

A Methodology for Structured Object-Oriented Elicitation and Analysis of Temporal Constraints in Hardware/Software Co-analysis and Co-design of Real-Time Systems

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Abstract

The hardware/software co-design of a high-quality real-time system relies heavily on the modeling of both the hardware and software components from three aspects: structures, functionalities, and constraints, especially the temporal constraints. However, there is not a systematic process for the elicitation and analysis of temporal constraints in hardware/software co-design. Furthermore, existing object-oriented methods provide no means for the explicit specification of system/component constraints in object models. This paper presents a systematic methodology for structured object-oriented analysis and specification of temporal constraints in hardware/software co-analysis and co-design using an extended High-Order Object-Oriented Modeling Technique (HOOMT). This methodology hierarchically elicits and analyzes the temporal constraints in hardware/software co-design based on the integration of the High-Order Object Model (HOOM) and Hierarchical Timed Automata (HTA). It helps to identify temporal constraints of hardware and software components as well as their interactions level by level. In addition, it helps trace the relationships among these constraints at multiple levels during the co-design of real-time systems. A case study from the hardware/software co-design of the simulated FACTS Power Transmission System is used to illustrate the feasibility and merits of this methodology.

Keywords

Temporal Constraints, Hardware/Software Co-analysis, Hardware/Software Co-design, Structured Object-Oriented Elicitation and Analysis, Hierarchical Decomposition.

1. Introduction

The design of a highly dependable real-time system

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relies heavily on the modeling of its 1) structure, 2) functionalities, and 3) constraints, especially its temporal constraints. It is desirable for designers to obtain the critical information that is relevant to either hardware or software components from all the three aspects in the object model. However, problems emerge during the hierarchical co-analysis and co-design of an advanced electric power transmission system [3] [15].

First, current object-oriented analysis and design techniques lack the notation to explicitly specify the temporal constraints of a real-time system in the object models, especially in the case of hardware/software co-analysis and co-design where the temporal constraints for hardware and software components as well as the interactions between them need to be clearly specified.

Second, very few object-oriented methods provide a built-in capability for the analysis of the relationships (such as traceability analysis) among elicited hardware and software temporal constraints at multiple abstract levels.

In order to integrate the relationship analysis of temporal constraints with the existing hierarchical hardware/software co-analysis and co-design of the advanced electric power transmission system, a process for the hierarchical elicitation and analysis of temporal constraints is needed.

Because traditional object-oriented modeling techniques do not provide a structured approach for the integrated analysis of object structure, hierarchical object-oriented techniques have been proposed [4] [7] [11] [13] [18]. However, these hierarchical OO techniques do not specify temporal constraints in the object models. In addition, built-in structural analysis of temporal constraints is not available in these techniques.

Timed automata is considered an appropriate technique for the modeling and verification of temporal behaviors. Khatib et al. proposed to transform existing temporal constraints into timed automata for model checking [12]. However, the issue of where to obtain these temporal constraints is not addressed.

Efforts have also been made to integrate object-

orientation with timed automaton to capture and verify the temporal behavior of a real-time system. A common approach is to transform the OO dynamic models into timed automata for verification [1] [16] [17]. Similar to the object-oriented modeling techniques, it is difficult to model a complex system using a flattened network of timed automata. Thus, hierarchical modeling techniques, such as Hierarchical Timed Automaton (HTA), were proposed by researchers [2] [6] [14]. HTA is capable of capturing and verifying the temporal behaviors at multiple levels. However, there is not a systematic process for the hierarchical elicitation and analysis of temporal constraints based on the integration of HTA and hierarchical OO techniques.

In view of the above problems, a more systematic hierarchical process for the elicitation, analysis, and representation of temporal constraints for the hardware/software co-design of real-time systems is developed during the hardware/software co-analysis and co-design of an advanced electric power grid. The High-Order Object-Oriented Modeling Technique (HOOMT) [3] [13] [15] was extended to incorporate the temporal constraints in the co-analysis/co-design object models, and a hierarchical temporal constraints elicitation and analysis methodology was developed.

The remainder of this paper introduces the HOOMT extension and the hierarchical temporal constraints elicitation and analysis methodology as follows. Section 2 introduces the hardware/software co-analysis and co-

design process from the perspective of temporal constraints. Section 3 presents a methodology for the hierarchical elicitation of hardware and/or software temporal constraints in hardware/software co-analysis and co-design. Section 4 illustrates the hierarchical elicitation methodology with an application example from the development of an advanced electric power transmission system. Section 5 contains the conclusion of this paper.

2. Co-analysis and Co-design Process from the Perspective of Temporal Constraints

The elicitation and influence of temporal constraints in a hardware/software co-analysis and co-design process is illustrated in Figure 1. The system objectives, which are derived from the voices of customers and the voices of developers, guide the development of the co-analysis and co-design models, including both the object models and the dynamic models. The co-analysis and co-design models can be decomposed in a hierarchical manner. As the co-analysis and co-design models become more detailed, their temporal behaviors can be refined accordingly. As a result, more specific temporal behaviors can be derived.

Temporal constraints are derived from temporal behaviors and the system functionalities, which are specified in the design models. Three types of temporal constraints can possibly be elicited: hardware temporal constraints, software temporal constraints, and constraints

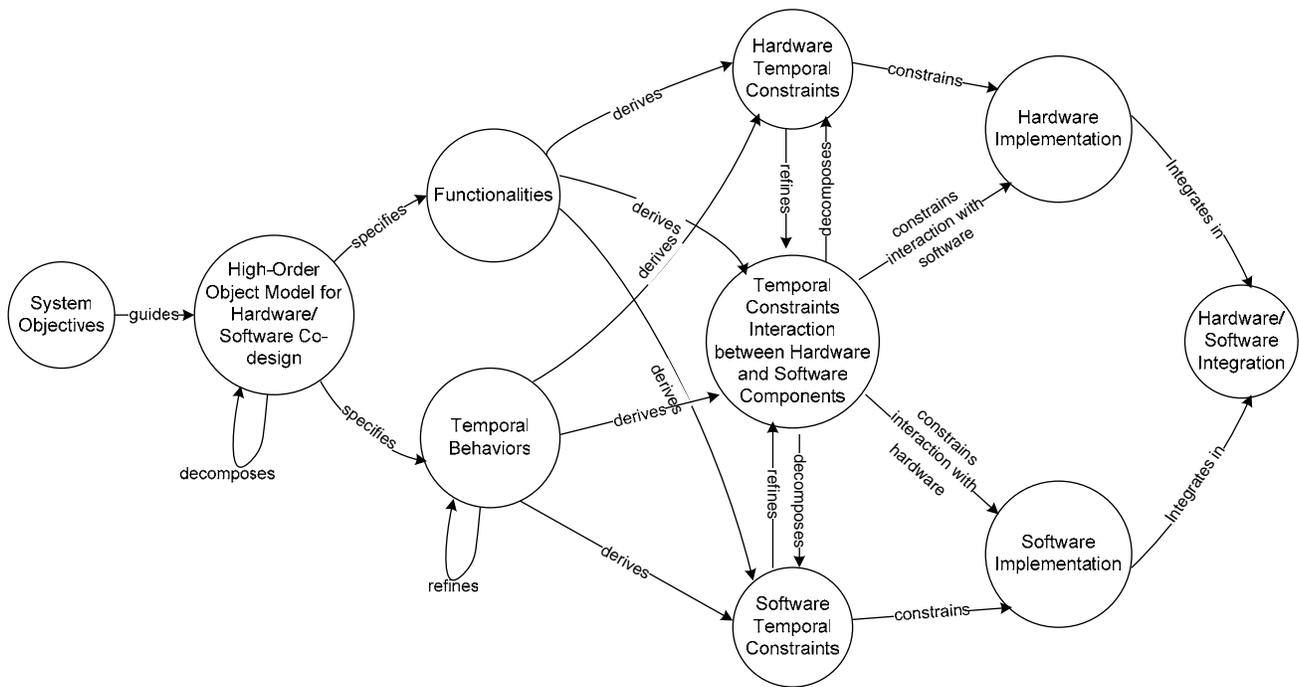


Figure 1. Hardware/Software Co-analysis and Co-design Process from the Perspective of Temporal Constraints

hardware/software co-analysis and co-design is that they make it easier for the designers of hardware and software components to divide their responsibilities.

The temporal constraints in the expression format as mentioned above can be transformed into temporal logics or natural language statements as needed. During the implementation of the hardware and software components, temporal assertions can also be derived from these constraints to monitor the dynamic behaviors of the hardware and software components in real time.

3.2. Hierarchical Elicitation of Temporal Constraints Based on HOOM and HTA

With the constraints box introduced to the objects in the object model, the next question is how to derive the temporal constraints, which can be entered in that box. Considering that HOOMT supports the object-oriented analysis and design of the system in a hierarchical manner, temporal constraints can be elicited with the help

of HTA, which is also hierarchical. Below are the detailed steps in the elicitation process.

Step 1: The top-level object model is developed with the system objectives being its constraints. As shown in the first column in Figure 3, the object model contains both the object decomposition and the high-level temporal constraints. They serve as the basis for the generation of the states and state transitions in the HTA.

Step 2: For each level of the object model, one or more timed-automata can be developed. In case the state transitions are complex, the timed-automata can be further refined for more details. This is illustrated in the second column in Figure 3. The optional “refines” arrow denotes the possibility of HTA refinement.

Step 3: The timed-automata are analyzed to produce temporal constraints. As mentioned in the previous subsection, these temporal constraints are specified in the expression format, which is composed of variables and values as shown in the last two columns in Figure 3. These expressions can easily be inserted in the program

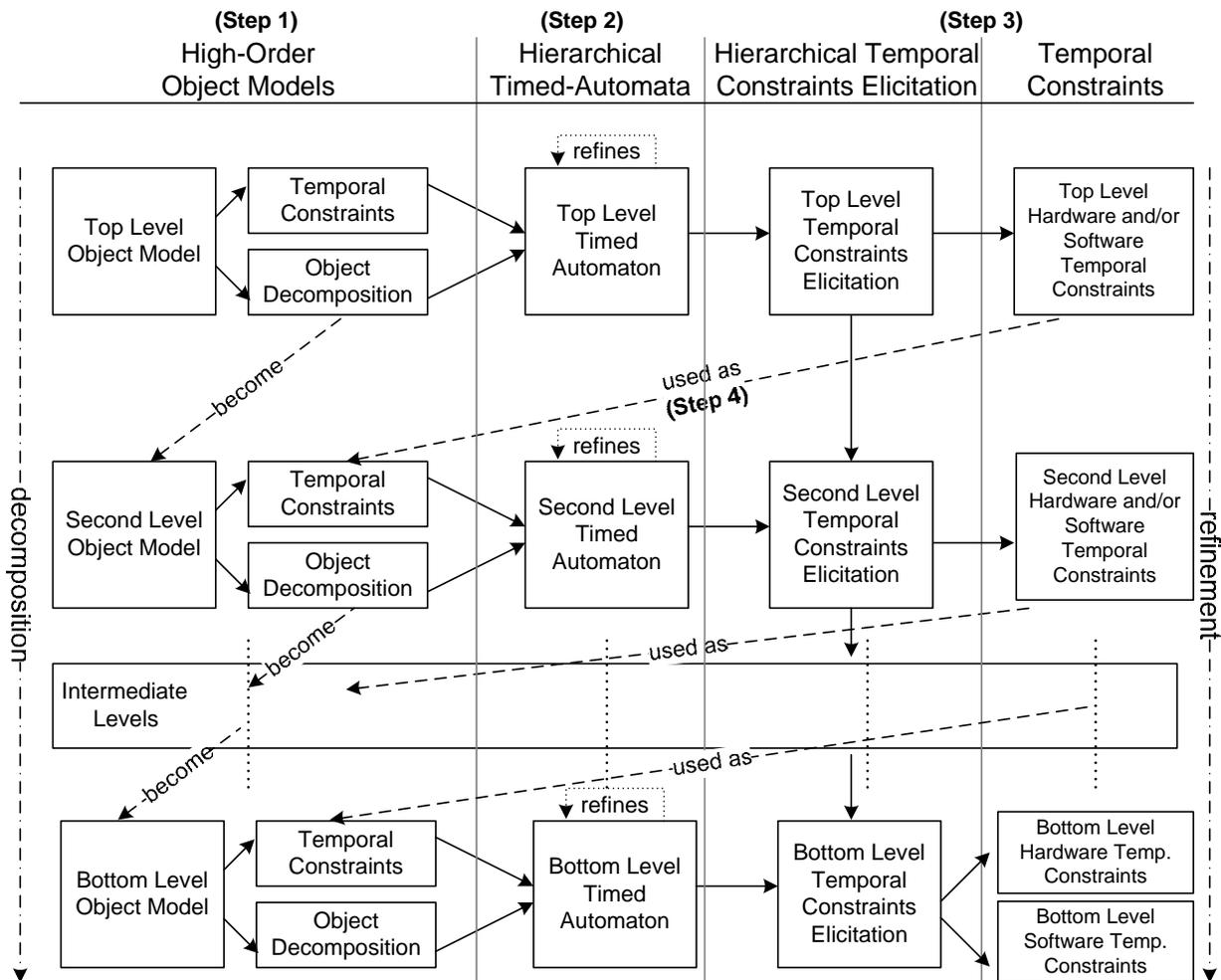


Figure 3. Hierarchical Elicitation of Temporal Constraints Based on HOOM and HTA

code as safety assertions. They can also be transformed to temporal logics or natural language statements as needed.

In each level of the hierarchical analysis, the temporal constraints may come from two sources: a) the decomposition of a constraint at a higher level, and b) the observation of the timed automata.

Because of the hierarchical characteristics of the object model and HTA, each of the constraint expressions needs to be examined for the possibility of decomposition. If a variable in an expression is not primitive, then it needs to be decomposed into new expressions consisting of variables relevant to the current-level object models and HTA.

It is also possible that the states and/or state transitions in the HTA reflect the interactions among the sub-objects in the object model. If the interactions are invisible to the upper-level HTA and are not reflected by any of the variables in the upper-level constraints, then there is no way to obtain them from decomposition. In this case, new temporal constraints are derived from the observation of HTA, and they are only applicable to this particular level of object model and HTA.

As mentioned earlier, in hardware/software co-analysis and co-design, the temporal constraints need to be specified explicitly as either hardware constraints or software constraints or both. In this way, the tasks for hardware and software designers are clearly assigned. This is specified in the last column in Figure 3.

Step 4: Each of the sub-objects in the object model at this particular level is decomposed into a low-level object model. The temporal constraints derived at this level can be used as the temporal constraints of the corresponding sub-objects in the low-level object model (illustrated by the “used as” arrow in Figure 3). They are entered in the constraints box of the corresponding sub-objects.

Step 5: Steps 2 to 4 are repeated for the following levels of objects. This hierarchical process is repeated when the primitive objects are modeled and the primitive temporal constraints are derived.

3.3. Relationship Analysis of Temporal Constraints at Multiple Levels

Because this methodology for the elicitation of temporal constraints is hierarchical, the analysis of the relationships among the elicited temporal constraints is straightforward. A tree-like graph as shown in Figure 4 can be used to illustrate all the temporal constraints elicited using this methodology.

The tree-like graph grows as the elicitation moves down the hierarchy, with each temporal constraint represented as a node. One-direction arrows (solid edges) are used to show the decomposition linkages. If a

temporal constraint is not derived from the decomposition, then it has no parent node. However, it must have relationships with the other temporal constraints at the same level. This relationship is represented as double direction arrows (dotted edges). For instance, in Figure 4, the temporal constraints of TC 0.0.1 and 0.0.0.1 have no parents because they are not derived from the decomposition of any high-level temporal constraints. However, TC 0.0.1 is related to TC 1.1.2. Thus, they are linked with a dotted edge.

Using this graph, a primitive temporal constraint can be traced backward to its ancestors, which justifies its existence. For instance, in Figure 4, the temporal constraint of TC 1.1.2.1 can be justified by showing that it contributes to the satisfaction of TC 1.

On the other hand, a high-level temporal constraint can be traced down the tree-like structure to its lowest descendant. This shows the designers what needs to be achieved in order to satisfy this high-level constraint. Figure 4 shows that in order to satisfy TC 1.1, primitive TC 1.1.1, TC 1.1.2.1, and TC 1.1.2.2 must be satisfied.

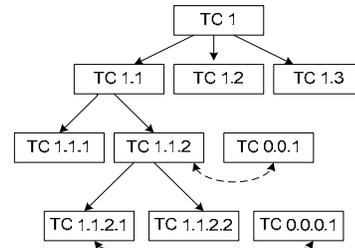


Figure 4. Temporal Constraints Relationship Analysis Graph

4. Application Example

Using the hierarchical temporal constraints elicitation and analysis methodology, a case study was conducted for the design of an advanced electric power grid, in which a number of FACTS (Flexible AC Transmission System) devices are used to monitor and adjust the power flows in a simulated power transmission system in real-time. The HOOMT is used for the hardware/software co-analysis and co-design of such a real-time system.

As introduced in Section 3, the HOOM is expanded to incorporate the temporal constraints. The temporal constraints are elicited hierarchically with the help of the object model and HTA. Due to the page limitation, only a portion of the results is shown in Figure 5. In order to show the process of the elicitation and analysis, the results are organized in the same format as shown in Figure 3.

The whole elicitation and analysis starts with the system objectives. As illustrated at the top of Figure 5, the objective of this advanced power grid is to be able to respond to contingencies in the system in a timely manner.

Objective of FACTS Power System:
System is responsive to contingencies in a timely manner

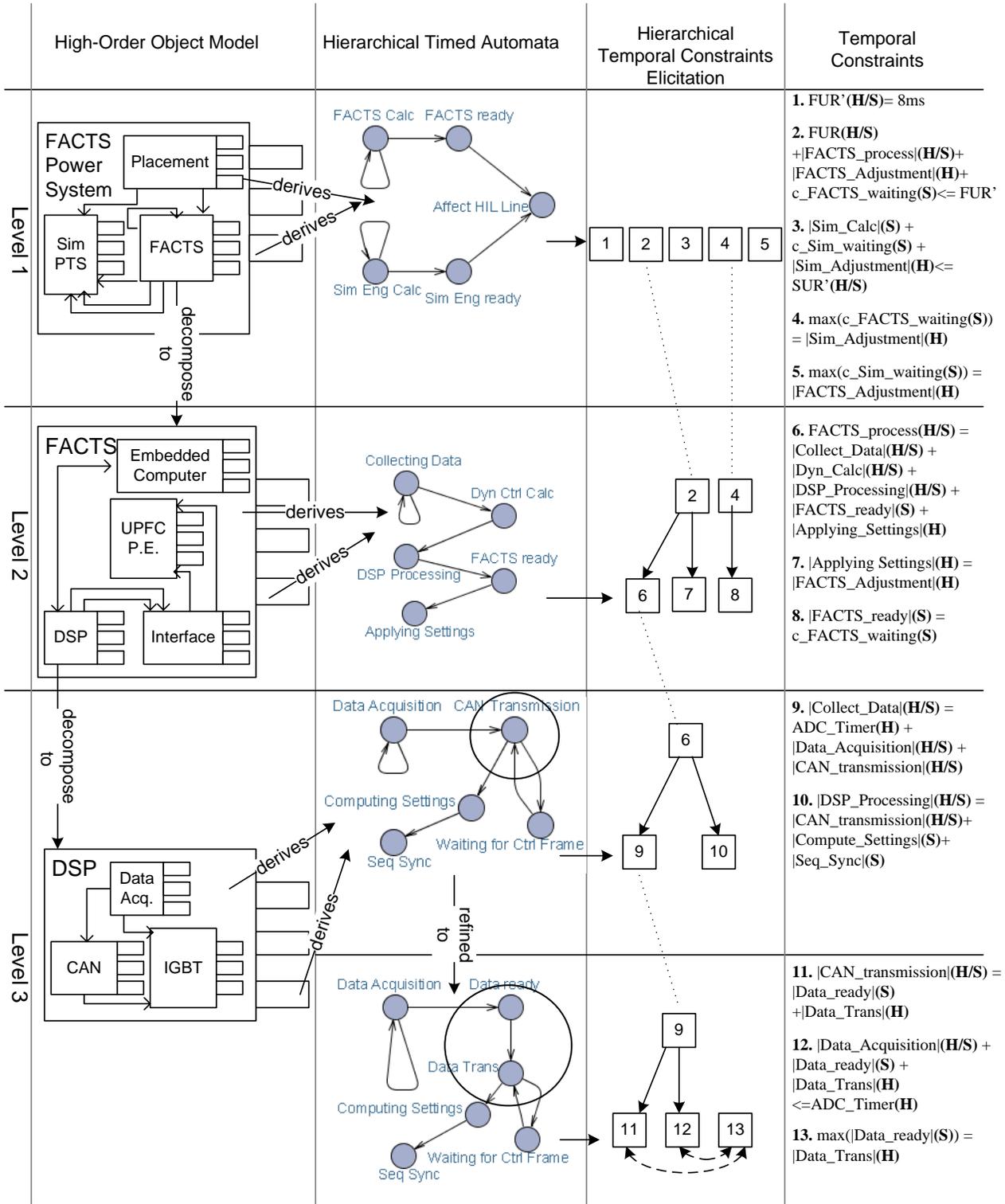


Figure 5. Hierarchical Temporal Constraints Elicitation and Analysis for FACTS Power Transmission System

This main objective guides the whole hardware/software co-analysis and co-design. The object decomposition is shown in the first column of Figure 5. Starting at the top of the hierarchy, the whole simulated FACTS power system should satisfy the main objective. Thus, a timed automaton is generated with the aim of satisfying this objective. Based on the analysis of the timed automaton, five high-level temporal constraints are derived. They are listed in the right column.

In order to relate the responsibilities of the hardware and software designers to the temporal constraints, each of the constraint variables is marked with either *H* (hardware constraint), *S* (software constraint), or *H/S* (constraint involving both hardware and software components). An example of the object model with elicited temporal constraints entered in the constraints box is shown in Figure 2.

Because the object model at this level is abstract, each of its sub-objects is decomposed. In Figure 5, the FACTS device object is chosen to illustrate the decomposition.

Relevant temporal constraints (constraints 1, 2, and 4) are selected from the five Level-1 constraints and entered in the constraints box of the FACTS object. Based on the Level-2 object structure and the relevant temporal constraints, a Level-2 timed automaton is developed and analyzed. Each of the temporal constraints of the FACTS object is examined. If any of the constraint variables is not primitive, then it is decomposed/refined to more detailed constraints. For instance, the variables of *FACTS_process* and *FACTS_adjustment* in Temporal Constraint 2 are not primitive. Thus, Temporal Constraint 2 is further decomposed to constraints 6 and 7. Similarly, Temporal Constraint 4 is refined to a new constraint relevant to a state in the HTA of this particular level. Again, the variables in the new temporal constraints are specified as either *H*, *S*, or *H/S*. The new constraints are entered in the constraints boxes of the corresponding sub-objects.

The same process is repeated for each level of the hierarchy. It should be noted that, as shown in Level 3 of Figure 5, for the same level object model, the timed automata can be refined to multiple levels. The circled states in Figure 5 showed the refinement. Thus, the temporal constraints can also be refined to multiple levels.

Because each of the variables in the temporal constraints is marked with *H*, *S*, or *H/S*, these temporal constraints can easily be used in the implementation and testing of the development of software and hardware components.

As mentioned in Section 3, new temporal constraints can also be elicited from the observation of HTA instead of from the decomposition. In Figure 5, Temporal Constraint 13 is:

$$\max(|Data_ready|(S) - |Data_Trans|(H)).$$

This temporal constraint is not derived from the

decomposition of any upper-level constraints. However, it put an upper limit to one of the variables in temporal constraints 11 and 12 (*Data_ready*). Thus, instead of having a solid edge from an upper-level constraint, it is connected with dotted edges to temporal constraints 11 and 12.

After the temporal constraints are elicited, they can be justified by using the technique introduced in Section 3.3. The analysis graph is illustrated in the third column of Figure 5. The high-level temporal constraints are linked to their descendents, and the primitive temporal constraints are linked back to their ancestors if available. If needed, these temporal constraints can be further specified formally and then verified.

5. Conclusion

The hardware/software co-analysis and co-design of a real-time system such as the advanced FACTS power transmission system needs the analysis and explicit specification of temporal constraints of hardware components, software components, and their interactions in a structured manner. However, there has been a lack of such a temporal constraints elicitation, analysis, and specification method in current object-oriented modeling techniques. This paper introduces a methodology for the elicitation and analysis of temporal constraints, thus making three contributions. (1) It extends the structured object-oriented modeling technique, HOOMT, by adding a constraints box to each of the objects in the object model. This allows the explicit specification of the temporal constraints corresponding to specific objects, which is beneficial to the hardware/software co-analysis and co-design of a real-time system. (2) This methodology integrates the hierarchical modeling techniques of HOOMT and HTA to provide a systematic process for the hierarchical elicitation of temporal constraints. (3) It also presents a method for the relationship analysis among temporal constraints. This methodology follows a top-down approach by decomposing and refining the temporal constraints to more detailed ones relating to lower-level objects in the real-time system. This shows what need to be satisfied level by level in order to achieve the overall temporal objective. If necessary, these temporal constraints can also be verified from the bottom up to prove that by satisfying the primitive temporal constraints, the overall objectives can be met. This verification step will be a future extension of the methodology.

6. References

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