PATTERNS FOR TEMPORAL REQUIREMENTS ENGINEERING
*A Level Crossing Case Study**

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Keywords: Model Transformation, Time-Constrained System, UML State Machines, Timed Automata, Verification and Validation.

Abstract: This work presents a method for verifying temporal requirements of time-constrained systems. The method predates by establishing a new time constraints (properties) taxonomy. Then, a basis of observation patterns relative to the predefined requirements is developed. Our approach allows the automated verification of temporal requirements, initially expressed in a semi-formal formalism, through model transformation and model-checking. The contributions of the paper are: the definition of a new time constraints (properties) typology as well as a basis of appropriate State Machines (SM) observation patterns. The second contribution consists in developing an algorithm for transforming UML SM with time annotations into Timed Automata (TA). In practice, in order to verify the temporal aspects of a given specification, the observation patterns relative to the investigated properties are instantiated to make appropriate observers. Then using our transformation algorithm, the system specification (denoted in the shape of an UML SM model) with time annotations as well as the obtained observers are translated into TA models. The TA system model is next synchronized with the TA observers. Thereby, the verification process is reduced to a reachability analysis.

1 INTRODUCTION

Given their practical implication on safety and correctness of critical applications (e.g. transportation systems, nuclear plants), specification and verification are one of the most important research topics in critical systems engineering since such kind of systems must achieve a high level of robustness and reliability. In addition, these systems usually involve time-dependent functionality. Consequently, methods for behavior modeling and verifying (especially temporal requirements) are increasingly important. The most used approaches for specifying timed systems are based on **T**imed **A**utomata (**TA**). TA are well suited for expressing timed behavior and for modeling real-time components. A number of automatic verification tools for TA have been developed and have proven to be efficient e.g., Uppaal (Larsen et al., 1997) and Kronos (Yovine, 1997). Nevertheless, specifying and verifying time constraints is becoming a more and more difficult task due to the widespread applications and increasing complexity of checked systems. Despite the different advantages proposed by TA, such as parallel composition, users often need to manually express the time properties into a set of clock variables with complex calculated clock constraints. This process is tedious, error-prone and requires sophisticated logical and/or mathematical skills.

On the other hand, in order to cope with the complexity of critical systems engineering, approaches based on **M**odel **D**riven **E**ngineering (**MDE**) seems to be very useful (Schmidt, 2004). The aim of this work is to introduce a new temporal requirements' verification method based on MDE. First, we define a Patterns' Basis for monitoring time constraints. Indeed, based on a new time constraints' classification, we developed a set of time observation patterns expressed in **U**nified **M**odeling **L**anguage (**UML**) **S**tate **M**achines (**SM**)(UML, 2009): this is expected to be a relatively inexpensive activity since this procedure is done once and for all. UML has been chosen since it is relatively intuitive, offers a graphic description, is

*This research has been partially supported by Rgion Nord Pas de Calais and European fund Feder under the FUI National project FerroCOTS, labelled by i-Trans.

Mekki A., Ghazel M. and Toguyeni A. (2010).
PATTERNS FOR TEMPORAL REQUIREMENTS ENGINEERING - A Level Crossing Case Study.
In *Proceedings of the 7th International Conference on Informatics in Control, Automation and Robotics*, pages 45-52
DOI: 10.5220/0002947500450052

implemented by several tools and finally is a standard notation well supported by the **O**bject **M**anagement **G**roup. This set of patterns facilitates high-level system design. These patterns cover a large class of common time constraints.

Since our aim is to keep a high precision level, a subsequent step consists in giving an accurate definition of each developed pattern. Hence, for each pattern, we give (1) a textual definition, (2) an UML SM model, (3) a structured English specification and finally (4) a temporal logic expression (**T**imed **C**omputational **T**ree **L**ogic (**TCTL**)) relative to the property concerned.

Concretely, the verification process is based on the set of patterns. The suitable patterns corresponding to the time constraints extracted from the system requirements are picked up and instantiated. This instantiation step generates a set of SM Observers. The SM observers are translated into more formal notation, the TA, which provides support for the properties' verification. The translation is made according to a transformation algorithm that will be discussed later in the paper. In this way, analyzers exploit the benefits of formal notations without having to go through the complex and expensive formal modeling phase. This transformation generates a set of TA Observers. A system's model, which is also generated by the same transformation algorithm, is synchronized with the obtained TA observers to obtain a global model. Hence, the verification task is performed, on this obtained model, with a reachability analysis while checking whether the observers' forbidden states - corresponding to constraints violation - are reachable.

The paper is organized as follows. In Section 2, we set the context and we briefly go through some related works. Section 3 describes our first contribution by introducing the new time-constraints taxonomy and the patterns basis. The second contribution of our method is outlined in Section 4 where the translation from UML SM, with time annotations, to TA is described. The method is illustrated using a **L**evel **C**rossing (**LC**) case study in Section 5. Section 6 concludes the paper while drawing some future work.

2 CONTEXT AND BACKGROUND

2.1 Related Work

There are many recent research efforts in the field of time-constrained system validation. Only two of these research will be discussed in this section. First, based on the Dwyer (Dwyer et al., 1999) pattern basis, Dhaussy (Dhaussy et al., 2009) defines a textual language, called "CDL", for requirement specification. The requirements are then translated into observer automata. Furthermore, Dhaussy defines for each requirement a path, called "context" where the requirement should be checked. Finally, the system model, the observer automata and the context are translated into IF notation (Intermediate Format). Then, the verification is carried out using the IFx tool. Second, Nascimento (Nascimento et al., 2009) presents an approach for automatic generation of network of timed automata from a functional specification depicted via UML class and sequence diagrams. Nascimento uses UML sequence diagrams for the property specification phase. However, sequence diagrams suffer from a limited expressiveness when dealing with temporal aspects, since they only depict order.

Unlike the above methods, our approach uses TA as target notation; TA are assumed to be more expressive and well supported.

On the other hand, several projects have introduced natural-language-based approaches where natural language is mapped into a more formal specification. (Dwyer et al., 1999) proposes several patterns applicable to properties specification expressed in different formalisms and logics such as LTL, CTL, GIL, and quantified regular expressions (QRE). (Konrad and Cheng, 2005) proposes an extension to Dwyer's classification and real-time properties are added to the original classification. Moreover, TCTL, MTL and RTGIL are used to specify the added real-time properties.

Comparatively to the above-mentioned works, our contribution offers the following advantages:

- Our method takes advantage of the flexibility and expressiveness of UML SM in modeling tasks and the precision of TA formalism in the verification tasks, also UML SM are more expressive than UML sequence diagrams or UML collaboration diagrams used in other works,
- TA are well supported,
- Patterns facilitate high-level specification and promote reusability and knowledge capitalization,
- The verification task is reduced to a reachability analysis, this allows us to overcome some limitations met with some existing tools, such as Uppaal.

2.2 Observer Technique

We deal with observer whenever we set artifacts to watch system behavior (Dong et al., 2008). Let us recall here that the goal of our approach is to check whether the temporal requirements expected from a given system are satisfied. Hence, we make use of observers in order to express the satisfaction vs the violation of the predefined requirements (Ghazel et al., 2009). Typically, checking a given temporal property consists in examining whether the error state of the corresponding observer is reachable.

3 OBSERVATION PATTERNS

In this section, we first propose a classification of all the common temporal requirements one may meet when dealing with critical systems. Then, we develop a structured English grammar that we use to express the predefined properties. Next, we introduce the patterns used in order to monitor the predefined temporal requirements. Finally, a standardized description of these patterns is suggested.

3.1 Main Time-constraints

We strive to identify all the common requirements one may meet when dealing with critical systems. The main identified requirements are defined and explained in Table 1 (The relation which denotes that a system **S** satisfies a requirement **R** is written **S**$\models$**R**) and also are depicted in the shape of a UML Class diagram (Figure 1). This classification offers the advantage that it deals with requirements on events only, since we used to express the requirements on states using two events: the first event represents the activation of the state and the other the deactivation.

3.2 Structured English

To facilitate the expression and the formalization of temporal properties, we have developed a structured English grammar. This grammar supports both qualitative and quantitative properties. Each sentence generated by our grammar describes a temporal property and serves as handler that helps expressing and understanding the requirement. Our grammar is expressed below using BNF (Backus-Naur Form) notation:

Property = {*<Scope>*: *<Specification>*};

Specification = {*<Entity><Obligation>***occur** *<Reference>*} ;

Scope = **Global** |**Before** *<Entity>*|**After** *<Entity>*|**Between** *<Entity>***and** *<Entity>*;

Entity = “Event” |“Active(State)” |“Desactive(State)”;

Obligation = **must** |**cannot**;

Reference = ((**exactly at** *<time>***over**) |(**After [a delay of** *<time>***over**]) |(<**Before [a delay of** *<time>***over**])) *<Entity>*;

Time = *<Number>***tu**;

Number = *<Digit>*+ ;

Digit = {**0**|**1**|**2**|**3**|**4**|**5**|**6**|**7**|**8**|**9**} ;

Literal terminals are given in **bold** font, non-literal terminals are delimited by quotation marks (“ ”) and non-terminals are given in *italics*. The start symbol of the grammar is property and the language $\mathcal{L}$ of the grammar is finite, since the grammar is non-circular and has no repetitions.

3.3 Observation Patterns Basis

A pattern is a commonly reusable model in software systems that guarantees a set of characteristics and functionalities. The identification of a pattern is based on the context in which it is used. The goal behind developing patterns is to offer a support for system design and development. Using patterns helps in keeping design standardized and useful and minimizes the reinventing in the design process, since they facilitate reusability and knowledge capitalization (Gamma et al., 1995).

In this work, we define a set of patterns which will serve as basis to generate observers for all the identified temporal requirements. The notation used is UML State Machines. The basis of patterns is introduced regardless the systems’ specification and is used to model all the common temporal requirement types that one may express. This pattern basis guarantees the reusability and the genericity of the mechanisms developed within our approach.

3.4 Pattern Formalization

We have introduced a new temporal requirement classification that is used in implementing our pattern repository. Additionally, we include a graphical representation of each pattern in the shape of UML SM diagram. This field will be used later as input model to the model transformation phase. Each pattern in the repository contains the following fields:

Pattern Name: The pattern name serves as a handle for the pattern’s use and describes the type of the pattern.

Pattern Definition: A short description and definition of the requirement for which the pattern is used.

Scoped Structured English Specification: The scoped structured English sentence captures the invoked property using the grammar defined previously. The scope, initially introduced by Dwyer in (Dwyer et al., 1999), is used to express the applicability interval (scope) of the property. Four scopes are used in our grammar: *globally*, *before* an event occurs, *after* an event occurs and *between* two events.

Table 1: Temporal Requirement's Taxonomy Descriptions.

Class	Category	Pattern Name	Description
Quantitative	QuantitativeAbsence	Forbidden Before	**R** ensures that an event (E_{mon}) must never occur before a minimum T_{before} (time unit over E_{Ref}). **S**$\models$**R** is true if this event does not occur before T_{before}.
		Forbidden After	**R** ensures that an event (E_{mon}) must never occur after a deadline T_{after} (time unit over E_{Ref}). **S**$\models$**R** is true if this event does not occur after T_{after}.
		Forbidden Between	**R** ensures that an event (E_{mon}) must never occur between a temporal interval $]t_{Begin}; t_{End}[$ (over E_{Ref}). **S**$\models$**R** is true if this event does not occur between temporal interval $]t_{Begin}; t_{End}[$.
	QuantitativePresence	MinimumDelay	**R** ensures that an event (E_{mon}) must occur after a minimum time T_{min} (time unit over E_{Ref}). **S**$\models$**R** is true if this event occurs after T_{min}.
		MaximumDelay	**R** ensures that an event (E_{mon}) must occur before a deadline T_{max} (time unit over E_{Ref}). **S**$\models$**R** is true if this event occurs before T_{max}.
		Punctuality	**R** ensures that an event (E_{mon}) must occur at one punctual date t (time unit over E_{Ref}). **S**$\models$**R** is true if this event occurs at the t date.
Qualitative	Recurrence	UnboundedRecurrence	**R** ensures that an event (E_{mon}) must occur infinity of time. **S**$\models$**R** is true if this event occur.
		BoundedRecurrence	**R** ensures that an event (E_{mon}) must occur k time. **S**$\models$**R** is true if this event occur k time.
	QualitativePresence	PresenceAfter	**R** ensures that an event (E_{mon}) must occur after E_{Ref} have been detected. **S**$\models$**R** is true if this event occurs at least once after E_{Ref}.
		PresenceBefore	**R** ensures that an event (E_{mon}) must occur before E_{Ref}. **S**$\models$**R** is false if E_{Ref} occurs before E_{mon}.
	QualitativeAbsence	AbsenceAfter	**R** ensures that an event must never occur after E_{Ref}. **S**$\models$**R** is true if this event does not occur.
		AbsenceBefore	**R** ensures that an event (E_{mon}) must never occu before E_{Ref}r. **S**$\models$**R** is true if E_{mon} does not occur before E_{Ref}.

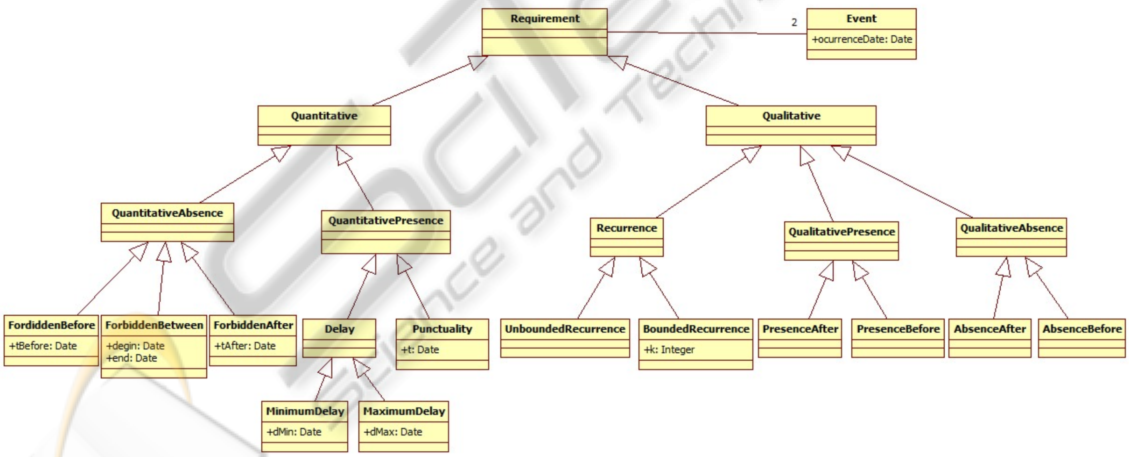


Figure 1: Temporal Requirements Classification.

Temporal Logic Description: Contains mappings of the property monitored by the pattern to TCTL for each of the four defined scopes. We chose TCTL since it allows quantitative temporal properties expression.

4 TRANSFORMATION APPROACH

Since the observation patterns' basis has been introduced, we will discuss now how to use this basis in the verification process. In practice, once the temporal requirements for the system under study are identified and extracted, the appropriate patterns for these requirements are selected and instantiated with the suitable parameters, thus resulting in some SM observers. Each SM observer monitors an elementary requirement. The SM observers are then translated into TA observers. This transformation will be presented hereafter.

4.1 Transformation Idea

In spite of the number of automated analyzers developed for TA, these tools suffer from two main limitations: the first is that users must be familiar with their formal notations. The second is the lack of patterns for high-level system design (hierarchy notion namely). On the other hand, semi-formal languages, such as UML SM, are suitable for expressing system requirements. However, the automatic verification of these models is unfeasible directly. The temporal requirement verification approach that we propose takes advantage of the expression flexibility of SM and the analysis facilities offered by TA formalism.

The various rules of the transformation algorithm we have defined are expressed according to the **M**odel-**D**riven **A**rchitecture (**MDA**) approach. MDA is an initiative and a standard proposed by the OMG, allowing developers to create systems entirely based on models. It points out the idea of separation of concerns by unlinking/uncoupling the application logic from the implementation platforms technology (Weis et al., 2003).

Figure 2 illustrates the use of the MDA four-layer metamodeling architecture for our transformation;

- The source model (resp. target model) is expressed according to the source metamodel (resp. target metamodel),
- The metamodels are defined and expressed according to the MOF metametamodel (in our transformation, we used the Ecore metametamodel, which is the Eclipse implementation of MOF),
- A metamodel is developed for TA. On the other side, we used the UML metamodel distributed in the Eclipse framework,
- All the rules are introduced at the metamodel level,
- The transformation takes a UML SM model as a source model and generates a TA model with a corresponding formatted code.

4.2 Time Annotations

Here we use SM as a modeling notation to take advantage of the flexibility they offer. However, since we strive to obtain an accurate specification, we should guide the user while introducing the temporal constraints. Concretely, we propose a set of timed annotations in order to express the states' characteristics as well as the transition guards. Table 2 shows some examples of them and defines the signification of each annotation.

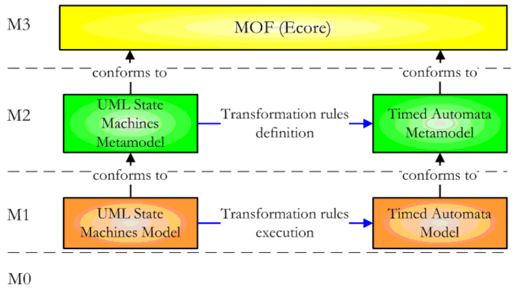


Figure 2: Transformation Approach.

Table 2: Time annotations used.

	Time annotation	Signification
1	at_most(T_{max})	t≤ T_{max}
2	at_least(T_{min})	t≥ T_{min}
3	after(d)	t=d
4	between(T_{min}, T_{max})	T_{min} ≤t≤ T_{max}
5	upper(T_{min})	t> T_{min}
6	lower(T_{max})	t< T_{max}

4.3 Transformation Algorithm

One of the key parts of our method is the translation of UML SM with time annotations into TA. For sake of space, we will briefly describe the transformation rules while giving the source and target element for each of them in 3. For more details, the reader can refer to (Mekki et al., 2010).

Table 3: Transformation Rules.

Rule Name	Source element: UML SM	target element: TA
FromStateMachine	StateMachine	TA
Simple2Simple	State	State
Final2State	Final Pseudostate	State
OR2Automata	State	Automaton
AND2Automata	State	Automaton
Trans2Trans	Transition	Transition
Entry2State	EntryAction	State
Exit2State	ExitAction	State
Do2State	DoActivity	State

The main rule of this algorithm is *FromStateMachine* rule. This rule is the first one carried out by the transformation algorithm. It picks elements in the source model, then calls on other rules to translate the selected elements into TA elements in the target model. Likewise, the called rules behave in the same way; they select elements in the source model and call the appropriate rule for transforming them. For example, the *FromStateMachine* rule is applied to elements of type “UML::StateMachine” and translates them into a “TA::AutomataMachine” element. Also, different element types are selected and different rules are called on in this rule. First, the rule selects all the UML states. Then for each selected state, according to its type, the rule *Simple2Simple* or *OR2Automata* or *AND2Automata* is called on. Secondly, it translates the “UML::Transition” elements by invoking rule *Trans2Trans*. Also, this rule deals with another element type, the “UML::Pseudostate”, by invoking some other rules such as *Final2State*.

This internal transformation process is the same for all the rules; each rule transforms the source element into the target one. Then, it selects subelements of the source element and calls on the appropriate rule to transform them.

4.4 Verification Process

Once our observation patterns’ basis is implemented, we introduce a verification process based on this basis. This section will outline the global architecture of our approach. The architecture is depicted graphically in Figure 3 (Mekki et al., 2009).

Concretely, our approach is composed of four processes: first, temporal requirements for the system under study are identified and extracted. Second, the appropriate patterns for these extracted requirements are selected and instantiated with the suitable parameters. This second process results in some SM observers. Each SM observer corresponds to an elementary requirement. Third, the SM observers are translated into TA observers. In parallel and in the same way, the specification under study (SM model with time annotations) is abstracted and translated into a TA model. The translation from the UML SM to TA is performed using the MDA model transformation technique as shown previously.

Finally, the generated TA are synchronized with the formal system’s specification model (TA) to generate a global model holding both the system specification and the requiements’ monitoring. Thus, the verification task is reduced to an error-state reachability search on the obtained global model.

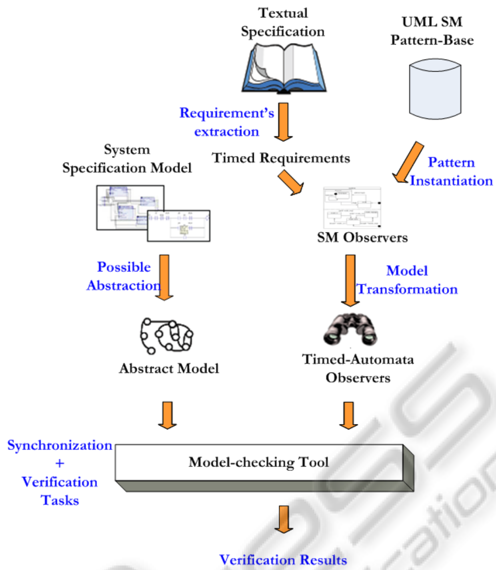


Figure 3: Method Global View.

5 CASE STUDY

5.1 Case Study Description

A classical automatic level crossing system is composed of several modules. The local **control** system which manages the traffic in the crossing area, a pair of barriers (**gate**), traffic **lights** whose role is to alert and prevent road users from entering the crossing zone and a **train**-sensing module which monitors trains approaching/leaving (Ghazel, 2009). The subsystems mentioned above execute in parallel and synchronize through events.

Several requirements * are given in textual specification in Figure 4. Next, using this textual specification, we will show how patterns are used to express and monitor requirements.

5.2 Using Patterns

For sake of space, only two requirements will be checked on the basis of the textual system specification. For each requirement, formalization is introduced using the defined generic template. First, a textual description of the requirement is presented, followed by an intuitive graphical representation in the shape of an UML SM (SM patterns). Then, a definition using our structured English grammar is given and finally a temporal logic expression is used to express formally the requirement. 1) The 1^{st} require-

*http://www.dagstuhl.de/fileadmin/redaktion/Programm/Seminar/07241/07241.CaseStudy.pdf

1. *"...As long as an approaching train runs over the activation sensor the sensor shall generate an occupied signal. When the last axle of the train has traversed the activation sensor it shall generate a free signal again. If the control unit receives an occupied signal from the activation sensor in the unsaved mode, it will enter the saving mode and gives the command to turn on the yellow lamp of the set of lights.* ***Three seconds after entering the saving mode the control unit has to give the command for switching off the yellow lamp and turning on the red lamp****..."*
2. *"...By entering saved mode the controller shall switch on the supervision signal to show signal aspect LC1, which means to turn on the blinking light.* ***Twelve seconds after the system has entered the safed mode it must start to lower the gate. The activity of lowering or raising the gate must not last longer than six seconds from one end position to the other.*** *When the gate has reached the lower end position within the six seconds interval the control unit will enter the mode saved and gates closed..."*

Figure 4: Specification Example.

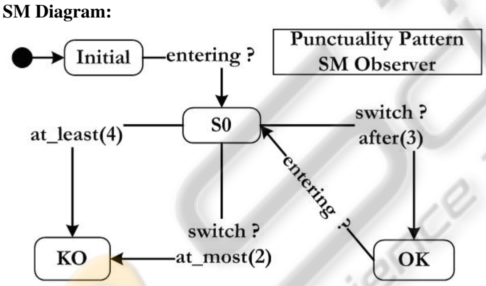
ments states that three seconds after receiving the *entering* signal, the controller should send command for *switching* lights. This requirement consists in a **punctuality** property (Figure 5) of 3 seconds between *entering* signal and *switch* signal.

Punctuality Pattern

Pattern Name: Punctuality

Textual Description: The Punctuality pattern is used to check that a given event execution is delayed by exactly d time units relatively to a given reference.

UML SM Diagram:



Structured English:
Scope "switch" **must occur exactly at** "3" **tu over** "entering".

Temporal Logic description:

Globally: **AG**[receive(entering) $\Rightarrow$ $\mathbf{AF}_{=d}$ receive(switch)]

After E_a**:** **AG**($E_a \rightarrow$(**EG**[receive(entering) $\Rightarrow$ $\mathbf{AF}_{=d}$ receive(switch)]))

Before E_b**:** **A**((**AG**[receive(entering) $\Rightarrow$ $\mathbf{AF}_{=d}$ receive(switch)]) **U** E_b)

Between E_b **and** E_e**:**
P=**AG**[receive(entering) $\Rightarrow$ $\mathbf{AF}_{=d}$ receive(switch)]
AG(($E_b \wedge \neg E_e$)$\rightarrow$(P) **U** E_e)

Figure 5: Punctuality Pattern.

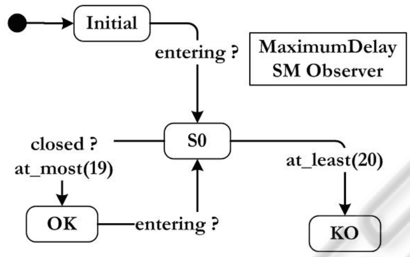
2) The 2^{nd} requirement states that the command signal *closed* should be detected at most 19 seconds after *entering* signal. This requirement consists in **maximumdelay** property (Figure 6) of 19 time units between *entering* and *closed* signals.

MaximumDelay Pattern

Pattern Name: MaximumDelay

Textual Description: The MaximumDelay pattern is used to check if event execution is delayed by at most a given value ℓ time units from a given reference. This value ℓ should be in [0, T_{max}] interval.

UML SM Diagram:



Structured English: *Scope* "closed" **must occur Before a delay of** "19" **tu over** "entering".

Temporal Logic description:

Globally: **AG**[receive(entering) $\Rightarrow$ $\neg$closed $U_{\leq 19}$ receive(closed)]

After E_a**:**
AG($E_a \rightarrow$(**AG**[receive(entering) $\Rightarrow$ ($\neg$closed $U_{\leq 19}$ receive(closed))]))

Before E_b**:**
A((**AG**[receive(entering) $\Rightarrow$ ($\neg$closed $U_{\leq 19}$ receive(closed))]) **U** E_b)

Between E_b **and** E_e**:**
P=**AG**[receive(entering) $\Rightarrow$ ($\neg$closed $U_{\leq 19}$ receive(closed))]
AG(($E_b \wedge \neg E_e$)$\rightarrow$(P) **U** E_e)

Figure 6: MaximumDelay Pattern.

5.3 Verification

The above step consists in instantiating the appropriate patterns in order to obtain observers for the extracted requirements. These observers are then translated into TA models to be synchronized with the system specification. The verification process consists in examining the reachability of the ***KO***-states within the observers. The verification of our case study is carried out using the UPPAAL model checker.

6 CONCLUSIONS

In this paper, we have presented a model-based method applicable to formal specification and validation of time-constrained systems. The approach uses a set of observation patterns that we have established and which act as watch-dogs for the defined temporal requirements. Each pattern has been defined using a standard template we developed. Using patterns offers genericity and reusability.

On the other hand, we have developed a transformation algorithm to translate SM with time annotations into TA. The aim being to make a basis for the verification process. For this purpose, we have introduced a TA metamodel using an extended definition of the original TA definition given by (Alur and Dill, 1994) (for briefness reasons, the TA metamodel description is omitted in this paper). Once the relationships (transformations rules) between UML SM metamodel elements and TA metamodel elements are defined, we expressed them in the **QVT** (**Q**uery/**V**iew/**T**ransformation) language, defined by the OMG as the standard for the transformation phase. Then we used QVTo -an Eclipse Plugin- to run the algorithm.

Processing the verification upon the TA observers synchronized with the system specification reduces the verification task to a reachability analysis of the **KO**-nodes within the observers.

Validation of the model transformation algorithm we have developed is a key issue to ensure the correctness of our approach. Hence, a rigorous validation step is still needed where several properties should be checked such as; syntactic and behavioral equivalence, termination and confluence (Küster, 2006).

Based on the structured English grammar we have developed, a prototype tool which offers interesting facilities in terms of requirements specification and requirements consistency-check has been implemented. A subsequent step will be to extend this tool with a new module which automatically instantiates observers for the entered requirements using the observation patterns repository.

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