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Composable Controllers in Fractal: Implementation and Interference Analysis

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***Abstract*—Component based software engineering supports the rapid assembly of software systems. These systems are highly structured yet flexible. In particular, Fractal introduces controllers for the extension of components. Fractal controllers intercept incoming and outgoing calls of component services and implement the extended behavior. However, controllers may interfere one with another. In this article, we propose two contributions. First, we extend Fractal component model with a support for composing controllers with reusable operators. Second, we show how to formally model and analyze in Uppaal such extended systems. This enables us to detect when controllers interfere, then to check whether their composition is interference-free. We illustrate our general approach with a running example: a wireless internet service of an airport.**

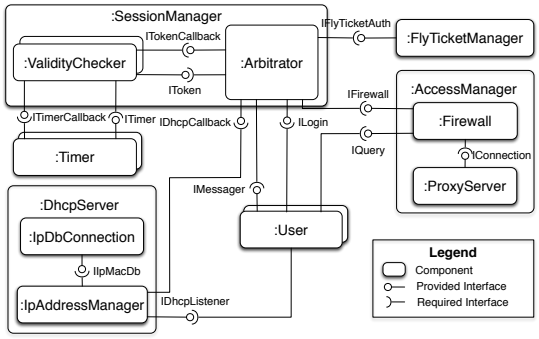

Fig. 1. Architecture of the airport internet access system

I. Introduction

Component based software engineering supports the rapid assembly of flexible software systems. These systems are highly structured yet flexible. In particular, Fractal [1] supports extending components' behaviors by means of controllers. In Fractal, controllers are plugged into components, they intercept incoming and outgoing messages, implement the extended behavior and proceed or discard messages. However, when a component have several controllers, there is no general way to compose them. They have to be composed in a programmatic way by explicitly calling a controller from another one. These limitations make the implementation of extensions a complex task with sometimes unexpected behavior.

In this article, we propose two contributions. First, we extend Fractal implementation with support for composable controllers. Second, we show how this can be formally modeled with Uppaal to check whether an extended system possesses the expected behavior. In particular, we check the interference-freeness of the added controllers. Our approach is illustrated with a running example of an airport service providing internet connection to customers. The example is extended with two controllers. We show how the system and its extensions can be formally modeled and analyzed with Uppaal. A formalization scheme is presented for this purpose. In the example, an interference is detected between the two added controllers and solved with a generic operator. In the paper, only two operators are discussed but others can be defined in a similar way. Our approach can be used at the assembly stage, so that potential interferences are statically detected and solved by choosing the right composition operators. It also can be used at runtime where the system is to be reconfigured. In this case, dynamic reconfigurations causing interferences are cancelled. Using Uppaal, the system can be simulated and potential errors in the system can be checked. When an interference is detected, it is reported to the user with a diagnostic trace that helps to determine the correct composition operator.

The rest of the paper is organized as follows. Section II presents our running example and its architecture. Section III describes the notion of composable controllers and how they can be implemented in Fractal. The description is illustrated with extending the example with two new functionalities. Section IV shows how the approach can be formally modeled in Uppaal, how interferences are detected and solved by instantiating templates of composition operators. Section V compares our approach to related works and section VI concludes and gives perspectives of the approach.

II. Case Study: Airport Internet Access

Our running example is a Fractal application that models an airport service for providing a wireless internet connection[1] [2], [3]. A free Internet access is granted for a limited time to customers owning valid fly tickets. A customer can log with his fly ticket number and use the network.

The Fractal architecture of this application is displayed in Figure 1. The `User` component models a customer in the system. The `User` first, requests an IP address from the `DhcpServer`, then it sends a login request to the

[1] In this article, we present a simplified version of the system (only one kind of customer, `FlyTicketManager` is a primitive component...). A more complete Fractal implementation and Uppaal formalization of the system are available by request to the authors.

SessionManager. Once connected, it sends queries to the AccessManager. The AccessManager forwards users' requests to the Firewall that blocks unauthorized internet connections. The requests of users with enabled IP addresses are actually sent to the net Proxy. The User component has multiple instances (one per customer) as noted with superimposed boxes. The DhcpServer delegates IP address requests to the IpAddressManager that provides dynamic IP address allocation. The allocated IP addresses are managed by the IpDbConnection component. The SessionManager manages sessions. When it receives a login request, its inner Arbitrator component retrieves the authorized access time from the FlyTicketManager, then the SessionManager instantiates a ValidityChecker. The Arbitrator in turn orders the AccessManager to enable communications for the user. When the authorized time elapses the ValidityChecker asks the Arbitrator to close the session. The Arbitrator in turn orders the AccessManager to disable communications for the user, and the DhcpServer to disable its IP address.

III. Component Extension in Fractal

Fractal [1] is a hierarchical component model developed by the OW2 consortium. Fractal supports a set of interesting features such as: component sharing and component behaviors extension through component controllers. Each component in Fractal has a content and a membrane. The content encapsulates the business logic, while the membrane exposes the provided and required interfaces and a set of controllers. Components are connected to each other via bindings. A binding connects a required interface of a component to a provided interface on the assumption that the provided interface type is a sub-type of the required interface type. Fractal provides an architectural description language called Fractal-ADL to describe the architecture of systems in a declarative style.

In Fractal, component behaviors are extended by means of controllers. Extensions can either be installed on: (1) a single component by adding a controller to a primitive component, (2) several components by adding a controller to a composite that encapsulates all the components to be extended. Component sharing enables the application of controllers to components belonging to different composites. A regular Fractal controller intercepts messages sent and received by a component and it can alter them, redirect or even discard them by calling or not a method invoke(). However, without an explicit discard call event, the composition of controllers has to be made in a programmatic and non-modular way by calling one controller from another. Here, we propose to extend Fractal with controllers that make discarding explicit. We call such controllers *composable controllers* and we provide a set of generic operators to compose them.

A. Composable Controller in Fractal

We define a composable controller as a pair (Dispatcher, Act). The Dispatcher is a regular Fractal controller used to intercept service calls, reify them into message objects and pass them to the Act object. An Act object is a regular object implementing the ICController interface (see Listing 1). It implements the behavior of the extension in a match(MessageContext) method. The match method inspects or modifies messages, executes extra codes and finally decides whether the message should actually be proceeded by returning the command Proceed or discarded by returning Skip. The Dispatcher controller calls its method invoke() to proceed the service call only if the Act object returns a Proceed command.

```
1 enum Cmd {Proceed, Skip}
2 interface ICController {
3   Cmd match(MessageContext c);
4 }
```

Listing 1. ICController interface

Like regular controllers, composable controllers can be plugged into components that have to be altered by the controller behavior. When the controller needs to be applied to several components that are scattered over the architecture, the system is reconfigured as follows: a new composite is created and the required components are added to that composite as shared components. This way, the controller is plugged into the new composite and the original configuration is preserved.

In the following, we show how composable controllers can be used to extend the airport service example with (1) adding a bonus time to customers and (2) alert customers five minutes before the end of their sessions.

B. Extension 1: Add a Bonus

Let us suppose that the airport decides to offer a bonus time to first class customers. Such an extension can be done by adding a composable controller with an ICController, named Bonus, to the ValidityChecker.

The Dispatcher controller intercepts service calls to the ITimerCallback interface that defines a timeout service. This service is called by the Timer to inform the ValidityChecker of the end of the session. The Dispatcher intercepts the call, reifies it into a message object and sends it to Bonus by calling its match method. The match method of Bonus behaves as follows: when it receives the first occurrence of timeout (*i.e.* the customer session should be closed), it checks if the customer has a first class ticket. If it is the case, it resets the timer for 10 more minutes (by calling the setTimeout(10) service on the ITimer interface of the corresponding Timer component), and informs the Dispatcher controller that it wants to skip the call by returning a Skip command. That means that the timeout, in this case, is not actually proceeded and the session continues. If it receives a second occurrence of timeout, the match method returns a Proceed command to Dispatcher. This causes the Dispatcher to call its invoke() method which proceeds the call and ends the current session of the user.

In our scenario, the composable controller with the Bonus

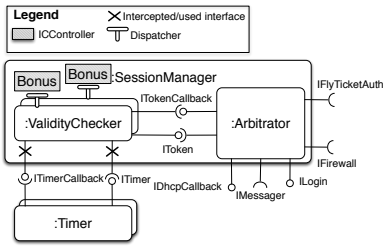

Fig. 2. The airport system extended with `Bonus`

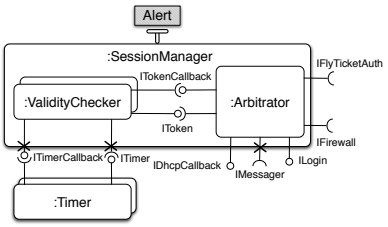

Fig. 3. The airport system extended with `Alert`

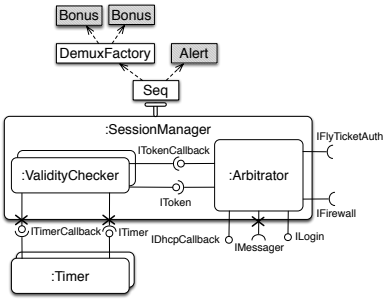

Fig. 4. The default composition of `Bonus` and `Alert` with `Seq`

ICController is attached to each `ValidityChecker` instance. This enables the interception of required services (*i.e.* `timeout` of the `ITimerCallback` interface) and the use of its provided services (*i.e.* `setTimeout` of the `ITimer` interface). Figure 2 shows the architecture of the airport system after the integration of `Bonus`.

C. Extension 2: End Session Alert

Now, suppose that the airport decides to add a service that alerts users five minutes before their authorized time connection expires. In this case, a session timer is initialized with five minutes less than the authorized time. When the time expires and a timeout is generated, an alert is sent to the user and the timer is reset for five more minutes. Here, we propose to integrate a composable controller with an ICController `Alert` that behaves as follows: when the `setTimeout` service call is intercepted on the `ITimer` interface of the `ValidityChecker` component, the `Alert` changes the parameter value of the call (*e.g.,* 60 minutes) by subtracting a time alert (5 minutes), and proceeds the call. Thus, the `ValidityChecker` will receive a `timeout` 5 minutes before the end of the session. When the `timeout` is intercepted, the `Alert` sends an alert message to the user (by calling the `show("you have only 5 min left")` on the `IMessager` interface required by the `Arbitrator`), resets the `Timer` for 5 minutes by calling `setTimeout(5)`[2], and skips the currently intercepted `timeout`. The `Alert` proceeds the next intercepted `timeout` to end the session. Note that the controller, in this case, is plugged into the `SessionManager` composite that encapsulates several instances of `ValidityChecker`(s). Thus, the `Alert` needs to store the identity of the `Timer` triggering the first `timeout` call, so that it can proceed the second triggered `timeout` and ends the right user session. Figure 3 shows the airport system after being extended with `Alert`.

D. Controllers Interferences and Compositions

Extending components with several controllers may give rise to interferences. For better understanding of controller interferences, let us consider the original airport system, its bonus and alert extensions. Let us also assume that the original session duration is 60 minutes, the bonus adds 10 minutes and the alert warns the user 5 minutes before the end of the session.

[2]A controller intercepts only services of the component it controls (*e.g.,* alert does not intercept its own call to *setTimeout(5)*).

When both controllers are plugged into the system, we wish users to get a bonus time and be alerted exactly 5 minutes before the actual end of their sessions (*i.e.* alert at 65 minutes, end of session at 70 minutes).

In our approach, when two controllers intercept common services, the default composition is made using a `Seq` operator. When the `Seq` operator is used and a service call is intercepted, the `match` method of both controllers are called sequentially and the service call is proceeded only if at least one of its underlying `ICControllers` returns `Proceed`, otherwise, `Seq` returns `Skip` to the `Dispatcher`. However, in Section III-B, we plugged an instance of `Bonus` into each instance of `ValidityChecker`, while in Section III-C we introduced a single instance of `Alert` for all the instances of `ValidityChecker` and we plugged it into the `SessionManager` component. In our approach, two controllers can be composed only if they are plugged into the same component which is not the case for `Bonus` and `Alert`. To tackle such a problem, we define an operator `DemuxFactory` that is both a factory of ICController(s) and a demultiplexer responsible for "routing" the intercepted messages to the right instances. In our example, the `DemuxFactory` is responsible for the instantiation of `Bonus` for each `ValidityChecker` instance, and when a `timeout` message is intercepted for a `Timer` instance, the `DemuxFactory` redirects the call to the correspondent `Bonus` instance (*i.e.* the one plugged into the `ValidityChecker` bound to the `Timer` making the call). Figure 4 shows the composition of the above controllers where the white boxes refer to composition operators and gray boxes refer to ICController(s). Note that the composition operators in our proposal also implement the `ICController` interface. This enables our controllers to be composed in a composite pattern way with a single `Dispatcher`.

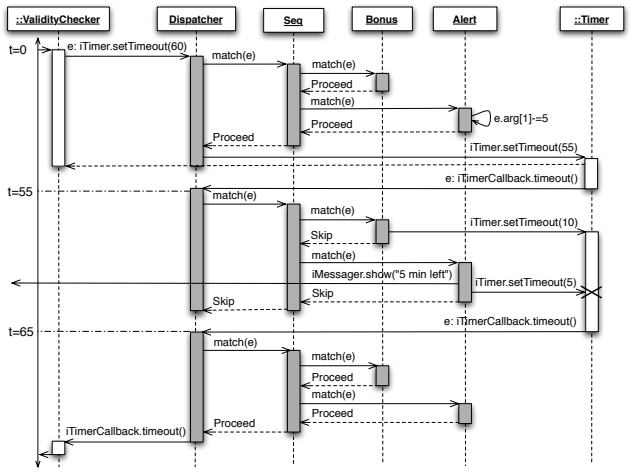

Fig. 5. `Seq(DemuxFactory(Bonus),Alert)` scenario

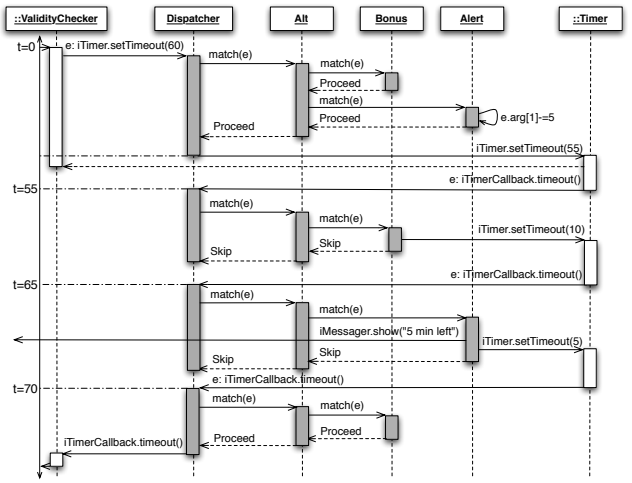

Fig. 6. `Alt(DemuxFactory(Bonus),Alert)` scenario

Figure 5 sketches the `Seq(DemuxFactory(Bonus), Alert)` scenario. At time 0, a user logs in for 60 minutes provided by his fly ticket. The message `setTimeout(60)` sent from a `ValidityChecker` to its `Timer` is intercepted by the `Dispatcher` controller. The `Dispatcher` invokes the `match` method of the `Seq` operator. The `Seq` then calls the `DemuxFactory(Bonus)` that instantiates a `Bonus` and calls its `match` method that proceeds the call (`setTimeout(60)` is not of interest to `Bonus`). The call is then sent to `Alert` that subtracts 5 minutes from 60 and proceeds the call with the new parameter value (55). As a result, the `Dispatcher` calls `setTimeout(55)`. At time 55, a `timeout` is intercepted. The `Dispatcher` invokes again the `match` method of the `Seq`. The `Seq` sends the message to the `DemuxFactory(Bonus)` first, that routs the message to the corresponding `Bonus` instance which resets the timer for 10 minutes and skips the message. Then, the message is sent to `Alert` that warns the user, resets the timer for 5 minutes and skips the message. This violates the expected behavior: the alert is sent too early (at time 55 instead of the expected 65). Moreover, the `Timer` has been set twice with different values and hence it is inconsistent whatever happens next. This is called an interference since the desired behavior is not ensured by the default sequential composition of controllers. To solve this interference, another composition strategy is needed: *the first occurrence of `timeout` should only be managed by `Bonus` and the second occurrence should only be managed by `Alert`*. This strategy can be abstracted with the `Alt` (alternate) composition operator. This binary operator aggregates two `ICController`(s) and a set of intercepted services common to both controllers. When a service common to both controllers is intercepted, its occurrences are passed alternately to the left and the right hand side controllers. When a service is not common to both controllers, the `Alt` operator passes the call to both controllers sequentially and the call is proceeded when both controllers returns `Proceed`, otherwise, the message is skipped. This works since the ICControllers are designed to return `Proceed` for irrelevant calls.

Figure 6 sketches the `Alt(DemuxFactory(Bonus), Alert, {"timeout"})` scenario. At time 0, a user logs in for 60 minutes provided by his fly ticket. The message `setTimeout(60)` sent from a `ValidityChecker` to its `Timer` is intercepted by the `Dispatcher` and sent to `Alt`. The `setTimeout` is not a common intercepted message, so `Alt` sends it first to `DemuxFactory(Bonus)` that instantiates a `Bonus` and calls its `match` method that proceeds the call. Second, `Alt` calls the `match` method of `Alert` that subtracts 5 minutes from 60 and proceeds the call. Since both controllers want to proceed the call, `Alt` returns `Proceed` which causes the `Dispatcher` to call `setTimeout(55)`. At time 55, a `timeout` is intercepted which is a common intercepted message by both controllers. Here, `Alt` sends it only to `DemuxFactory(Bonus)` (first occurrence) that routs it to the corresponding `Bonus` instance which resets the timer for 10 minutes and skips the message. Thus, the `Dispatcher` ignores this `timeout` call. At time 65, a second `timeout` is intercepted. `Alt` sends it only to `Alert` (second occurrence) that warns the user, resets the timer for 5 minutes and skips the message (the `Dispatcher` ignores again the `timeout` call). At time 70, a third `timeout` is intercepted. `Alt` this time, sends it only to `DemuxFactory(Bonus)` (third occurrence) that returns `Proceed`. As a result, the `Dispatcher` calls `timeout` and the session is ended which is the desired behavior.

IV. Formal Verification in Uppaal

Uppaal [4] is a model checker used to design, simulate and verify systems that can be modeled as networks of timed automata. Each timed automaton models a part of the system (*e.g.,* component). A timed automaton is a finite state-machine extended with local variables, data types and clock variables. A clock variable is modeled by float values and all clocks of the same system progress synchronously. An automaton specification is called template and its instantiation is called

process. Besides its time support, other interesting features are also provided by Uppaal. For example, it enables passing data between processes, automatic and multiple instantiation of templates, declaring a set of C functions with loops to be used as transitions guards or state variables assignments. A system in Uppaal is modeled as a parallel composition of timed automata. In Uppaal, properties to be verified are specified in a subset of CTL (computational tree logic). When the verification of a particular property fails, a diagnostic trace is automatically reported by Uppaal. The use of timed automata is important to model the `Timer` component and the timing constraints of our case study. In the following we describe the general modeling process of Fractal components with composable controllers in Uppaal.

A. Formalization of Primitive Components

Each primitive component is modeled as a Uppaal process. Here, we assume that each primitive component comes with its specification in Uppaal with the following notations:

1) each transition label is a concatenation of the component, interface and service identifiers. For example `user_iLogin_login` denotes the *login* service of the `ILogin` interface of the `User` component.
2) a synchronous communication is modeled with a pair of transitions (and the asynchronous communication by a single transition). For example, the synchronous login message is decomposed into `user_iLogin_login` (for call) and `E_user_iLogin_login` (for return).
3) arrays on transition labels are used for passing data between processes. For example, a customer uses his fly ticket number to login and passes it to other processes. This is denoted as: `user_iLogin_login[id]`.
4) parametrized templates are used for automatic instantiation of processes. For example, the `User` template is parametrized with `int[0, FLYTICKET_ID_NB] id` where `FLYTICKET_ID_NB` is a constant that defines the number of users to be instantiated.

For instance, Figure 7 shows a simplified Uppaal template modeling the `User` component[3]. The template can be read clockwise from the initial location. The initial location $S0$ labeled `Disconnected` is distinguished with a double circle. A user first sends its `mac` address to the DHCP server to request an IP address (`requestIpAddress[mac]!`). When it receives an IP address (`requestIpAddress[ip]?`), it stores it in a local variable `ips`, then it requests to login with his fly ticket `id` (`login[id]!`). When he succeeds to login, he requests connections to web addresses (`connect[ips][wips]!`), that can succeed or fail. When it receives a `timeout[id]?`, it returns to the initial location.

B. Formalization of Composite Components

A composite is modeled as a set of Uppaal processes, one for each bound interface. Each template of these processes has

[3]This template has more locations and transitions that are not shown here.

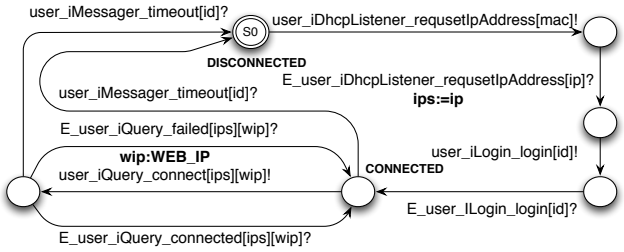

Fig. 7. Formal Model for the `User` Component

a central initial location and a set of directed cycles from and to that location. Each cycle describes one service. Asynchronous services are represented by cycles of two transitions (receives a message, then forwards it). Synchronous services are represented by cycles with four transitions (receives a message, forwards it, waits for the reply, and forwards the reply).

C. Formalization of Bindings

We model component bindings with renaming. The binding of a required interface i of a component c_1 to a provided interface j of a component c_2 is modeled by replacing each transition label occurrence `c1_i_s` in the template of c_1 by `c2_j_s`, for each service name `s`.

D. Formalization of component systems

A component system $\mathcal{B}$ is a tuple $(\mathcal{A}_b, \mathcal{P}_b, Inv_b)$ where:

1) $\mathcal{A}_b$: is the parallel composition of processes modeling primitive and composite components after applying the binding (see Section IV-C).
2) $\mathcal{P}_b$: is a set of CTL formulas describing the behavior of the system.
3) Inv_b: is a subset of $\mathcal{P}_b$ that should always be satisfied even if the system has been extended.

The complete airport system is modeled by 20 templates (9 for primitive components and 11 for composite components' interfaces). The system is designed to satisfy different (liveness, safety, and reachability) properties. These are given at the top of Table I ($\mathcal{P}_{airport}$). In particular, a user can not stay connected forever (*Live 1*), the system is deadlock free (*Safe 1*), a user cannot stay connected more than the validity time indicated in his fly ticket (*Safe 2*), all users can be connected at the same time (*Reach 1*). The formulas rely on different constants, variables and auxiliary functions: `IDS` denotes the range for user identifiers, `Connected` and `Disconnected` are identifiers denoting particular locations of the user process, the `validity(id)` is a global function that returns the authorized connection time of a user `id`, and `cl` is a local clock associated to the user process.

Definition IV.1 *A component system $\mathcal{B} = (\mathcal{A}_b, \mathcal{P}_b, Inv_b)$ is well defined if its modeling process satisfies all its desired properties:*

$$\mathcal{W}(\mathcal{B}) \stackrel{\text{def}}{=} \mathcal{A}_b \models \mathcal{P}_b$$

TABLE I
PROPERTIES OF THE AIRPORT SYSTEM

Properties for the Airport Base System ($\mathcal{P}_{airport}$)	
Live 1	`User(id).Connected --> User(id).Disconnected`
Safe 1	`A[] not deadlock`
Safe 2	`A[] forall(id:IDS) User(id).Connected imply User(id).cl<=validity(id)`
Reach 1	`E<> User(0).Connected and (forall(id:IDS) id!=0 imply User(id).Connected)`
Properties for the Bonus controller ($\mathcal{P}_{bonus}$)	
Safe 2'	`A[] forall(id:IDS) User(id).Connected imply User(id).cl<=validity(id) + BonusTime`
Properties for the Alert controller ($\mathcal{P}_{alert}$)	
Live 2	`Use(id).Connected --> User(id).Disconnected and User(id).isAlerted`
Safe 3	`A[] forall(id:IDS) User(id).Alerted imply User.cl== validity(id) - AlertTime`

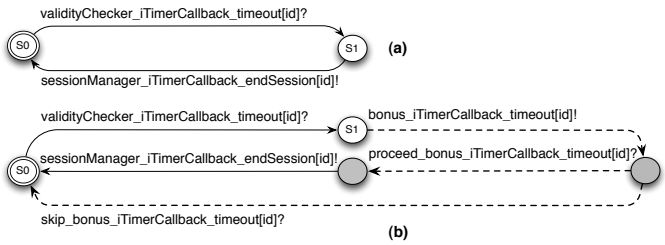

Fig. 8. `ValidityChecker` template adaptation (a) original, (b) adapted

E. Formalization of controllers

Each composable controller of the form `(Dispatcher, ICController)` is modeled in two steps. First, a Uppaal template is generated to model the behavior of the `ICController`. Compared with primitive component templates (see Section IV-A), `proceed_e` and `skip_e` are used as transition labels to denote proceeding and skipping a service call `e`, respectively. Second, the generic `Dispatcher` is modeled by adapting the templates of the components to be affected by the controller. This enables the synchronization of `ICController` process with the controlled components on the services that have to be intercepted. For instance, when a bonus is applied to the `ValidityChecker`, its corresponding template must be adapted as detailed in Figure 8. Part *(a)* shows an excerpt of the original `ValidityChecker` template and part *(b)* shows the same excerpt adapted. As a result, when `timeout` is received, it is forwarded to the bonus controller process. The `ValidityChecker` waits for either `skip` to return to the original location, or `proceed` to forward the `timeout` to the `SessionManager` component.

In addition to the above specification, a set of intrinsic properties the controller ensures when it is applied to the system should be given. The properties for the bonus ($\mathcal{P}_{bonus}$) and the alert ($\mathcal{P}_{alert}$) controllers are shown in the middle and bottom part of Table I, respectively. The bonus controller ensures that the user can stay connected a bonus time (`BonusTime`) after its authorized time expires (Safe 2'). While the alert ensures that the user is always alerted before it is disconnected (Live 2) and the alert is intercepted exactly before a `TimeAlert` of its expiration time (Safe 3). In the formulas, `Alerted` is an identifier denoting a particular location in the user process, `isAlerted` is a local boolean variable of the user indicating whether a user reached the `Alerted` location, and `BonusTime` and `AlertTime` are constants denoting the bonus and the alert time, respectively.

Definition IV.2 *Given a component system $\mathcal{B} = (\mathcal{A}_b, \mathcal{P}_b, Inv_b)$ and a composable controller $\mathcal{CC} = (\mathcal{A}_{cc}, \mathcal{P}_{cc})$ where, $\mathcal{A}_{cc}$ is the process modeling the controller behavior, and $\mathcal{P}_{cc}$ is the set of its intrinsic properties. A composable controller is said to be correct with respect to a component system $\mathcal{B}$ if the following condition holds:*

$$\mathcal{A}'_b \| \mathcal{A}_{cc} \models Inv_b \wedge \mathcal{P}_{cc}$$

Where $\|$ denotes the parallel composition of processes and $\mathcal{A}'_b$ is the parallel composition of the $\mathcal{B}$ processes after adapting the templates modeling the components affected by $\mathcal{CC}$.

For our case study, when the bonus is applied to the airport system, the invariant is defined by all the $\mathcal{P}_{airport}$ properties except (Safe 2), since bonus allows the user to connect for more than the time indicated in his fly ticket (see Safe 2'). While in the case of alert the invariant is simply $\mathcal{P}_{airport}$.

F. Formalization of Composition Operators

A composition operator is defined as a template to be instantiated. For instance, Figure 9 details the template for the alternate operator `Alt`. In the figure, when a service call is intercepted (`e?`), the function `swap()` is executed. This latter maintains a boolean `isLeft` to indicate which controller should be applied. If it is the left-hand side controller turn (`isLeft`), `e` is forwarded to this controller (`cc1_e!`), otherwise, `e` is forwarded to the right-hand side controller (`cc2_e!`). In both cases, the operator waits for either `proceed_cci_e` or `skip_cci_e` and forwards the intercepted command to the caller (`proceed_e` or `skip_e`).

The template is instantiated by substituting `e` with the service to be intercepted (*e.g.,* `ITimerCallback_timeout`), `cc1` with the identity of the first controller (*e.g.,* `bonus`), and `cc2` with the identity of the second controller (*e.g.,* `alert`). These substitutions synchronize the composition operator process with its underlying controllers.

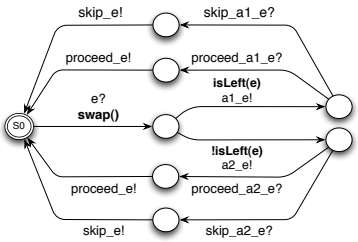

Fig. 9. The `Alt` template

G. Interference detection and resolution

For interferences detection, two composable controllers are interference-free with respect to a base program, if: (1) each composable controller is correct with respect to the base program, (2) when both composable controllers are added to the system, the result process satisfies all the properties of the underlying controllers and the system invariant. Formally:

Definition IV.3 *Given a base system* $\mathcal{B} = (\mathcal{A}_b, \mathcal{P}_b, Inv_b)$ *and two composable controllers* $\mathcal{CC}_1 = (\mathcal{A}_{cc_1}, \mathcal{P}_{cc_1})$, $\mathcal{CC}_2 = (\mathcal{A}_{cc_2}, \mathcal{P}_{cc_2})$, $\mathcal{CC}_1$ *and* $\mathcal{CC}_2$ *are interference-free if the following conditions hold:*

1) $\mathcal{W}(\mathcal{B})$ *: the base system is well defined*
2) $\mathcal{A}'_b \| \mathcal{A}_{cc_1} \models Inv_b \wedge \mathcal{P}_{cc_1}$ *:* $\mathcal{CC}_1$ *is correct w.r.t* $\mathcal{B}$
3) $\mathcal{A}''_b \| \mathcal{A}_{cc_2} \models Inv_b \wedge \mathcal{P}_{cc_2}$ *:* $\mathcal{CC}_2$ *is correct w.r.t* $\mathcal{B}$
4) $\mathcal{A}'''_b \| \mathcal{A}_{cc_1} \| \mathcal{A}_{cc_2} \models Inv_b \wedge \mathcal{P}_{cc_1} \wedge \mathcal{P}_{cc_2}$ *: the composition is correct w.r.t* $\mathcal{B}$

Where $\mathcal{A}'_b$, $\mathcal{A}''_b$ and $\mathcal{A}'''_b$, denote the parallel composition of $\mathcal{B}$ processes after adapting the templates affected by $\mathcal{CC}_1$, $\mathcal{CC}_2$, and $\mathcal{CC}_1$ and $\mathcal{CC}_2$, respectively.

In our case study, when both bonus and alert are added to the system and composed with the default composition operator `Seq` (by instantiating its correspondent template), Safe 3 property is violated which reports an interference with a diagnostic trace. After analyzing the reported trace, we decided to use the `Alt` operator that solved the problem. In general, a composition operator solves an interference if when it is instantiated for two controllers and composed to the system, the interference disappears. Formally:

Definition IV.4 *Given a base system* $\mathcal{B} = (\mathcal{A}_b, \mathcal{P}_b, Inv_b)$ *and two interfering controllers* $\mathcal{CC}_1 = (\mathcal{A}_{cc_1}, \mathcal{P}_{cc_1})$, $\mathcal{CC}_2 = (\mathcal{A}_{cc_2}, \mathcal{P}_{cc_2})$, *a composition operator* Op *solves an interferences if the following condition hold:*

$$\mathcal{A}'_b \| Op(\mathcal{CC}_1, \mathcal{CC}_2) \models Inv_b \wedge \mathcal{P}_{cc_1} \wedge \mathcal{P}_{cc_2}$$

where $Op(\mathcal{CC}_1, \mathcal{CC}_2)$ denotes the parallel composition of the processes of $\mathcal{CC}_1$ and $\mathcal{CC}_2$ and the instantiated template Op for $\mathcal{CC}_1$ and $\mathcal{CC}_2$ as described in Section IV-F.

We should mention here that our example is a large case study. It is instantiated with three users for the base system and two users for the extended version. The instantiation of the system with more users leads to state explosion in UPPAAL. However, in our example, merely one user is enough to detect the interference of `Bonus` and `Alert`.

V. Related Work

Our work can be compared with two categories of works: extending components with aspect-orientation and aspect and feature interactions.

Extending Components with Aspects There are several aspect oriented extensions to Fractal. FAC [5], Fractal-AOP [6], and Safran [7] extend Fractal with aspects. In FAC an aspect is not a controller but several components. The application of an aspect to several components is achieved by creating a so called *aspect domain*. This latter, encapsulates all the components to be managed by the aspect and the components modeling the aspect itself. Fractal-AOP is quite similar to FAC but it provides an explicit controller interface *Proceed* to execute the original services. Safran focuses on adaptation: it proposes to insert a component to intercept service calls instead of their original targets, it executes the adaptation strategy and it possibly proceeds the calls. The main drawback of these approaches is that the extensions (*i.e.* aspects) are composed in a programmatic way (there are no predefined operators and `skip` is implicit). In addition, no interference detection support is provided.

Other component models have also been extended with aspects. The PRISMA framework [8] comes with an architecture language PRISMA AOADL to define where the extensions should be applied to the system. Aspects are defined as separate architectural elements. However, users are responsible to detect potential interferences among aspects and when one is detected the only composition strategy provided by the model is sequential ordering. LEDA is another component framework and AspectLEDA [9] is its extension with aspects. Aspect behaviors are represented by regular LEDA components. Aspect execution is ordered following a predefined priority order. In particular, JAsCo [10] is not a hierarchical component model and it provides an API to compose aspects in a programmatic way. But no interference detection support is provided.

Interference detection and resolution Interference detection and resolution is still a challenge for features [11] and aspects [12]. Current works on features are focussing on domain specific interferences. For example, Gouya et al. [13] propose an algorithm for feature interactions in IP multimedia subsystem (IMS). The algorithm uses a predefined interference rules based upon traces on service calls. Some of these interferences with their solutions are defined in a database, if the interference is not in the database, it is reported to the user. Goldman et al. [14] is the closest related work with respect to our formal verification approach. They model the base program, the aspects, and the woven system with state machines in order to formally check properties. Their weaving process is implemented by inlining the aspect state machine directly in the base system. Moreover, they focus on LTL and use two kinds of properties. First, they check if the base system satisfies aspect assumptions that enable their weaving. Second, they check if the woven system guarantees the expected behavior of the aspect. They weave

an aspect at a time. When an interference is detected (*i.e.* a property is not satisfied) the programmer is responsible to fix it: they do not provide composition operators. Note that they only consider weakly invasive aspects. Krishnamurthi et al. [15] also use state machines to model both aspects and base systems. However, the proposed approach defines a state machine for each advice. Moreover, the work is limited to treat aspects that do not modify data variables of base systems. Temporal logic as previously been used by Katz et al. [16] to describe the expected behavior of aspects. In this work, a semi-automatic interactive process is proposed to define the assume-guarantee properties of aspects in LTL formulas. Aspect interferences are checked independently of any base system by checking their guaranties properties. At the weaving stage, another check should be performed to show if the base system satisfies the assumptions of all the aspects to be woven. In [17] advices are annotated with assumptions about their composition. Interferences are detected by matching the assumptions of an advice and all the other advices. However, these approaches focus only on interference detection at shared joinpoints. Our experience shows that controllers may interfere even if they are not applied to common components [18]. Our current proposal is a byproduct of our previous work on aspect interference detection and resolution [19] and formalization of aspects in a concurrent context [20]. The first work focuses on interferences at shared joinpoints and introduces composition operators. The second models the woven system as FSP processes and checks properties with LTSA.

VI. Conclusion and Future work

In this article we have shown how to extend Fractal with composable controllers. Our controllers with explicit actions (proceed and skip) are easily combined with composition operators. Composition is not restricted to ordering controllers and it is not restricted to controllers intercepting common services (*e.g.,* `Alert` intercepts `setTimeout` but `Bonus` does not). In fact, two controllers with no common intercepted services can be composed together. For instance, an ICController $\mathcal{CC}_1$ (that maintains a predicate) and an ICController $\mathcal{CC}_2$ could be composed with a `Cond` operator that calls the `match` method of $\mathcal{CC}_2$ only if the condition holds. In particular, the composition `Cond(Overload,Bonus)` would add bonus times only when the server is not overloaded. Note that, other operators can also be developed in a similar way. Take for example, the operator `And` that calls the second ICController only when the first one proceeds the call, or the `Xor` that calls the second only when the first skips the call. We have also shown how Fractal components and composable controllers can be formally modeled in Uppaal. This way, the properties of the extended system can be checked and traces violating properties help to select the right composition operator.

Our proposal is currently partly supported by tools. The introduction of controllers is fully automated: our tool parses VIL expressions [18] that define the components to be controlled and the services to be intercepted in a declarative style. Then, it transforms accordingly the Fractal ADL definition by introducing controllers and new composites of shared components if the required ones are scattered in the original architecture. The `Dispatcher` and different composition operators are also implemented. In this article we have identified the transformation scheme required to produce a Uppaal model of the complete extended system. We believe that some parts of the scheme can be automated such as the generation of composites and bindings from Fractal-ADL. We plan to develop such an Uppaal transformer.

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