parallel computer. Tasks are independent threads of execution running on the nodes. The network system allows tasks on different nodes to communicate with each other. Nodes can be commercial-off-the-shelf hardware components with no special provisions for hardware FT. A general-purpose operating system (OS) is required on each node. No special purpose, distributed, or fault-tolerant OS is required. The system obeys the *timed asynchronous distributed system model* [5]:

- Tasks communicate through the network via a datagram service with omission/performance failure semantics [4].

- Services are timed: specifications prescribe not only the outputs and state transitions that should occur in response to inputs, but also the time intervals within which a client task can expect these outputs and transitions to occur.
- Tasks (including those related to the OS and the network) have crash/performance failure semantics [4].
- Tasks have access to a node-local hardware clock. If more than one node is present, clocks on different nodes have a bounded drift rate.
- A “time-out” service is available at application-level: using it, tasks can schedule the execution of events so that they occur at a given future point in time, as measured by their local clock.

In particular, this model allows a straightforward modeling of system partitioning—as a consequence of sufficiently many omission or performance communication failures, correct nodes may be temporarily disconnected from the rest of the system during so-called periods of instability [5]. A message passing library is assumed to be available, built on the datagram service. Such library offers asynchronous, non-blocking multicast primitives. As clearly explained in [5], the above hypotheses match well to nowadays distributed systems based on networked workstations—as such, they represent a general model with no practical restriction. The following assumptions characterize the user application:

- The service is supplied by a distributed application.
- It is written or is to be written in a procedural or object-oriented language such as C or Java.
- The application is non safety-critical.
- The target application is characterized by soft real-time requirements. In particular, performance failures may occasionally show up during error recovery.
- Inter-process communication takes place by means of the functions in the above mentioned message passing library. Higher-level communication services, if available, must be based on the message passing library as well.

As suggested, e.g., in [27], any effective design including dependability goals requires provisions, *located at all levels*, to avoid, remove, or tolerate faults. Hence, as an *application-level* structuring technique, $\mathcal{R}\mathcal{E}\mathcal{L}$ is complementary to other approaches addressing FT at *system level*, i.e., hardware-level and OS-level FT. In particular, a system-level architecture such as GUARDS [24], that is based on redundancy and hardware and OS provisions for systematic

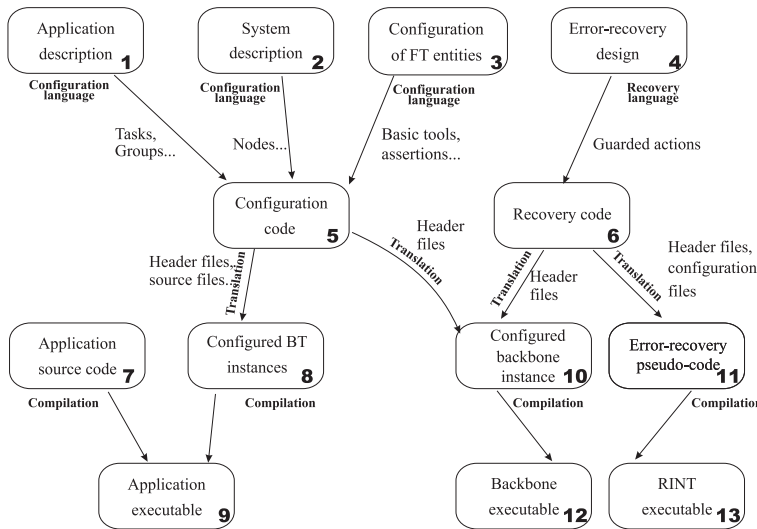


Figure 2. A workflow diagram for $\mathcal{R}\mathcal{E}\mathcal{L}$. Labels refer to usage steps and are described in Sect. 2.2.

management of consensus, appears to be particularly appropriate for being coupled with $\mathcal{R}\mathcal{E}\mathcal{L}$ which offers application-level provisions for N-version programming and replication (see Sect. 3).

2.2. Workflow of $\mathcal{R}\mathcal{E}\mathcal{L}$

This section describes the workflow corresponding to the adoption of the $\mathcal{R}\mathcal{E}\mathcal{L}$ approach. Figure 2 summarizes the workflow. The following basic steps have been foreseen:

- In the first steps (labels 1 and 2 in the cited figure), the designer describes the key application and system entities, such as tasks, groups of tasks, and nodes. The main tool for this phase is the configuration language.
- Next (step 3), the designer configures a number of basic FT tools (BTs) he or she has decided to use. The configuration language is used for this. The output of steps 1–3 is the configuration code.
- Next (step 4), the designer defines which conditions need to be caught, and which actions should follow each caught condition. The resulting list is coded as a number of guarded actions via a recovery language.
- The configuration code and the recovery code are then converted via the translator into a set of C header files, C fragments, and system-specific configuration files (steps 5 and 6). These files represent: configured instances of the BTs, of the system and of the application; initialization files for the communication man-

agement functions; user preferences for the BB; and the recovery pseudo-code.

- On steps 7–9, the application source code and a set of configured instances of BTs are compiled in order to produce the executable codes of the application.
- Next, the BB and the recovery interpreter are compiled on steps 10–13.

The resulting components, i.e., the executable codes of the application, the backbone, and RINT, represent the entities portrayed in Fig. 2.

In the following we briefly summarize the specific differences between ours and other novel approaches.

2.3. Specific Differences with respect to Other Approaches

Numerous techniques have been devised in the past to solve the problem of optimal and flexible development of dependability services to be embedded in the application layer of a computer program. In [6], some of these approaches are critically reviewed and qualitatively assessed with respect to a set of structural attributes (separation of design concerns, syntactical adequacy and adaptability). A non-exhaustive list of the systems and projects implementing these approaches is also given in the cited reference. In particular, approaches based on metaobject protocols [20] (MOPs), FT distributed programming languages [26] and aspect-oriented programming [21] (AOP) are reviewed therein.

Metaobject Protocols. The key idea behind MOPs is that of “opening” the implementation of the run-time executive of an object-oriented language like C++ or Java so that the developer can adopt and program different, custom semantics, adjusting the language to the needs of the user and to the requirements of the environment. Using MOPs, the programmer can modify the behavior of fundamental features like methods invocation, object creation and destruction, and member access. The key concept behind MOPs is that of *computational reflection*, or the causal connection between a system and a meta-level description representing structural and computational aspects of that system [23]. An architecture supporting this approach is FRIENDS [17]. FRIENDS implemented a number of FT provisions (e.g., replication, group-based communication, synchronization, voting) as MOPs.

A number of studies confirm that MOPs reach efficiency in some cases [20], though no experimental or analytical evidence allows to estimate the practicality and the applicability of this approach [25, 22]. MOPs only support object-oriented programming languages and require special extensions or custom programming languages.

Aspect-oriented Programming Languages. Aspect-oriented programming [21] is a programming methodology and a structuring technique that explicitly addresses, at system-wide level, the problem of the best code structure to express different, possibly conflicting design goals like for instance high performance, optimal memory usage, or dependability.

Developed as a Xerox PARC project, AspectJ is an aspect-oriented extension to the Java programming language [19, 22]. A study has been carried out on the capability of AspectJ as an AOP language supporting exception detection and handling [22]. It has been shown how AspectJ can be used to develop so-called “plug-and-play” exception handlers: libraries of exception handlers that can be plugged into many different applications. This translates into better support for managing different configurations at compile-time. Up to now, no AOP tool or programming language exists for flexible development of *dependable* services: AspectJ only addresses exception detection and handling. Remarkably enough, the authors of a recent study on AspectJ and its support to this field conclude [22] that “whether the properties of AspectJ [documented in this paper] lead to programs with fewer implementation errors and that can be changed easier, is still an open research topic that will require serious usability studies as AOP matures”.

3. The ARIEL Configuration and Recovery Language

This section describes a prototypic architecture based on $\mathcal{R}\mathcal{E}\mathcal{L}$ that has been developed during recently ended project TIRAN. In the following, in Sect. 3.1 we present the contents of TIRAN. The main components of the TIRAN architecture are then briefly introduced in Sect. 3.2. In particular, the TIRAN recovery language, ARIEL, is reported in Sect. 3.3 and a few case studies in Sect. 3.4.

3.1. The TIRAN Project

The main objective of project TIRAN (ESPRIT 28620) has been to develop a software framework that provides fault-tolerant capabilities to automation systems. Application-level support to FT is provided by means of a $\mathcal{R}\mathcal{E}\mathcal{L}$ -compliant architecture, which is described in the rest of this section. The framework provides a library of software FT provisions that are parametric and support an easy configuration process. Using the framework, application developers are allowed to select, configure and integrate provisions for fault masking, error detection, isolation and recovery among those offered by the library. Goal of the project is to provide a tool that significantly reduces the development times and costs of a new dependable system.

The target market segment concerns non-safety-critical distributed soft-real-time embedded systems [3]. TIRAN explicitly adopts formal techniques to support requirement specification and predictive evaluation [16]. This, together with the intensive testing on pilot applications, is exploited in order to:

- Assess the correctness of the framework.
- Quantify the fulfillment of time, dependability and cost requirements.
- Provide guidelines to the configuration process of the users.

Most of this framework has been designed for being platform independent. A single version of the framework has been written in the C programming language making use of a library of “basic services” (BSL) developed by the TIRAN consortium. The TIRAN framework is currently running on Windows-NT, Windows-CE, the Virtuoso microkernel [28], VxWorks, and the TEX microkernel [29].

The project results, driven by industrial users’ requirements and market demand, is being integrated into the Virtuoso microkernel and adopted by ENEL and SIEMENS within their application fields.

3.2. The TIRAN Framework

Figure 3 draws the TIRAN architecture and positions its main components into it. In particular, the box labeled “Ariel” represents the TIRAN recovery language, ARIEL. The central, whiter layers represent the TIRAN framework. In particular:

- Level 0 hosts the BSL (see Sect. 3), which gives system-independent access to the services provided by the underlying run-time system.
- Level 1 services are provided by a set of BTs for error detection and fault masking (level 1.1) and by another set addressing isolation, recovery and reconfiguration (level 1.2). These services are not distributed on multiple nodes.
- Level 2 hosts the TIRAN BB [10]. This is the component responsible for the management of the distributed database (DB) that maintains records describing errors detected by Level 1.1 BTs. It also includes a time-out management system, called TOM [11], and a recovery interpreter, RINT, actually a virtual machine executing the r-code. The BB executes an algorithm, described in [10], which allows it to tolerate node and component crashes and to withstand partitioning caused by temporary periods of communication instability. The BB

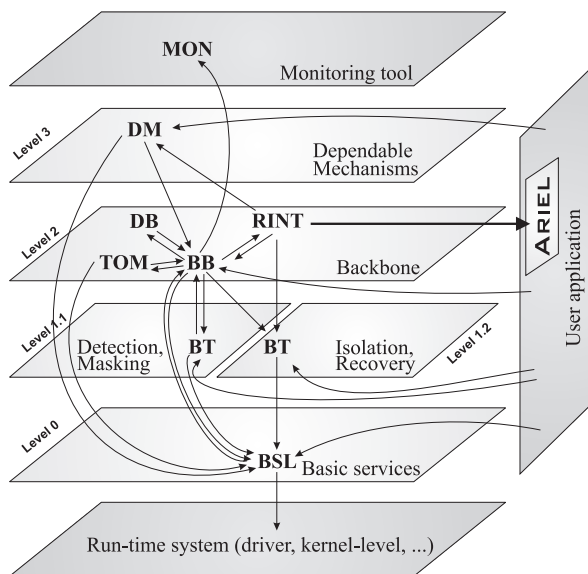


Figure 3. A representation of the TIRAN elements. The central, whiter layers constitute the TIRAN framework. This same structure is replicated on each processing node of the system.

straightforwardly supports the α -count fault identification mechanism [1] by feeding α -count filters immediately after the arrival of each new error detection notification. In Fig. 3, the edge connecting RINT to ARIEL means that RINT actually implements (executes) the ARIEL programs. Note the control and data messages that flow from BB to TOM, DB, and RINT. RINT also sends control messages to the isolation and recovery BTs. These are low-level messages that request specific recovery actions. Data messages flow also from BB to a monitoring tool [13].

- Dependable mechanisms (DMs), i.e., high-level, distributed FT tools exploiting the services of the BB and of the BTs, are located at level 3. These tools include a distributed voting tool [9], a distributed synchronization tool, and a data stabilizer [12]. The DMs receive notifications from RINT in order to execute reconfigurations such as, for instance, introducing a spare task to take over the role of a failed task.

The layers around the TIRAN framework in Fig. 3 represent (from the layer at the bottom and proceeding counter-clockwise):

- The run-time system.
- The functional application layer and the recovery language application layer (again, box labeled “Ariel”).

- A monitoring tool, for hypermedia rendering of the current state of the system within the windows of a WWW browser.

Next section focuses on the key component of the TIRAN prototype, namely, the ARIEL recovery language.

3.3. The ARIEL Language

Within TIRAN, a single syntactical framework—provided by the ARIEL language—serves the application designer as both a configuration and a recovery language. ARIEL is a language with a syntax somewhat similar to that of the UNIX shells. ARIEL deals with five basic types: “nodes”, “tasks”, “groups”, integers, and real numbers. A node is a uniquely identifiable processing node of the system, e.g., a processor of a MIMD supercomputer. A task is a uniquely identifiable process or thread in the system. A group is a uniquely identifiable collection of tasks, possibly running on different nodes. Nodes, tasks, and groups are generically called *entities*. Entities are uniquely identified via non-negative integers; for instance, NODE3 or N3 refer to processing node currently configured as number 3. Symbolic constants can be “imported” from C language header files through the statement INCLUDE. When curly brackets appear around a string, the value of the corresponding symbolic constant is returned.

The key statement in ARIEL is the IF, which is used to code a recovery action as follows:

```
IF [ guard ] THEN actions,
```

where a *guard* checks whether an entity, according to the current contents of the database, is in one of the following states: active; affected by a fault; affected by a transient fault; isolated; restarted. A guard can also check the current “phase” of a task, e.g., its current algorithmic step, that the task can declare via a custom BSL function. Actions can be guards—which allows to represent recovery actions as trees—and remote or local commands for: sending messages to tasks and groups; terminating, isolating, starting or restarting an entity. Restarting a node means rebooting it, terminating a node means performing a node shutdown. Isolating a task means disabling its communication descriptors. A local command is executed by the local BB component, while a remote one is first sent to the corresponding BB component and then executed by it.

ARIEL allows also to configure its BTs. For instance, the following syntax:

```
INCLUDE "mydefinitions.h"
WATCHDOG {MYWD} WATCHES TASK {MYTASK}
    HEARTBEATS EVERY {HEARTBEAT} MS
    ON ERROR WARN TASK {CONTROLLER}
END WATCHDOG
```

produces a source code configuring a watchdog that, once enabled by its first heartbeat, expects new such messages every HEARTBEAT milliseconds, or sends task CONTROLLER an alarm message. Note that in this case the error detection code intrusion is reduced to the function call for sending heartbeats. Configuration also includes replicated tasks and N-version programming. Syntaxes for retry blocks and consensus recovery blocks have been also implemented.

The ARIEL translator, called “art”, produces both the configured instances of the BTs and the recovery pseudo-code (r-code). The latter can either be output as a binary file, to be read by RINT at run-time, or as an include file to be compiled with RINT. This r-code is then re-executed by RINT each time the backbone notifies it that a new event has been stored in the database—as described in Fig. 1.

3.4. Case Studies

The ARIEL language and the TIRAN framework have been exercised in the course of project EFTOS and project TIRAN on a number of case studies, in as different an application domain as postal automation, electrical substation automation, and airport lighting systems. These case studies were formulated by two members of the EFTOS and TIRAN consortia (Siemens and ENEL) and have their origin within the internal strategies of those companies. One of these case studies is reported in [14]. Another noteworthy case study has been the development of a Level 3 FT mechanism supporting distributed voting. This tool exploits two features of ARIEL: first, it makes use of spare components—error recovery strategies like reconfiguration and graceful degradation (when spares are exhausted) can be expressed in terms of ARIEL scripts and result in no code intrusion. Secondly, it exploits the built-in support of the α -count fault identification mechanism in order to let the user express different error recovery strategies depending on the nature of the corresponding faults. This allows to express recovery actions such as:

```

IF [ FAULTY TASK {MYTASK} ]
THEN
  IF [ TRANSIENT TASK {MYTASK} ]
  THEN Conservative strategy
       (e.g., restart the task)
  ELSE Reconfiguration
FI
FI.

```

This aims at keeping reconfiguration as the ultimate solution in order to minimize the rate at which redundancy is “consumed”. Markov modeling of this approach shows that it allows to enhance considerably reliability [6]. For the sake of brevity we refer to the cited sources for a full description of the case studies and their evaluation.

4. Conclusions and Future Work

A novel fault tolerance linguistic structure for distributed applications has been briefly described. Such structure is at the core of the strategy that is currently being designed within IST-2000-25434 Project “DepAuDE” to allow dependable real-time applications with intra-site and inter-site distribution aspects to adapt to a changing environment ([8] briefly mentions the key ideas behind the DepAuDE strategy). The design of the elements of the architecture sketched in this paper, which explicitly addresses requirement **R1**, **R2** and **R3**, is one of the goals of DepAuDE. As mentioned before, $\mathcal{R}\mathcal{E}\mathcal{L}$ is being used in several case studies with promising results. One of these case studies is described in [14]. The adoption of a recovery language within a generative communication infrastructure (such as the one of LINDA [18]) is also currently being experimented [7].

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