A CONCEPTUAL SCHEME FOR COMPOSITIONAL MODEL–CHECKING VERIFICATION OF CRITICAL COMMUNICATING SYSTEMS

Luis E. Mendoza Morales[1], Manuel I. Capel Tuñón[2], María A. Pérez[1] and Kawtar Benghazi Ahklaki[2]

[1]*Processes and Systems Department, Simón Bolívar University, PO Box 89000, Caracas 1080-A, Venezuela*

[2]*Software Engineering Department, University of Granada, Aynadamar Campus, 18071 Granada, Spain*

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Abstract: When we build complex business and communication systems, the question worth to be answered: How can we guarantee that the target system meets its specification? Ensuring the correctness of large systems becomes more complex when we consider that their behaviour is the result of the concurrent execution of many components. This article presents a compositional verification scheme, that integrates MEDISTAM–RT (Spanish acronym of *Method for System Design based on Analytic Transformation of Real-Time Models*), which is formally supported by state–of–the–art Model–Checking tools. To facilitate and guarantee the verification of large systems, the proposed scheme uses CCTL temporal logic as the *property specification* formal language, in which temporal properties required to any system execution are specified. In its turn, CSP+T formal language is used to formally describe a *model of the system* being verified, which is made up of a set of communicating processes detailing specific atomic–tasks of the system. In order to show a practical use of the proposed conceptual scheme, the critical part of a realistic industry project related to mobile phone communication is discussed.

1 INTRODUCTION

Nowadays, computer systems are used in almost all realms of human life. The term *pervasive systems* has become popular when we are talking about the human–computer interaction in which information processing has been thoroughly integrated into everyday business and activities. There are systems, such as the ones related with electronic commerce, telephonic nets, train control and air traffic control, in which a failure is unacceptable. Thus, the reliability of this kind of system should be guaranteed. Design and verification methods have been developed over recent years to give a response to this non–functional requirement and for guaranteeing their correctness.

In order to contribute to the achievement of this objective, a compositional verification scheme that integrates MEDISTAM–RT —Spanish acronym of *Method for System Design based on Analytic Transformation of Real–Time Models*— (Benghazi et al., 2007) is presented in this paper, which can be proved as a sound verification approach since it is based on the formal aspects of Model–Checking (MC). The integration is attained by using two formalisms that are under the same formal semantics of *Kripke structures*[1]: CCTL for temporal properties and CSP+T for system processes formal specification. To show the usefulness of our proposal, the application of the verification scheme is presented by means of a case study that has critical temporal requirements.

Thanks to the compositionality that present the aforementioned specification languages and a possible common interpretation, semantically compatible, of the models they describe, state–of–the–art MC tools can be incorporated to facilitate the verification of some complex software systems.

Similar works about combining compositional verification and MC can be found in the literature. Some of these (Clarke et al., 1989; Grumberg and Long, 1991; Bultan et al., 1996) use the composi-

[1]Called also a transition graph, consists of a set of states, a set of transitions between states, and a function that labels each state with a set of properties that are true in this state (Clarke et al., 2000).

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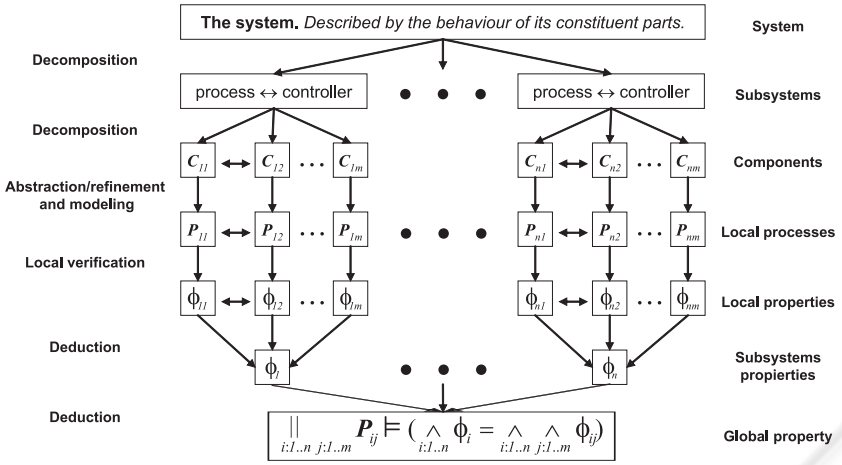


Figure 1: The proposed compositional verification scheme. Adapted from (Mendoza and Capel, 2007).

tional capacity of temporal logics to address the complex software systems verification problem. Whereas others, such as (Giese et al., 2003; Yeh and Young, 1991), take advantage of the process algebra operators to allow the checking of the system behaviour with respect to its predefined properties. Differently from other research, our work is aimed at giving a systemic, integrated vision of analysis, design and verification tasks, by incorporating the use of MC tools in the system development cycle within a compositional verification framework so as to allow the verification of the complete system design.

The paper is organized as it follows. In the next section, we give a brief description of our compositional verification scheme and MEDISTAM–RT design method. Then, we give the formal framework (CCTL and CSP+T) used in the MC technique integrated into the scheme. Afterwards, we establish how CCTL and CSP+T are combined into the MC technique. Finally, we apply our proposal to a real project related to mobile phone communication. The last section gives our conclusions and discusses future work.

2 INTEGRATED ELEMENTS

2.1 Compositional Verification

In order to mitigate complexity, modular software development makes use of *system decomposition* and *abstraction/refinement* concepts. Every module, or more accurately, each system component, is individually verified, and its results are *deductively* combined to obtain the system global characteristics. Moreover, the behaviour of the entire system can be derived from descriptions of system components (Lukoschus, 2005; Mendoza and Capel, 2007), it being unnecessary to take into account any other information about modules or components' internal structures (*black box* principle (Lukoschus, 2005)). Figure 1 shows the proposed compositional scheme.

Decomposition. The initial division of the system into smaller modelling entities is gradually performed until the smallest possible entity's level is reached, which corresponds to capsules (according to UML–RT[2]).

Abstraction, Refinement and Modelling. Each subsystem or component needs to be modelled at the correct abstraction level. These models should be as abstract as possible, but keeping the details needed to infer the properties of their observable behaviour. The described compositional approach ought to be able to conciliate both apparently opposing descriptions of system's components (the rather abstract structural view and the behavioural one).

Local Verification. Every system component should be tested against its formal specification. This step can be automatically carried out by using MC.

Deduction. In order to check the global system properties, the local processes specifications are composed by using the laws of process algebra and CSP+T operators. The properties specification, by using logical conjunction operators, see Figure 1. Hence, the complete system verification is achieved by taking advantage of the CSP+T (Žic, 1994) and

[2]An extension to UML which adds four new building blocks to the standard UML: capsules, ports, protocols, and connectors (Selic and Rumbaugh, 1998).

CCTL (Rüf and Kropf, 1997) compositional capacities with the use of deductive techniques (Lukoschus, 2005).

2.2 MEDISTAM–RT

With MEDISTAM–RT we can perform the specification of the structural and behavioral aspects of RTSs systematically (Benghazi et al., 2007). These two different viewpoints of a system are usually attained in UML–RT by using class and composite structure diagrams, and by using state machine diagrams, respectively. We apply a transformational method, based on a proposed set of transformation rules (Benghazi et al., 2007), which allow us to create a CSP+T model from a UML–RT analysis model of a given RTS. As can be seen in Figure 2, MEDISTAM–RT is divided into two main phases: the first one (top–down modelling process) to model the system using UML–RT, while the second one (bottom-up specification process) obtains the formal specification in CSP+T by the transformation of each UML–RT submodel.

2.3 Formal Framework

2.3.1 CCTL

Clocked Computation Tree Logic (CCTL) (Rüf and Kropf, 1997) is a temporal logic extending CTL (Clarke et al., 2000) with quantitative bounded temporal operators. CCTL is used to reason with sequences of states, where a state gives a time interpretation of atomic propositions at a certain time instant and time is isomorphic to the set of non–negative integers. See (Rüf and Kropf, 1997) for more details.

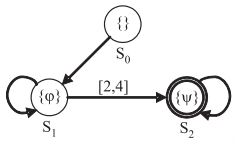
CCTL includes the CTL with the operators *until* (U) and the operator *next* (X) and other derived operators in LTL, such as R, B, C and S, useful to facilitate RTS properties specification. All "LTL-like" temporal operators are preceded by a run quantifier (A universal, E existential) which determines whether the temporal operator must be interpreted over one run (existential quantification) or over every run (universal quantification) starting in the actual configuration, see (Rüf and Kropf, 1997) for details. In the Table 1 can be seen a textual description of some temporal operators usually deployed in CCTL specifications.

Interval logics allow us to carry out a logical reasoning at the level of time intervals, instead of instants. Within our approach, the basic model for understanding RTS is the *interval structure*[3] Because

[3]A state transition system with labelled transitions, assuming that every interval structure has exactly one clock for the measure of time (Rüf and Kropf, 1997).

Table 1: Informal description of the temporal operators. φ and ψ are arbitrary CCTL formulae, and $a \in \mathbb{N}$ and $b \in \mathbb{N} \cup \{\infty\}$ are time bounds.

$X_{[a]}\varphi$	The formula φ has to hold after exactly the time a.
$F_{[a,b]}\varphi$	The formula φ has to hold at least once within the interval $[a,b]$.
$G_{[a,b]}\varphi$	The formula φ has to hold at all time of the interval $[a,b]$.
$\varphi U_{[a,b]}\psi$	The formula ψ has to become true within the interval $[a,b]$ and all time steps before, the formula φ has to be valid.



$\varphi U_{[2,4]}\psi$

Figure 3: Kripke structure example of a CCTL formula.

the CCTL MC algorithms represent sets of states and transitions, we need to operate on entire sets rather than on individual states and transitions.

Temporal logic MC takes a structure (representing the system property) which is unwound into a model and a formula, and automatically checks if the structure (model) meets the specification (formula). The fundamental structures are *timed Kripke structures* (unit–delay, temporal) (Clarke et al., 2000); i.e., the model checker determines whether the Kripke structure is a model of the formula. Figure 3 shows a graphical example (a Büchi automaton (Alur and Dill, 1994)) of the Kripke structure a CCTL formula.

2.3.2 CSP+T

CSP+T (Žic, 1994) is a real–time specification language which extends Communicating Sequential Processes (CSP) (Roscoe, 1997) to allow the description of complex event timings, from within a single sequential process, of use in the behavioural specification of RTS. CSP+T is a superset of CSP, as a major change to the latter, the traces of events are now *pairs* denoted as $t.e$, where t is the global *absolute* time at which event e is observed. The operators, related with timing and enabling–intervals included in CSP+T are: (a) the special process instantiation event denoted $\star$ (star); (b) the time capture operator ($\bowtie$) associated to the time stamp function $a_e = s(e)$ that allows storing in a variable a (marker variable) the occurrence time of an event e (marker event) when it occurs; and (c) the event–enabling interval $\mathrm{I}(T,t_1).a$, representing timed refinements of the *untimed* system behaviour and facilitates the specification and proof of temporal

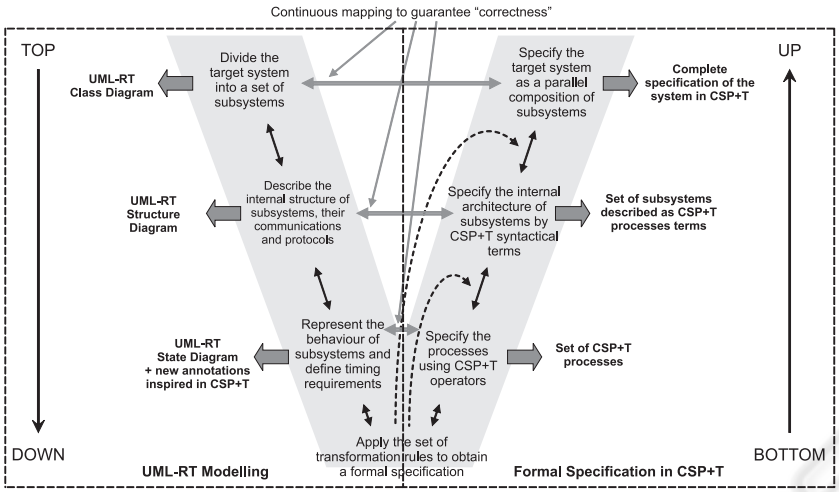
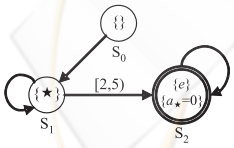


Figure 2: MEDISTAM–RT structure (Benghazi et al., 2007).

system properties (Žic, 1994).

CSP is a formal specification language that allows descriptions of a process' behaviour in terms of the set of observed events sequences (traces semantic[4]) (Roscoe, 1997). The set of all traces associated to process P, $traces(P)$, is denoted as $\tau(P)$ and uses several notions of process refinement[5] ($\sqsubseteq$). These ideas can be extended automatically to CSP+T, because CSP+T proposes some extensions to the traces model which would allow the description of process timing properties (Žic, 1994).

CSP or CSP+T MC tools takes a process (representing the system implementation), and automatically checks whether the process fulfils the system specification. Büchi automata (Alur and Dill, 1994) have emerged as formal models derived from Kripke structures (Clarke et al., 2000) to allow the analysis and verification of system behaviour. A variant of these are *timed Büchi automata* (TBA), see Figure 4, which are able to describe the time at which events happen on any system run and the temporal properties holding in the next possible set of system states.



$$P = 0.\star \rightarrow \mathrm{I}(2,3).e \rightarrow S_2$$

$$\text{where: } \begin{cases} a_\star = s(\star) = 0 \\ \{e\} \equiv occur(e) \end{cases}$$

Figure 4: Kripke structure example of a CSP+T process term.

[4]A trace is just a finite sequence of events, which may be observed when a process is executing (Roscoe, 1997).

[5]Since A and B are processes, we say that A *refines* B, i.e., $B \sqsubseteq A$, when process A is more deterministic than process B, i.e., $traces(A) \subseteq traces(B)$ (Roscoe, 1997).

3 OUR INTEGRATED VIEW OF VERIFICATION

Figure 5 is a graphical summary of how the MC concepts support the integration of MEDISTAM–RT, UML–RT, CSP+T, and CCTL, into the compositional verification scheme.

As we can observe in section 2.1, to perform the system verification we need the specification of the local processes that implement the system's behaviour, as well as the specification of properties that these have to satisfy. Both the description of the system and the specification of its properties must be oriented by the system's requirements.

The complete description of the system's behaviour is obtained as result of using MEDISTAM–

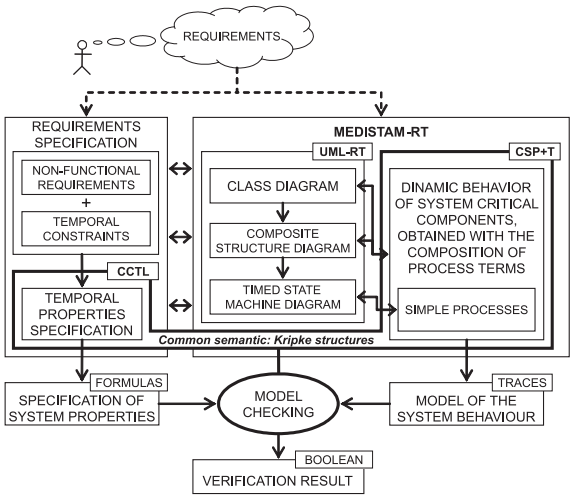


Figure 5: Integrated view according to our compositional verification scheme.

RT. A series of system views represented by class diagrams, composition structure diagrams and state–machines are obtained when the concepts of decomposition, abstraction/refinement and modelling, following the alignments of UML–RT, are applied. After that, these views are specified through CSP+T process terms, which share a refinement and satisfaction relationship equivalent to the one existing between UML–RT diagrams. To have a better detail of this relationship, review the work in (Mendoza et al., 2007; Mendoza and Capel, 2007).

In parallel to the above described process, the non-functional requirements and temporal constraints that the system must fulfill are specified with CCTL formulas.

Once the CSP+T process terms and the CCTL formulas are obtained, we can proceed to the system's verification in the same semantic domain given by Kripke's structures. As you can see in the Figures 3 and 4, we can translate a CCTL formula and a CSP+T process term to a graphical Kripke structure (i.e., a Büchi automaton) that allow to compare these specifications. By using MC tools it is possible to check whether CSP+T process terms (which constitute a possible model of the system under development) satisfy the expected temporal behaviour of the system specification given by CCTL formulas (system's properties). As result, we obtain the verification of local system processes through the interpretation of boolean expressions (*True*, *False*).

Formally, it is possible to assure and get the complete verification of the system by using the relationship[6]:

$$\Big\|_{i:1\ldots n} \Big\|_{j:1\ldots m} P_{ij} \models \bigwedge_{i:1\ldots n} \bigwedge_{j:1\ldots m} \phi_{ij} \qquad (1)$$

4 CASE STUDY

A way to validate a scheme's applicability and consistency is by applying it to a case study. To this end, we selected a real project related to mobile phone communication. The aim was the verification of an application whose estimated daily transaction volume is in the order of millions. The case study is related to monitoring the state of cell sites[7] (CSs). A CS is composed of a tower or other elevated structure for mounting antennas, and one or more sets of transmitter/receivers transceivers, digital signal processors, control electronics, a GPS receiver for timing, regular and backup electrical power sources, and sheltering. In Figure 6 a simplified scheme of case study is shown.

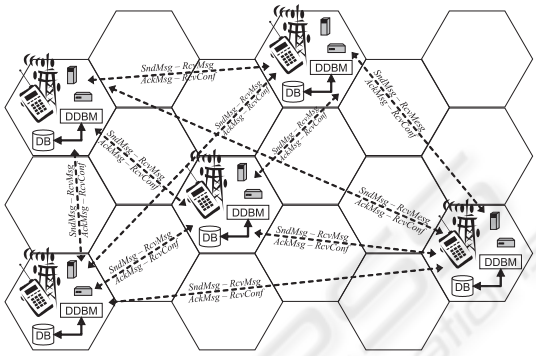


Figure 6: Case study simplified scheme.

To obtain a good functioning of the network, it is required to guarantee the integrity of the information state of each one of the devices that constitute each CS by using a Distributed Data Base (DDB) modelling approach. Each CS has its local Data Base (DB) and its own Distributed Data Base Manager (DDBM) that sends to the rest of the CSs the changes occurring in the devices that exist in the CS. After updating the local DBs at the rest of the CSs, its DDBM sends a confirmation message to the CS that requested the update, notifying the change. Moreover, there is a DDBM for each CS. Therefore it is required that the DDBMs globally assure the integrity, among the *n* DDBM of the distributed data when they are updated. These data are locally replicated for the *n* CSs As part of the system integrity only one data update of the DDBMs should be carried out at any one time.

In the following text, we show the scheme application for verifying the component considered as the most critical for one of these systems, the DDBM. It should be noted that we present a simplified version of this component.

4.1 Specification of Properties

In order to guarantee the data integrity between the different local DDBB of the DDB, each DDBM must satisfy the following conditions:

- Only one *send–and–update* message can be performed at same time within $[a,b]$ time interval: $\phi_1 := \neg \mathsf{EF}_{[a,b]}(SndMsg(s) \wedge SndMsg(s'))$.
- The DDBM is in the state *receiving message* (s) until the next message (s') is sent, which occurs

[6]The operators $\|$, $\models$, and $\wedge$, denotes *parallel composition*, *satisfaction*, and *conjunction*, respectively.

[7]A site where antennas and electronic communications equipment are placed to create a cell in a mobile phone network.

within the $[a,b]$ time interval:
$\phi_2 := \mathsf{AG}_{[a,b]}(RcvMsg(s) \rightarrow \mathsf{A}[RcvMsg(s) \; \mathsf{U}_{[a+1,b-1]} \; (\neg RcvMsg(s) \wedge \mathsf{A}[\neg RcvMsg(s) \; \mathsf{U}_{[a+2,b]} \; SndMsg(s')])])$.

- The DDBM is in the state *sending message* (s') until the receiver sends the acknowledgement of the previously received message (s), within the $[a,b]$ time interval:
$\phi_3 := \mathsf{AG}_{[a,b]}(SndMsg(s') \rightarrow \mathsf{A}[SndMsg(s') \; \mathsf{U}_{[a+1,b-1]}(\neg SndMsg(s) \wedge \mathsf{A}[\neg SndMsg(s) \; \mathsf{U}_{[a+2,b]} \; RcvMsg(s) \wedge AckMsg(s)])])$.

The dynamical state of the transmitted messages must satisfy the following formulae:

- Every data message generated by the Sender DDBM is eventually received and the *sent* state holds until the confirmation message arrives, thus setting the message state to *acknowledged*, within $[a,b]$ time interval:
$\phi_4 := \mathsf{AG}_{[a,b]}(SndMsg \rightarrow \mathsf{AF}_{[a+1,b-1]}[SndMsg \; \mathsf{U}_{[a+2,b]} \; AckMsg])$.
- Every data message generated by the Sender DDBM is always confirmed by the Receiver DDBM, i.e. the state of any *sent* message will eventually change to *acknowledged*, within $[a,b]$ time interval:
$\phi_5 := \mathsf{AG}_{[a,b]}(SndMsg \rightarrow \mathsf{AF}_{[a+1,b]}[AckMsg])$.

Finally, the DDBM which initiated the data updating in the replicated servers must be assured that all the *acknowledgement messages* have arrived before returning to its initial state:
$\phi_6 = \neg(AckMsg(s_1) \wedge AckMsg(s_{i-1}) \wedge AckMsg(s_{i+1}) \wedge AckMsg(s_n)) \; \mathsf{U}_{[a,b]} \; RcvConf$.

To guarantee the liveness of the system, each DDBM must be satisfy:

- Every data message generated by the Sender DDBM will ultimately be *confirmed* by the Receivers DDBMs within the $[a,b]$ time interval:
$\phi_e := \mathsf{AG}_{[a,b]}(\mathsf{AF}_{[a,b-1]} SndMsg(s_i) \rightarrow \mathsf{AF}_{[a+1,b]}[RcvConf(s_i)])$.
- Every data message generated by the Sender DDBM will be *granted infinitely* often by the Receivers DDBMs within the $[a,b]$ time interval:
$\phi_j := \mathsf{AG}_{[a,b]}(\mathsf{AF}_{[a,b-1]}[\neg SndMsg(s_i)] \vee \mathsf{AF}_{[a+1,b]}[RcvConf(s_i)])$.

4.2 DDBM Modelling

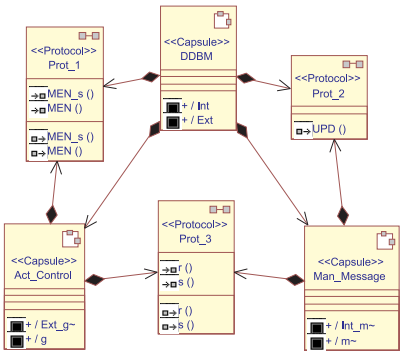
Since the solution is based on keeping data replication globally coherent, we must model one DDBM taking into account the following conditions:

- All the data are replicated in n different CSs, each one of these is managed by a distinct DDBM (DDBMs = $\{DDBM_1, DDBM_2, \ldots, DDBM_n\}$.
- The global data integrity is guaranteed by sending the appropriate messages to the rest of the DDBMs, $SndMsg = \{(s,r) | s,r \in DDBM \wedge s \neq r\}$.
- Each DDBM updates its local copy of global data, then it has to send a message to the other DDBMs: $AckMsg(s) = \Sigma_{r \in DDBM - \{s\}} 1'(s,r)$.
- The states that can be reached by each one of the DDBMs are: *Inactive* (before a local update or a remote message reception), *Waiting* (acknowledgement messages of data updates in remote DDBMs), and *Updating* (one local update requested by other DDBM).
- The states that can be reached by each one of the messages in transit are: *Not_used*, *Dispatched*, *Received*, and *Confirmed*.

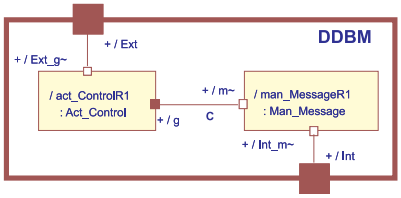
The architecture of each DDBM is shown in Figure 7. The DDBM is made up of two subcapsules, *Act_Control* y *Man_Message*, both in charge of managing the states of the DDBMs and the states of messages, respectively. Through the port *Ext*, the capsule DDBM communicates with the others DDBMs and through the port *Int*, the DDBM communicates with the local DB. The communication between the subcapsules *Act_Control* and *Man_Message* are carried out through the connector *C* and the ports *g* y *m*, respectively.

In Figure 8 we can observe the state machines that model the behaviour of each one of the subcapsules *Act_Control* and *Man_Message*.

The CSP+T process terms that specify the behaviours of prior UML–RT submodels are presented

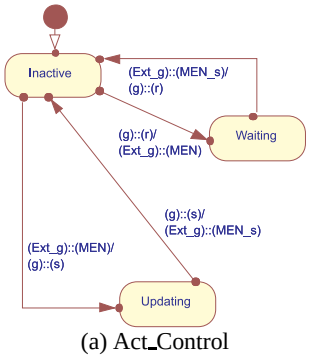


(a) Class diagram

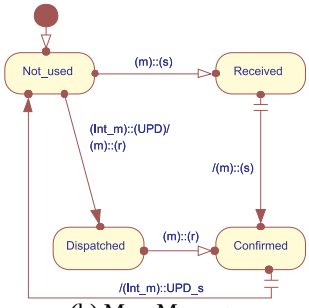


(b) Composite structure diagram

Figure 7: DDBM architecture.



(a) Act_Control



(b) Man_Message

Figure 8: State machines.

$$
\begin{array}{lll}
DDBM = & \multicolumn{2}{l}{CSP+T_{g,m}(Act\_Control, C, Man\_Message)} \\
 & \multicolumn{2}{l}{V_g(CSP+T(Act\_Control))[[g_{in}, g_{out}]]C[[m_{in}, m_{out}]]} \\
 & \multicolumn{2}{l}{V_m(CSP+T(Man\_Message))} \\
Act\_Control = & \star.t_0 \rightarrow Inactive & \\
 & Inactive = & (g?r \rightarrow (Ext\_g!MEN\_s \rightarrow Waiting) \ \square \\
 & & Ext\_g?MEN \rightarrow (g!s \rightarrow Updating)) \\
 & Waiting = & Ext\_g?MEN\_s \rightarrow (g!r \rightarrow Inactive) \\
 & Updating = & g?s \rightarrow (Ext\_g?MEN\_s \rightarrow Inactive) \\
V_{Ext_g}(CSP+T(Act\_Control)) = & \multicolumn{2}{l}{\{MEM,\ MEN\_s\}} \\
V_g(CSP+T(Act\_Control)) = & \multicolumn{2}{l}{\{s,\ r\}} \\
Man\_Message = & \star.t_0 \rightarrow Not\_used & \\
 & Not\_used = & (m?s \rightarrow Received \ \square \\
 & & Int\_m?UPD \rightarrow (m!r \rightarrow Dispatched)) \\
 & Received = & m!s \rightarrow Confirmed \\
 & Dispatched = & m?r \rightarrow Confirmed \\
 & Confirmed = & Int\_m!UPD\_s \rightarrow Not\_used \\
V_{Int\_m}(CSP+T(Man\_Message)) = & \multicolumn{2}{l}{\{UPD,\ UPD\_s\}} \\
V_m(CSP+T(Man\_Message)) = & \multicolumn{2}{l}{\{s,\ r\}}
\end{array}
$$

Figure 9: Act_Control and Man_Message specification in CSP+T terms.

in Figure 9. As the works (Mendoza et al., 2007; Mendoza and Capel, 2007) demonstrate, adequate *DDBM*, *Act_Control*, and *Man_Message*, CSP+T process terms can be found to appropriately specify the behaviour of the UML–RT submodels shown in Figures 7 and 8.

4.3 Component Verification

First, we perform the verification of each subcomponent (*Act_Control* and *Man_Message*) with respect to the subproperties that they must each accomplish (*ESP_Act_Control* and *ESP_Man_Message*), respectively. Afterwards, we check that the component *DDBM* $((Act\_Control \| Man\_Message) \setminus C)$ accomplish the *ESP_DDBM* $(ESP\_Act\_Control \wedge ESP\_Man\_Message)$ property. In prior works (Mendoza et al., 2007; Mendoza and Capel, 2007) formal proofs have been carried out to show how these verification processes are supported.

Taking the specification of the properties of section 4.1, which represent the properties specification of the system, and the processes specification in section 4.2, which represent a possible model of DDBMs, we proceed to their verification. In this case, considering that we are working with a simplified representation of DDBMs, we use the MC tool FDR2 (Formal Systems (Europe) Ltd, 2005). As can be observed in Figure 10, the verification execution of each subcapsules (*Act_Control* and *Man_Message*) system implementation satisfies (green check marks at rows one and two, respectively) the expected behaviour of each one, with respect to the failure and divergence semantic models.

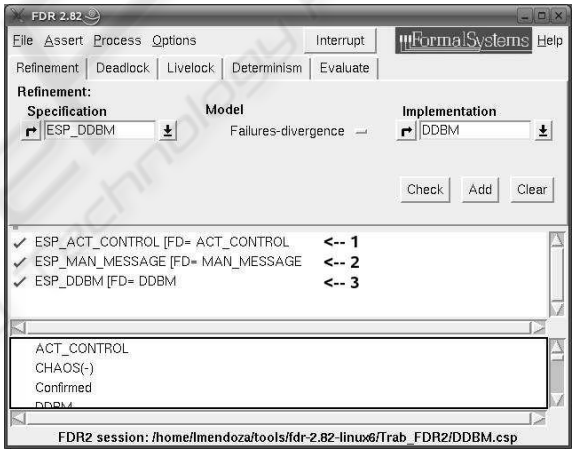


Figure 10: DDBM verification screen shot.

Finally, as it can be observed in Figure 10, the verification execution shows that the component implementation *DDBM* satisfies (green check mark at row three) the *ESP_DDBM* property, with respect to the failure and divergences semantic models.

The application scheme in this case shows the feasibility of our vision of compositional verification, supported by a state–of–the–art MC tool, and its integration with MEDISTAM–RT design method, under the same formal semantics as the temporal logic CCTL and the process algebra CSP+T. We obtain: (a) the CCTL expressed properties that the system must fulfill, (b) the UML–RT model of the system, (c) the CSP+T processes that specify the system behaviour, and (d) the verification of the system. We can say

that our conceptual verification scheme and application proposal integrate within the same framework the activities regarding analysis, design and verification of a critical communicating system.

5 CONCLUSIONS

In this paper, we describe a compositional verification scheme that integrates MEDISTAM–RT, which can be proved as a sound verification approach since it is based on the formal aspects of MC. The integration is attained by using two formalisms that are under the same formal semantics of Kripke structures: CCTL for temporal properties and CSP+T for system process formal specification. Thanks to the compositionality that both specification languages present and their interpretation under the same semantics, MC tools can be incorporated that facilitate the proposed application scheme as well as the design verification of large and complex systems.

Finally, the compositional verification scheme proposal is applied to a real project related to mobile phone communication. In the short term we will apply our approach again to the case study to obtain real data about its performance, setting the temporal constraints according to the system requirements.

The future and ongoing work is aimed at the application of our integrated view of verification in other case studies of application in industrial RTS modelling; thus, our goal is to conduct in–depth research about the verification of these specifications, and achieve its support with state–of–the–art MC tools.

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