Formal Specification of Real-Time Systems by Transformation of UML-RT Design Models

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Abstract. We are motivated to complement our methodology by integrating collaboration diagrams to facilitate the specification of capsules in UML-RT design models. An improved systematic transformation method to derive a correct and complete formal system specification of real-time systems is established. This article aims at integrating temporal requirements in the design stage of the life cycle of a real-time system, so that scheduling and dependability analysis can be performed at this stage. The application of CSP+T process algebra to carry out a systematic transformation from a UML-RT model of a well known manufacturing-industry paradigmatic case, the "Production-Cell", is also presented.

1 Introduction

UML (Unified Modelling Language) [1], has become one of the most widely used standards for modelling and designing the industrial software systems, essentially, because it is a semi-formal notation relatively easy to use and well supported by tools. An extension to UML, named UML-RT [2], has been defined on the basis of ROOM language [3], an architectural definition language specifically developed for modelling complex real-time software systems. However, the lack of formal semantics for UML-RT makes it very difficult to assure the correctness of a hard real-time and critical system under development

Formal methods [4] have demonstrated to be effectively applicable in the industrial development of real-time systems, and they are advocated as a means of providing a higher level of confidence in the correct functioning of software. Nevertheless, they have not the same acceptance in the industry as semi-formal ones, such as the case of UML. The problem is that formal methods are hard to master and too expensive to be used extensively during the entire software development process [5].

On the other hand, it is well known that the combination of UML modelling notation with formal specification languages may take advantage of their benefits and overcome its deficiencies if the integration scheme between formal constructs and

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UML analysis entities is well performed.

In a previous work [6], we have presented a software specification method that combines UML-RT and the CSP+T formal specification language. The method is based on an initial UML-RT model of the system under development, which uses extended UML State and class diagrams to model the behaviour, timing and architectural aspects of the system. Then, the UML model is mapped into CSP syntactical terms by applying a set of transformation rules, which permits to derive a formal system specification of a target system.

Typically, the complete specification of the structure of a complex real-time system is obtained through a combination of class and collaboration diagrams [7]. For this reason, we are now motivated to complement our previously proposed procedure with collaboration diagrams, to obtain a more complete and modifiable system specification of real-time systems. Similar approaches have been proposed in other articles, for instance, [8] maps UML-RT capsules to the formal language Circus [9]. Our approach differs from the aforementioned in that it integrates the specification of timing properties, and gives a complete view of the system behaviour. It can therefore be said that the specification of RTS from a global view (i.e., including behavioural, static and timing aspects) becomes feasible in a flexible and easy way. As to show its applicability, we have used the method to carry out the specification, including real-time constraints, of two basic components of the "Production Cell", which is a well known manufacturing-industry paradigmatic case. The rest of this paper is structured as follows: section 2 provides an overview of the UML-RT, section 3 describes the CSP+T Language and section 4 explains the system specification method proposed here. In Section 5, we present the specification of central elements of the Production Cell components (the robot and the Press). Finally, some conclusions are drawn and the references are listed.

2 UML-RT

UML-RT extends the basic UML analysis entities with constructs to facilitate the design of complex embedded real-time software systems. The origin of the UML-RT modelling notation is the real-time specific modelling language ROOM, which has been modified to follow the UML standardized framework. The language focuses primarily on the specification of the architecture of software systems, i.e., their major components, the externally visible properties of these, and the communication between them. The importance of the software architecture definition in the development cycle is argued by considering that decisions made during the architectural design will have a very important impact on the later system design, being also this phase that can profit the most from a good modelling language.

UML-RT adds four new building blocks to the standard UML (see Fig. 1):

Capsules. A capsule is a stereotype of a UML class entity with some specific features. Capsules are constructs for isolating functionality with a very clearly defined interface. Each capsule operates according to a state diagram, which responds to events and generates actions through its ports.

- Ports. A port represents an interaction point between a capsule and its environment. They convey signals between the environment and the capsule. The port notation is shown as a small hollow square symbol. If the port symbol is placed overlapping the boundary of the rectangle symbol, it denotes a public visibility. If the port is shown inside the rectangle symbol, then the port is hidden and its visibility is private. When viewed from within the capsule: two types of ports are defined: *relay* and *end* ports. A relay port transmits signals between a capsule and its subcapsules. An end port is a component that represents the transmission of signals between the capsule and its Statechart.

- Protocols. A protocol captures a set of valid communications (signal exchanges) between two or more capsules.

- Connectors. A connector is an abstraction of a message-passing channel that connects two or more ports. Each connector is typed by a protocol that defines the possible interactions that can take place across that connector.

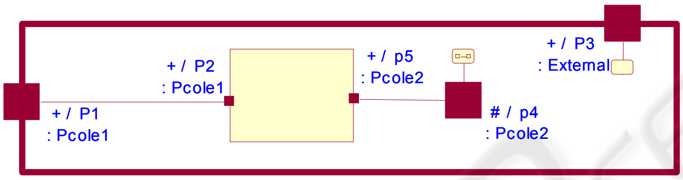


Fig. 1. Port notation - collaboration diagram.

3 CSP+T

CSP+T [10] extends the well-known CSP [11] [12] (Communicating Sequential Processes), formal specification language with timing primitives. CSP is an *event* based notation primarily aimed at describing the sequencing of events within process behaviour and the synchronisation (or *communication*) between processes. CSP+T, which is a new real-time specification language, extends CSP, by introducing a new set of constructs, to allow the description of complex event timings from within a single sequential process, thereby providing a valuable insight into the behavioural specification of real-time systems.

The syntax of CSP+T, which is a superset of the CSP one, has been adapted to our method. The differences between the two formal specification languages are described as follows:

- Every process P defines its own set of communication symbols, termed the *communication alphabet* $\alpha(P)$. These communications represent the events that process P receives from its *environment* (constituted of all the other processes in the system) or that occur internally, such as the event τ which is not externally visible. External events can be understood as the pure synchronization between an asynchronous process and its environment. Any type of event causes a state change of the process in which it is observed.

- The communication interface *Comm_act(P)* of a given process P contains all the CSP-like communications, i.e. the synchronous, one-to-one, communications between parallel processes, in which process P can engage and it also includes the alphabet $\alpha(P)$, representing signals and events occurring in P. Therefore, the communications of process P are given by the set $Comm\_act(P) = (Interface(P) \cup \alpha(P))$.

- A new operator, ∗ (star), is introduced in the programming notation to denote process instantiation. An instance of a process term must be created before it can execute. This event is unique in the system since it represents the origin of a global time at which processes can start their execution. As an example, let us consider a process P that initially can only engage in the event *a*. In *CSP*, this process would be denoted as: $P = a \rightarrow STOP$, but it must be instantiated before being executed in *CSP+T*. Given *P'*, the timed version of *P*, which is instantiated at time 1, where *s* is a time stamp associated to the abstract communication *a,* the specification of *P'* becomes,

```
P'= 1.* → s.a → STOP where s ∈[1, ∞[
```

It should be noted that event *a* occurs only once in the interval.

– A new event operator >< is introduced to be used jointly with a "marker variable" to record the time instant at which the event occurs. *ev>< v* means that the time at which *ev* is observed during a process execution is in the marker *variable v.* The value of time stamps is taken from the set of positive real numbers, so that successive events form a non-decreasing monotonic sequence. As several successive events can instantiate the same variable at different times, if we specify the process P as follows:

```
P= 1.* → a >< var → STOP
```

- For each process execution, the marker variable *var* will record the corresponding time value at which event *a* occurred, and it will always satisfy $var > 1$.

The scope of marker variables is strictly limited to one sequential process. They cannot be referenced or accessed in any other way within a concurrent composition of processes.

- Each marker event is usually associated with a time interval, which is called its "*event-enabling" interval* and represents the period of time over which the event is continuously available to the process and its environment. During this interval, the event can be detected, then provoking an instantaneous change of state either in the process or in the environment. The initial times for intervals are relative to a preceding event or to a marker variable, which is instantiated during current process execution. A process is considered to be the STOP process if it cannot engage in the marker event or in an alternative event during the enabling interval. Let us suppose, for instance, that there is a process *P,* a process which can only engage in event *a,* which can only occur between 1 and 2 units of time from the process instantiation time (the preceding event), recording in the *marker variable v* the time at which the event *a* occurred. The specification of this process is therefore:

```
P= 0.* → [1, 2].a >< v → STOP
```

After the process execution, the value of the *marker variable* satisfies the inequality $1 \leq v \leq 2$. The enabling interval can be defined in a more compact way by using the function I, I (T,*v*), where *v* is the marker variable that records the time instant at which the preceding event occurred, and T defines the duration of the time interval starting at the time instant stored in *v*. An example is:

```
P = 1.* → a >< v → I(3,v).c → d → STOP,
```

in which the event c can occur at least three time units after the process P engages in the event *a*.

If the marker variable does not appear in the signature of function I, the enabling interval is relative to the previous marker variable in the scope of the process, otherwise the enabling interval for that process is considered the default interval [0, ∞].

The times for events are absolute and the times for intervals are relative to the preceding time stored in marker variable.

- The semantics of the parallel composition of two processes with enabling intervals which must be synchronized depends on whether the values of these intervals are identical, partially overlapping or disjoint. In the first case, the processes synchronize on the common initial events, as established in *CSP* communication semantics, i.e., given $P= E1.Q$ and $R= E2.S$, then

$$P||Q \neq STOP \text{ iff } \alpha(Q)\cap \alpha(S)\neq\emptyset \wedge E1\cap E2\neq\emptyset$$

In the case of disjoint enabling intervals ($E1 \cap E2 = \emptyset$), the parallel composition of processes behaves as the *STOP* process.

4 Formal Specification and Transformation Methodology from UML-RT

To manage the complexity of real-time systems, a bottom-up, compositional strategy is proposed here. The methodological procedure consists of first dividing the target system into a set of subsystems and then considering the architecture of the entire system model as a net of capsules connected by ports that intercommunicate according to a previously defined protocol. For instance, the system Sys in Fig. 2.a has been divided into two subsystems (Capsules).

- The *entire system architecture* is modelled using a Class Diagram, which represents each system components by a UML capsules, and their interactions are defined by a set of operations (signals) encapsulated in protocols. In Fig. 2a the signals e_1, e_2 of the protocol *PROT-AB* are the events exchanged between the capsules Caps A and Caps B.

- S*ubsystems internal structure* is described by a Collaboration Diagram, which identifies the components of the lower level subsystems and how they are connected. In Fig. 2b Caps A is composed of the subcapsules X and Y that are connected through the ports Px and Py. Caps A and caps B communicate through the ports Pa and Pb which convey "Prot_AB" signals between these capsules.

- Subsystems *behaviour and timing requirements* are modelled using the extended State Diagram (UML-SD), established in a previous work [6], which extends the standard UML-SD with new constructs inspired on CSP+T syntax to capture timing properties. The extension consists of an annotation for describing timing events, enabling intervals assigned to events to restrict their time execution, and a new type of transition labelled with a special event, called timeout. Timeout triggers a state change to a Skip state. In Fig. 2c, we mark the occurrence of the events e_1 by the annotation t_{e1}*= gettime (),* and we restrict the execution of the event e_2 to an interval I by the annotation $I.e_2$.

To overcome the lack of formal semantics of UML and to ease the usually difficult applications of formal methods, we systematically derive the formal specification in terms of CSP+T from the UML-RT models, by applying a set of rules already established in previous works [6] [13].

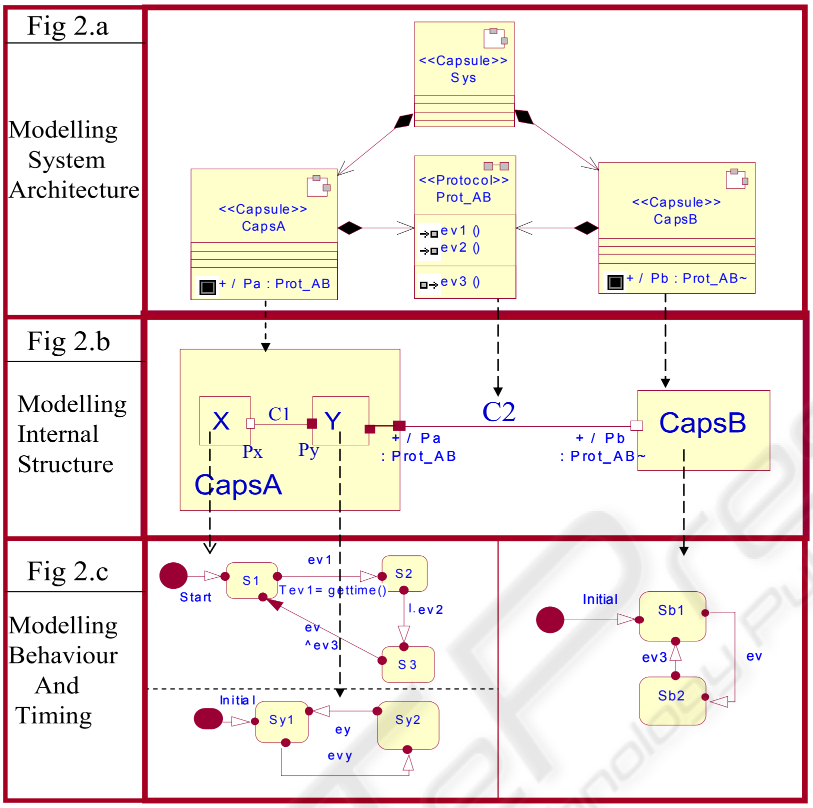


Fig. 2. Real-Time system Model

The complete system specification is obtained by the composition of a set of processes that specify subcapsules by using CSP operators, such as the parallel composition one. By the example shown in Fig.2, we can describe the compositional construction of a system specification. We first specify the entire architecture by mapping the class diagram (Fig. 2.a) into CSP process terms as discussed in [6]:

Sys = (**CapsA**||**CapsB**)\{ev1, ev2, ev3}.

Then, we specify the internal structure of each capsule on the class diagram by mapping the collaboration diagram into CSP processes, according to a procedure established in [13]. The transformation of CapsA in a collaboration diagram (Fig. 2.b) yields the next CSP syntactical terms:

X = X [Px → C1], Y = Y[Py → C1,P'y → C2]
CapsA = (**X** || **Y**) \ C1

The specification technique is compositional. The specification of the dynamic behaviour of a capsule can therefore be obtained by composing the individual subcapsule behaviour specifications. From the transformation of the SD that represents the behaviour of capsule X and capsule Y (Fig. 2.c), we obtain:

X= Start → S1

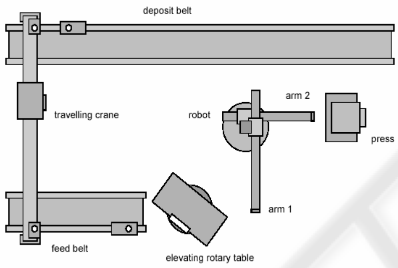
S1= ev1><t_{ev1} → S2
S2= I(T, t_{e1}).ev2 → S3
S3= ev3 → S1.

Y= Start → Sy1
Sy1= evy → Sy2
St2= ey → ST1.

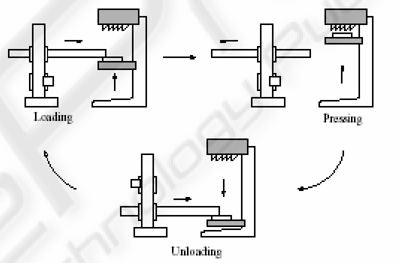
The behaviour of CaspA is obtained by parallel composition of X and Y processes.

5 The Production Cell Case Study

The case study [14] presents a realistic industry-oriented problem, where safety requirements play a significant role and can be met by the application of formal methods. The design activity of the Production Cell (PC) system is of manageable complexity; thus, it allows us to experiment with several alternative designs before making the decision to take a particular one. Fig. 3a shows a top view of the plant that holds the PC.



3a. Top View of the plant



3b. Robot and Press

Fig. 3. Production Cell.

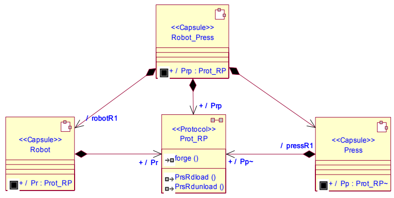
The model includes several machines that must be coordinated in order to forge metal blanks. The machines process metal blanks at the greatest possible speed, and at the same time, they must avoid dropping blanks to the floor or colliding to each other. There is a conveyor belt that feeds blanks into a rotary table. The table rotates and lifts the blanks so they can be picked up by the first robot arm. The robot has two arms, one for feeding the press with blanks and the other for removing forged blanks from the press. The robot is very efficient and it can simultaneously use an arm to place a forged blank into the deposit belt and the other arm to convey a new blank to the press.

We decide to model the central elements of the system: the press and the robot. The robot task consists in taking metal blanks from the elevating rotary table to the press and transporting forged plates from the press to the deposit belt. The task of the press is to forge metal blanks. The above two components work simultaneously: the mobile part of the press is initially in the middle position until the robot places a blank into the press. After being loaded, the press starts moving upwards and presses the blank until it becomes forged. It starts moving downwards to the unloading position and finally the robot picks up the forged piece and the cycle starts again. Figure 3b graphically represents these steps.

To specify the system composed of the Robot and the Press components, we follow the methodology described in the previous section. First, we decompose the system into two principal components: Press and Robot, which can be separately modelled as capsules in UML-RT notation.

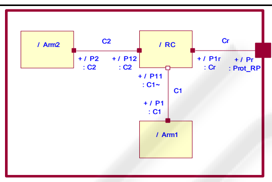
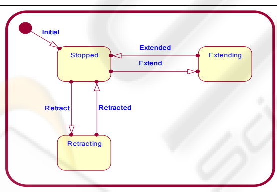
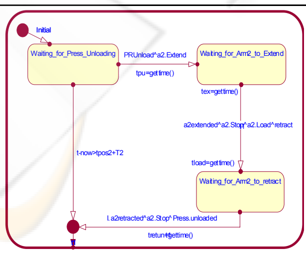
The architecture of the system composed of the robot and the press is specified by mapping the class diagram into CSP processes.

Table. 1. Model of the Robot and the Press interaction.

UML-RT Model	Derived Specification on CSP+T terms
	**Robot-Press** = (**Robot** || **Press**) \ {forge, prsRdload, prsRdunload}

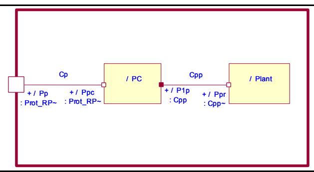
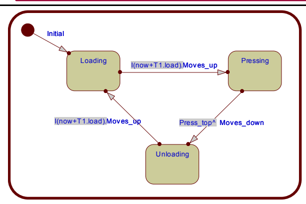
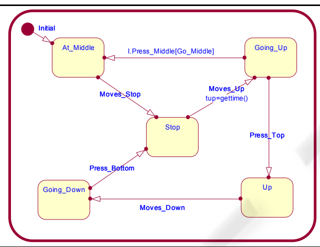
We model the behaviour and the internal structure of each capsule by using the extended UML state diagrams and collaboration diagrams, respectively. The application of the set of rules proposed by the methodology allows us to derive system specifications in CSP+T terms, as it is shown in Tables 2 and 3.

Table. 2. Model and the derived specification of the behaviour and the internal structure of Robot.

UML-RT Model	Derived Specification on CSP+T terms
	RC= RC [P12→ C2, P11 → C1, P1r → Cr] Arm1= Arm1 [P1 → C1] Arm2= = Arm2 [P2→ C2] **Robot** = (**RC** || **Arm1** || **Arm2**)\ C1,C2.
	**Arm1**= start → A1_stopped A1_stopped= retract1 → Retracting1| extend1 → extending1 Retracting1= retracted1 → A1_stopped Extending1= Extended1 → A1_Stopped
	**RC** = *Start* → WFT WPU= ((I(T_{PR},t_{pos2}).PrUnload >< t_{pr} → A_2.extend) → $WA_2 2_1$) | I(T_{TR},t_{pos1}) → time-out WA_2E_2=I(T_{EX},t_{tr}).A_1Extended><t_{ex} → A_1.stop → A_1.load >< t_{load} → WA_1R_1 WA_1R_1= I(T_{ret},t_{load}).A_1retracted><t_{ret} → A_1.stop → Table.Unload → Turn(left) → CWW ...

Timing requirements are also taken into account to avoid a collision between two components. For instance, the press may only move when no robot arm is positioned inside it. So, we mark in the Robot SD the time when the arm1 is retracted (back to its rotating position) by the annotation t_{ret}= *gettine(),* and we restrict in the SD of the press, the occurrence of the event move_up within an interval depending of t_{ret} by the annotation: I(T, t_{ret}).

Table. 3. Model and the derived specification of the behaviour and the internal structure of Press.

UML-RT Model	Derived Specification on CSP+T terms
	PLANT = Plant[Ppr → Cpp] PC= PC[Ppc → Cpp, P1p → Cp] **Press** = (**PLANT** || **PC**) \ Cpp
	**PC =** Start → Loading Loading= forge → timeout → Pressing Pressing= presstop → moves(down) → Unloading Unloading= unloaded → timeout → moves(up)
	**PLANT**= Start → Atmiddle Atmiddle= moves (Stop) → Stopped Stopped= moves(up)>< tup → Going_up Going_up= I(Tmid, tup)&gomiddle → at-middle ❙ press(top) → up. Up = moves(down) → Going_down Going_down= press(bottom) → Stopped

6 Conclusions

In this work, we have complemented our methodological approach discussed in a previous paper [6], with the integration of a collaboration diagram in order to capture the internal structures of system components and their connections. These new contribution strengthens our method, since we can systematically obtain a detailed system specification from an initial UML model of high level of abstraction. We have profited of the UML Object Oriented Paradigm to obtain a compositional technique based on specifying each system capsules individually and subsequently composing them by using CSP+T operators. Timing properties specification has been included in the proposal, so that are taken into account to assure that real-time system properties are fulfilled.

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