A formal approach for correct-by-construction system substitution

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Abstract—The substitution of a system with another one may occur in several situations like system adaptation, system failure management, system resilience, system reconfiguration, etc. It consists in replacing a running system by another one when given conditions hold. This contribution summarizes our proposal to define a formal setting for proving the correctness of system substitution. It relies on refinement and on the Event-B method.

Keywords: system substitution, state recovery, correct-by-construction, Event-B, refinement

I. MOTIVATION

Several efforts were devoted to the formal development of complex systems. Different formal approaches have been defined, they led to numerous system developments in real life applications like transportation systems, web applications, information and data management, etc.

One of the major concerns in system development relates to the substitutability of a system by another one. This capability can be seen throughout different concerns. Among these ones we are mainly interested in two of them: functional and behavioural concerns.

1) The functional concern deals with the function of the system i.e. what it does. We have identified three main substitutions:
   - a system may be replaced by an equivalent one;
   - a system may be degraded i.e. replaced by a system achieving less functions, the problem being to identify that the critical ones are still achieved;
   - a system may be upgraded i.e. replaced by a system achieving more functions.

The functional concern relates to the preservation of the functions of the substituted system by the substitute one. This preservation is studied through property verification. Classical formal verification techniques guarantee that the substituted and the substitute systems refine the same specification.

2) The behavioural concern deals with the behaviour of a system in terms of execution sequences. We have identified two main substitutions:
   - a system may be replaced at a given state by another system recovering this state and pursuing the execution of the system from this recovered state. This corresponds to a warm start or hot start substitution.

Through these concerns several properties like dependability [1], adaptation [2] [3], resilience, self-healing systems [4], loss of QoS can be addressed.

System substitution is performed when an event requiring this change occurs. In several cases, this event is (or these events are) triggered by monitors in case of monitored systems, or by evaluating a given situation in autonomous systems (self-* systems).

This paper overviews the formal approach we propose to handle system substitutions.

II. OUR APPROACH

In the following, we consider systems that are expressed as states and transitions describing state changes. Our approach is a correct-by-construction one, it relies on refinement and on the Event-B method [5] [6] [7] [8]. It addresses system substitution and covers both concerns, functional and behavioural.

A. The functional concern: refinement

Refinement relates an abstract system to a concrete one. The refined concrete system preserves the properties of the abstract one. Both of the three identified cases of the functional concern may be encoded by refinement. Indeed, several concrete representations of a given specification can be given at different abstraction levels, linked by a refinement relationship. Invariants represent the key feature for describing equivalent, degraded or upgraded systems.

B. The behavioural concern: refinement and variants

Once the functional concern has been addressed, it becomes possible to assert that a system may substitute another one in one of the three identified cases above. When a system runs, one obvious substitution case corresponds to a re-start of the substitute system. But, when the sequence of system running states is recorded, one may identify correlations between the states of the substitute system and the current state of the substituted system. Our proposal is to use explicit variants...
to identify the substitution state and invariants to express such state correlation. Indeed, variants describe the sequence of running states. Correspondences between states of the substituted and of the substitute system are expressed by the variant values. Invariants define properties between the states of both systems, enabling the copy of the substituted state variables to the substitute state variables.

C. Why Event-B ?

The Event-B method is set-up in order to formalise our approach. Event-B is a state-based method that promotes correct-by-construction development paradigm and formal verification by theorem proving. Indeed, Event-B supports the definition of state-based systems where transitions recording state changes are encoded by events. Moreover, it offers the capability to explicitly express variants and invariants, and to build systems using refinements.

1) Event-B refinement for the functional concern: a top level machine, representing the main function(s) of a system may be refined by one or more other machines leading to different concrete system designs. All the obtained machines are possible system substitutes.

2) Event-B refinement and variants for the behavioural concern: it is possible to link two substitute systems of the same system into a single refinement. The idea consists in linking these two substitutes with a property establishing a relation between the state variables of one substitute system

The following Event-B fragment results from the previously described model.

- **Variables** defines the carrier set containing all the system variables
- **Values** is the carrier set of the values of the variables
- **VariablesSets** = \( P(\text{Variables}) \) a set of sets of variables to identify the variables of each system (partition)
- **Valuations** = Variables \( \rightarrow \) Values functions that give the value of a variable
- **Systems** = VariablesSets \( \times \) (Valuations \( \rightarrow \) N) a system is a pair composed of a group of variables and a variant function
- **Systems_states** = Systems \( \times \) Valuations: all the states of the systems, i.e. pairs (system – variables values)

IV. CASE STUDY

To illustrate our approach a case study issued from electronic commerce is shown. We consider an online purchase of goods composed of four steps: selection of goods by filling a cart, payment, billing and delivery. Solely the selection step is detailed below. Moreover, for this case study, we consider that a failure may occur while the client is filling his cart with goods during the selection step. Failure is the event that triggers system substitution.

Setting up our approach led to the following steps.

A. Functional concern

- an upper model level with an abstract selection of a set of goods in a cart has been designed (corresponding to the Event-B machine \( M1 \));
- a first basic selection system (Sys1) composed of one cart located on a website, has been created by refining \( M1 \) (machine \( M11 \));
- a second basic selection system (Sys2) composed of two carts located on different websites, without failures, has been created by refining \( M1 \) (machine \( M12 \));
- a system composed of the previous ones. The used system is chosen at initialisation (machine \( M13 \) refining \( M1 \)).

B. Behavioural concern

- The first step towards handling the behavioural concern was the creation of an abstract selection feature, refining \( M1 \) and introducing the possibility to switch from Sys1 to its substitute Sys2 . Here, we detail the switching process only. (Machine \( M14 \))
- **Cold start.** \( M14 \) is refined, by defining a mechanism that substitutes Sys1 by Sys2 with a reinitialisation on the
TABLE I

| Event-B Machine | Total PO | Automatic proof | Interactive proof |
|-----------------|----------|----------------|------------------|
| M1              | 31       | 27             | 4 (13%)          |
| M11             | 28       | 27             | 1 (4%)           |
| M12             | 57       | 56             | 1 (2%)           |
| M13             | 99       | 97             | 2 (2%)           |
| M14             | 133      | 129            | 4 (3%)           |
| M141            | 230      | 214            | 16 (7%)          |
| Generic model   | 37       | 28             | 9 (24%)          |
| Instanciation   | 53       | 39             | 14 (26%)         |

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initial state of Sys2. The event triggering the substitution re-initialises Sys2 from its initial state. (Machine M14)
- Hot or Warm start. M14 is refined to a machine where Sys1 is substituted by Sys2 with preservation of the previous Sys1 executions. The event that triggers the substitution restores the current state of Sys2 to a state that functionally matches with Sys1 state before substitution. By functionally, we mean that there is no selected goods of Sys1 cart that are lost. (Machine M142)

C. Instanciation of the generic model

We instantiated our model, according to the previously overviewed generic model, with the following definitions.
- Variables = \{C1, C2a, C2b\} corresponding to the carts. C1 for Sys1 and C2a, C2b for Sys2;
- ValueElements = \{Prod1, Prod2, Prod3, Prod4, Prod5\} is the set of goods;
- Valuations = \{(C1) → P(ValueElements)\} ∪ \{(C2a, C2b) → P(ValueElements)\} associates a subset of goods to each cart;
- VariablesSets = \{\{C1\}, \{C2a, C2b\}\} identifies the variables of each system Sys1 and Sys2;
- Sys1 = \{C1\} → (\text{val} \cdot \text{val} ∈ \{C1\} → \mathcal{P}(\text{ValueElements}) | \text{card}(\text{ValueElements}) − \text{card}(\text{val}(C1)));
- Sys2 = \{C2a, C2b\} → (\text{val} \cdot \text{val} ∈ \{C2a, C2b\} → \mathcal{P}(\text{ValueElements}) | \text{card}(\text{ValueElements}) − \text{card}(\text{val}(C2a) ∪ \text{val}(C2b)));
- Systems = \{Sys1, Sys2\};
- Systems_states = Systems × Valuations

We were then able to refine this machine with one expressing directly C1, C2a and C2b carts, and prove the refinement. Moreover, the following safety properties have been proved on each of the machines.
- All the desired products are selected after the selection action. If P ⊆ PRODUCTS is the set of products to purchase, and carts ∈ SITES × PRODUCTS is the variable denoting the pair of selected products on a given website. This property is expressed as
  \(\text{selection\_done} ⇒ \text{ran}(\text{carts}) = P\)
- There is no product selected twice i.e. no product in both of the two carts, expressed as \(∀p, p ∈ \text{ran}(\text{carts}) ⇒ \text{card}(\text{carts}^{-1}\{[p]\}) = 1\)

Here, the horizontal invariant is val(C1) = val(C2a) ∪ val(C2b), where val is the corresponding valuation.

This generic model together with this case study have been modelled on the Rodin platform \cite{9} \cite{10} and the statistics of table \[I\] (proof obligations PO) have been obtained.

V. ONGOING WORK

This paper presented a global view of our approach for system substitution. This approach exploits the notion of refinement, invariants and variants. System substitution has been illustrated with a use case from electronic commerce.

Currently, our work is pursued in two directions. On the one hand, we are building a generic model for system substitution formalised within the Event-B method. A set of generic machines, to be instantiated, defining system substitution is under construction. It is planned to study within this framework adaptation, self-healing, reliability, ... situations. On the other hand, we plan to integrate a monitor in order to monitor a property of the system behaviour and trigger system substitution. For example, monitored properties could be identification of system failures or loss of quality of service.

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