A Methodology for Synthesizing Formal Specification Models From Requirements for Refinement-based Object Code Verification

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Abstract—**Formal verification has become the bedrock for ensuring software correctness when dealing with safety-critical systems. One of the biggest obstacles in applying formal techniques to commercial systems is the lack of formal specifications. Software requirements are expressed only in natural language. We present a structured approach for synthesizing formal models from natural language requirements. Synthesizing formal specification models from natural language requirements is a hard problem. Our approach is structured in that, while our procedures do most of the work in the synthesis process, it allows for structured input from the domain expert. The uniqueness of this paper is the novel approach that can synthesize natural language requirements to formal specifications that are useful for refinement-based verification, a formal verification technique that is very effective for the safety-critical Internet of Things (IoT) embedded systems. A number of safety requirements for insulin pumps have been used to demonstrate the effectiveness of the approach.**

Keywords–requirements analysis; safety-critical IoT embedded devices; formal model; formal verification.

I. INTRODUCTION

Ensuring the correctness of control software used in safety-critical embedded devices is still an ongoing challenge. For example, from 2001 to 2017, the Food and Drug Administration (FDA) has issued 54 Class-1 recalls on infusion pumps (medical devices used to deliver controlled doses of fluid medications to patients intravenously) due to software issues [1]. Class-1 recalls are applied to medical device models whose use can cause serious adverse health consequences or death. With the advent of IoT, such safety-critical embedded devices incorporate a whole slew of additional functionality to interface with the network and other components, in addition to their core control functions. These additional functions significantly exacerbate the challenge of ensuring that the core functionality of the control software is correct and intact.

The use of formal verification has become an industry standard when addressing software correctness of safety-critical devices. There are many success stories and commercial adoption of formal verification processes. Examples include Intel [2], Microsoft [3] and [4], and Airbus [5].

Refinement-based verification [6] is a formal verification technology that has been demonstrated to be applicable to the verification of embedded control software at the object-code level [7]. In formal verification and refinement-based verification, typically the design artifact to be verified is called the implementation and the specification is a formal model that captures the correct functionality of the implementation. The goal of refinement-based verification is to mathematically prove that the implementation behaves correctly as defined by the specification. In refinement-based verification, both the implementation and specification are modeled as transition systems.

One of the key features of refinement-based is the use of refinement maps, which are functions that map implementation states to specification states. In practice, these refinement maps have a very favorable property in that they abstract out behaviors of the implementation not relevant to the specification, but only after determining that these additional behaviors do not actually impact the behaviors of the implementation relevant to the specification. This property of refinement maps makes the refinement-based verification very suitable for the verification of control software used in IoT devices as refinement maps can be used to abstract out the additional functionality of software in IoT devices; again, only after determining that these additional functionality are not impacting the behavior of the core functionality of the implementation as defined by the specification.

One of the crucial challenges in applying refinement-based verification to commercial devices is the availability of formal specifications. For commercial devices, typically, the specification of a device is given as natural language requirements. There are many approaches towards transforming natural language requirements to formal specifications, however none targeted towards refinement-based verification. In this paper, we present a methodology for transforming natural language requirements into formal specifications that can be used in the context of refinement-based verification.

The rest of the paper is organized as follows. An overview of the background is presented in Section II. Section III details the related work. A formal model describing the synthesis procedure is presented in Section IV. Section V details the case study. Section VI gives the verification results for the proposed formal model. Conclusions and direction for future work are noted in Section VII.

II. BACKGROUND

This section explores the parsing tree and the definition of transition systems as main topics related to our work.

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A. Parsing tree

A parse tree is an ordered tree that pictorially represents how words in a sentence are connected to each other. The connection between each word in the sentence gives the *syntactic categories* for the sentence. The parsing process represents the syntactic analysis of a sentence in natural language. For example, when the parsing process is applied on a simple sentence like "Adam eats banana", the parse tree categorizes the two parts of speech: N for nouns (Adam, banana) and V for the verb (eats). Here N, V are the syntactic categories. The parsing process is considered to be a preprocessing step for some applications, where natural language should be converted into other forms. Usually, the system requirements are written in natural language, which needs to be converted into a structural form that can then be used to create the transition system(s) (explained in Section II-B). Enju [8] is an English consistency-based parser, which can process very long complex sentences like system requirements using an accurate analysis (the accuracy relation is around 90 percent of news articles and bio-medical papers). Besides, Enju is a high-speed parser with less than 500 msec per sentence. The output is the resulting tree in an XML format which is considered to be one of the commonly used formats by various applications. As will be described later, the case study used to describe the proposed methodology is from the bio-medical area, Enju was the perfect tool as the natural language processing (NLP) parser.

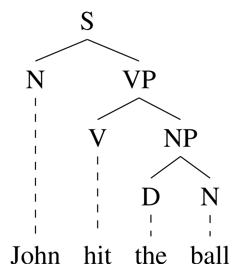

Figure 1. A simple example of a parsing tree using Enju parser [9].

Figure 1 shows a simple tree example using Enju. Here, Enju distinguishes between terminal nodes (John is a terminal node) and non-terminal nodes (VP is a verb phrase). The abbreviations of the syntactic categories of Figure 1 are: S stands for sentence (the head of the tree), N stands for noun, VP stands for verb phrase (which is a subtree), NP stands for noun phrase, V stands for verb, and finally D stands for determiner (comes with noun phrases). Using these syntactic categories, we have developed an extraction technique that would help in translating the natural language to a formal model of the requirements.

B. Transition systems

The implementation and specification in refinement-based verification are represented using Transition Systems (TSs) [6], [7]. The definition of a TS is given below:

Definition 1: A TS $M = \langle S, R, L \rangle$ is a three tuple in which S denotes the set of states, $R \subseteq SXS$ is the transition relation that provides the transition between states, and L is a labeling function that describes what is visible at each state.

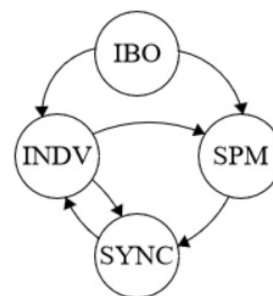

Figure 2. An example of a transition system (TS).

An Atomic Proposition (AP) is a statement that can be evaluated to be either true or false. The labeling function maps state to the APs that are true in every state. An example of a TS is shown in Figure 2. Here S = {IBO, SPM, SYNC, INDV}, R = {(IBO, SPM), (SPM, SYNC), (SYNC, INDV), (INDV, SYNC), (INDV, SPM), (IBO, INDV)} and, $L(SPM)$ represents the atomic propositions that are true for the SPM state. Similarly, labeling function can be applied to all the states in this TS.

III. Related Work

In the last few years, there has been a tremendous growth in finding the optimal technique of requirement transformation into a formal model. While most of them proposed system-driven models, our approach is user-driven to ensure a safe product.

Automatic Requirements Specification Extraction from Natural Language (ARSENAL) [10] is a system based framework that applies some semantic parsers in multi-level to get the grammatical relations between words in the requirement. ARSENAL transforms natural language requirements into formal and logical forms expressed in Symbolic Analysis Laboratory (SAL) (a formal language to describe concurrent systems), and Linear Temporal Logic (LTL) (a mathematical language that describes linear time properties) respectively. The LTL formulas are then used to build the SAL model. Multiple validation checks are applied on Natural Language Processing (NLP) stage and LTL formulas to check for their correctness. However, ARSENAL records some inaccuracies in NLP stage that need a user intervention.

Aceituna et al. [11] have proposed a front end framework that builds a model to exhibit the system behavior (for synchronous systems only) and help in creating temporal logic properties automatically. This framework can be used before applying the model checking technique, it exposes accidental scenarios in the requirements. The framework is designed in a manner that helps in understanding the errors in a non-technical manner for users who do not have a formal background. In contrast, our work does not need the temporal logic in defining the specifications for a model.

A semantic parser has been developed by Harris [12] to extract a formal behavioral description from natural language specifications. The proposed semantic parser was employed to extract key information describing bus transactions. The natural language descriptions are then converted to verilog (a hardware description language) tasks.

Kress-Gazit et al. [13] have proposed a human-robot interface to translate natural language specification into motions.

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This interface allows a user to instruct the robot using a controller. LTL formulas are employed to formalize the desired behavior requested by the user.

An approach supporting property elucidation (called PROPEL) has been introduced by Smith et al. [14], it provides templates that capture properties for creating property pattern. Natural language and finite state automation are used to represent the templates.

Two approaches have been proposed by Shimizu [15] to solve the ambiguity of natural language specifications using formal specification. The first approach simplifies the formal specification development for the popular PCI bus protocol and the Intel Itanium bus protocol. The second approach explains how formal specifications can help in automating many processes that are now done manually.

A natural language parsing technique has been used with the default reasoning, which is a requirement formalism to support requirement development, this work helps stakeholders to easily deal with requirements in a formal manner, in addition, a method has been proposed for discovering any existed requirements inconsistencies. A prototype tool called CARL was used for implementation and verification by Zowghi et al. [16].

Gervasi et al. [17] have also worked on solving the requirement's inconsistencies issues by using a well-known formalism called monotonic logic, it has been used especially for requirement's transformation. Multiple natural language processing tools [18]–[21] in additional to grammatical analysis methodologies for requirement's development have been done to get requirements in a formal manner.

However, the main advantages of our work over prior algorithms in requirements engineering is its ability to generate a full formal model directly from natural language requirements by an expert supervision to emphasis on the safety transformation. Also, our work does not require that the expert user know any temporal logic languages.

IV. Formal Model Synthesis Procedure

The first step to computing the TSs is to extract the APs from the requirements. We have developed three Atomic Proposition Extraction Rules (APERs) that work on the parse tree of the requirement obtained from Enju. The resulting APs are then used to compute the states and transitions. The APERs are described next.

A. Atomic Proposition Extraction Rule 1 (APER 1)

APER 1 is based on the hypothesis that noun phrases in a requirement correspond to APs. Each subtree of the parse tree with an NX root (called an NX head) corresponds to a noun phrase and hence an AP. Therefore, APER 1 computes the subtrees corresponding to NX heads. If NX heads are nested, then the highest-level NX head is used to compute the AP. The terminal nodes of the subtree are conjoined together to form the noun phrase. APER 1 returns AP-list, which is the set of APs corresponding to a parse tree.

We now describe the procedure corresponding to APER 1 in detail. Firstly, AP-List is initialized to the empty set (line 1). The procedure then iterates through each terminal node n (line 2). The head of a node is its parent. If a terminal node is part of an NX subtree, its level two head will be marked as NX, which

Procedure 1 APER1

Require: Parse-tree
1: AP-list $\leftarrow \emptyset$;
2: **for each** $n \in$ TerminalNodes(Parse-tree) **do**
3: Start-cat = head(head(n));
4: **if** Start-cat = NX **then**
5: $X =$ Sub-tree(Start-cat);
6: **while** (head(X) = NX) $\vee$ (head(X) = COOD) $\vee$ (head(X) =NX-COOD) **do**
7: $X =$ Sub-tree(head(X));
8: AP-list $\leftarrow$ AP-list $\cup$ TerminalNodes(X) ;

is checked in line 3. The level-two NX node of the terminal node is stored in variable State-cat. If the Start-cat is of NX category (line 4), a function called Sub-tree is used to get the resulting subtree (line 5), which is stored in variable X. A while loop is used to traverse the tree of X upwards checking if the head syntactic category is NX or COOD or NX-COOD (line 6). Only when one of the conditions is satisfied the subtree is stored in X (line 7). The terminal nodes of the resulting sub tree 'X' will be added to AP-List as a new suggested AP (line 8). Figure 3 gives a sub tree example for APER 1. Note that APER 1 may result in the same AP being duplicated. Duplicates are checked and removed from the AP list in the overall approach.

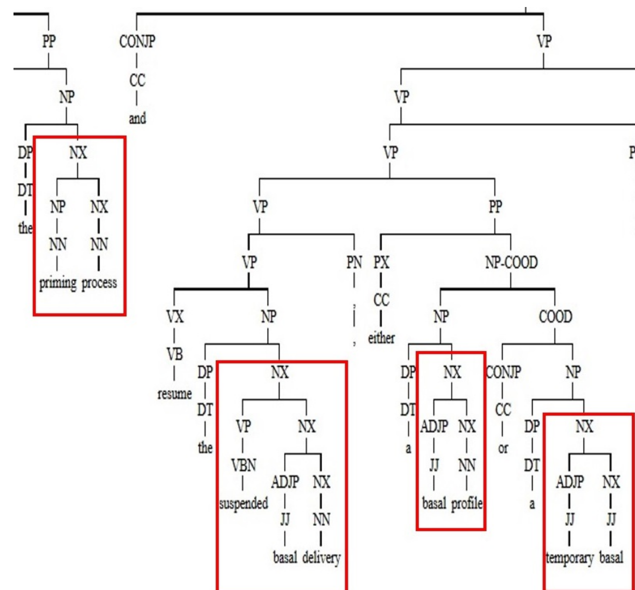

Figure 3. An Enju parsing tree portion shows some resulting APs by applying APER 1.

As shown in Figure 3, the terminal nodes 'the' and 'priming' does not have head(head(n)) = NX. The first terminal node that has the NX category is 'process'. Traversing upwards, the NX related categories gives us the subtree which contains 'priming process'. This now constitutes the first AP for this part of requirement. Applying the APER 1 rule on the visible part of the sentence in Figure 3 gives us the following APs: 'priming process', 'suspended basal profile', 'basal profile', and 'temporary basal'.

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B. Atomic Proposition Extraction Rule 2 (APER 2)

APER 2 and APER 3 correspond to the two other parse tree patterns that also lead to noun phrases. APER 2 examines the parse tree for noun categories along with its upper verb head. APs will be the conjoined terminal nodes of the resulting sub tree. APER 2 states that APs are the terminal nodes under the head VP passing through NX (or its related phrases such as NX-COOD, COOD), NP (or its related phrases NP-COOD, COOD), and VX phrase. APER 2 is built on top of APER 1

Procedure 2 APER 2

Require: Parse-tree
1: AP-list $\leftarrow \emptyset$;
2: **for each** $n \in$ TerminalNodes(Parse-tree) **do**
3: Start-cat = head(head(n));
4: $X_1 \leftarrow \emptyset$;
5: **if** Start-cat = NX **then**
6: X = Sub-tree(Start-cat);
7: **while** (head(X) = NX) $\vee$ (head(X) = COOD) $\vee$ (head(X) =NX-COOD) **do**
8: X= Sub-tree(head(X));
9: **while** (head(X) = NP) $\vee$ (head(X) = COOD) $\vee$ (head(X) = NP-COOD) **do**
10: X_1 = Sub-tree(head(X));
11: **if** (head(X_1) = VX) $\wedge$ (head(head(X_1)) = VP) **then**
12: X = Sub-tree(head(head(X_1));
13: **else**
14: **if** (head(X_1) = VP) **then**
15: X = Sub-tree(head(X_1);
16: AP-list $\leftarrow$ AP-list $\cup$ TerminalNodes(X);

to get atomic propositions for requirements that APER 1 is not able to collect. While APER 1 looks only for APs that are noun phrases, APER 2 looks for noun phrases that are further characterized by verb phrases. For example, if APER 1 finds the AP "suspended basal delivery," APER 2 will find "resume the suspended basal delivery."

APER 1 and APER 2 have the same algorithmic flow until finding the sub tree of X that is the top NX head (line 8). However, APER 2 does not consider the resulting X to be an AP like APER 1 does. Instead, X is the input of the next step. A while loop is used to search if the head category of X is in NP category or one of its related phrases (line 9). Only when the while loop condition is true, the new sub-tree is stored temporarily in the variable X_1 (line 10), where X_1 is a temporary variable initialized to null (line 4). This ensures that X does not change in this step for future use. The search for VX and VP categories is to be performed only when X_1 is not null.

On the successful completion of NP category search, the search for VX category followed by VP categories is performed (line 11). When the if condition is satisfied, X is updated with the new sub-tree (line 12). In the case of failure of the if condition in line 11, a new search for VP category is performed on the head of NP category sub-tree (line 14). On success, X is updated with the new sub-tree (line 15). If either of the if conditions (line 11 and line 14) fail, then X will remain as the sub-tree of NX category. The terminal nodes of the resulting subtree in X is appended to the AP-list (line 16). Figure 4 shows a resulting sub tree example by applying APER 2. Figure 4 shows that the procedure starts from left to right

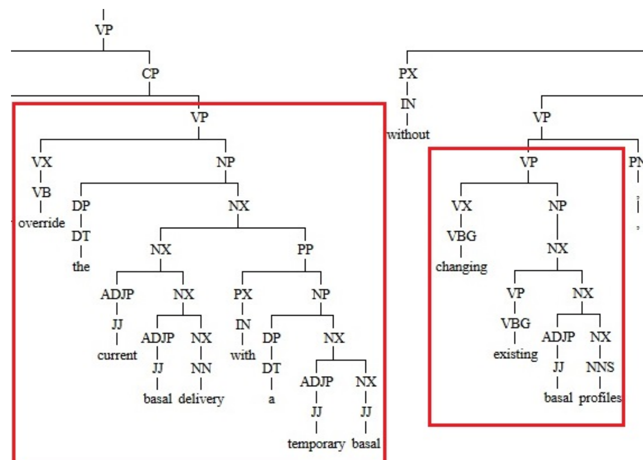


Figure 4. An Enju parsing tree portion shows some resulting APs by applying APER 2.

looking for level two NX nodes and traversing upward until higher NX nodes are accounted for. NP phrases are selected to expand the tree. Then choosing the upper level which is VP in this particular case (sometimes its VX $\rightarrow$ VP). The output of APER 2 for this tree portion is 'override the current basal delivery with a temporary basal', and 'changing existing basal profiles'.

C. Atomic Proposition Extraction Rule 3 (APER 3)

APER 3 is built on top of APER 2, it explores the verb head levels in the parse tree like APER 2, but APER 3 eliminates some verb phrases that is not part of APs. This elimination is done based on the head of the VP category as illustrated in Procedure 3 below. APER 3 and APER 2 have the same stream up to line 10. The algorithm starts with initializing temporary variables X_1 and Y to null (line 4). The search for syntactic categories start with the top NX phrase (line 7) and the resultant sub tree is stored in X (line 8). Then, the search begins for the top NP phrase (line 9) and the resultant sub tree is stored in X_1 (line 10) since the sub tree in X is needed for future use. As in APER2, the search for either VX phrase followed by VP phrase or just VP phrase is performed on X_1 and the resultant sub tree is stored in Y (lines 11-15). If and only if Y is not empty then the check on the head syntactic category is performed to ensure that it does not contain CP or COOD categories. In this case, X gets only the right child (line 16-18) i.e. the left child of Y is pruned. On the other hand, if Y has a CP or COOD head, X value will be updated to be equal to Y (line 20). Finally, terminal nodes of the resulting sub tree X will be saved in the AP-list as a new AP. The pruning process (line 18) is done to remove some action verbs which are not part of an AP.

Like APER2, APER3 also works on verb head categories. However, APER3 has some pruning techniques to remove parts of the sentence that should not be part of an AP. Consider the snippet in Figure 5, the sub tree "issue an alert" is subjected to left branch pruning to remove the verb 'issue' since such verbs do not add value in the AP. According to the algorithm, since the head node of VP is COOD, only the terminal nodes of the

Procedure 3 APER 3

Require: Parse-tree
1: AP-list $\leftarrow \emptyset$;
2: **for each** $n \in$ TerminalNodes(Parse-tree) **do**
3: Start-cat = head(head(n));
4: $X_1 \leftarrow \emptyset$, $Y \leftarrow \emptyset$;
5: **if** Start-cat = NX **then**
6: $X =$ Sub-tree(Start-cat);
7: **while** (head(X) = NX) $\vee$ (head(X) = COOD) $\vee$ (head(X) =NX-COOD) **do**
8: $X =$ Sub-tree(head(X));
9: **while** (head(X) = NP) $\vee$ (head(X) = COOD) $\vee$ (head(X) = NP-COOD) **do**
10: $X_1 =$ Sub-tree(head(X));
11: **if** (head(X_1) = VX) $\wedge$ (head(head(X_1)) = VP) **then**
12: $Y =$ Sub-tree(head(head(X_1));
13: **else**
14: **if** (head(X_1) = VP) **then**
15: $Y =$ Sub-tree(head(X_1);
16: **if** ($Y \neq \emptyset$) **then**
17: **if** head(Y) $\neq$ CP) $\wedge$ (head(Y) $\neq$ COOD) **then**
18: $X =$ Sub-tree(RightChild(Y));
19: **else**
20: $X = Y$;
21: AP-list $\leftarrow$ AP-list $\cup$ TerminalNodes(X);

right child are considered as an AP. Applying APER 3 on the visible part of the requirement in Figure 5 gives the following APs: 'pump', 'an alert', and 'deny the request'. The proposed

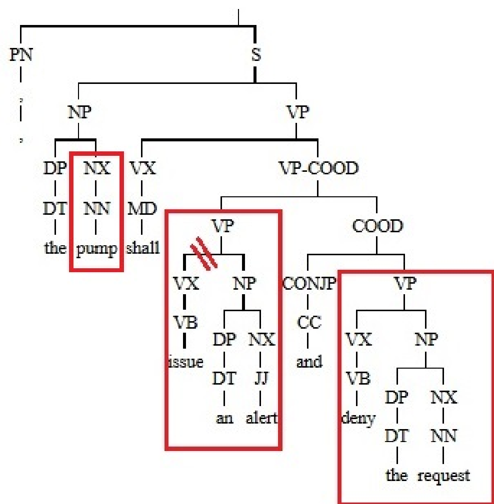


Figure 5. An Enju parsing tree portion shows some resulting APs using APER 3.

APERs may be used individually or in combination depending on the system requirement and model functionally. However, no one rule is considered to be the best for all models because of the natural language structure.

Procedure 4 Procedure for synthesizing TSs from system requirements

Require: set of requirements (System-requirements)
1: TS-set $\leftarrow \emptyset$;
2: **for each** $Req \in$ System-requirements **do**
3: Parse-tree $\leftarrow$ Get(Req_tree.xml);
4: AP-list $\leftarrow$ APER(Parse-tree);
5: AP-list $\leftarrow$ Eliminate_Dup(AP-list);
6: AP-list $\leftarrow$ USR_IN(AP-List);
7: AP-truth-table $\leftarrow$ Relation(AP-list);
8: AP-truth-table $\leftarrow$ USR_IN(AP-truth-table);
9: S-list $\leftarrow \emptyset$;
10: **for each** A $\in$ AP-truth-table **do**
11: S-list[i] = A_i ;
12: S-list $\leftarrow$ USR_IN(S-list);
13: T $\leftarrow$ CreateT(S-list);
14: T $\leftarrow$ USR_IN(T);
15: TS $\leftarrow$ CreateTS(T, S-list);
16: TS-set $\leftarrow$ TS-set U TS;
17: return TS-set;

D. High-Level Procedure for Specification Transition System Synthesis

Procedure 4 shows the overall flow for computing the TSs. A set of system requirements in natural language are fed as input to the procedure. TS-set is the output of the procedure and will contain the set of transition systems that capture the input requirements as a formal model. TS-set is initialized to null (line 1). Each requirement is input to the Enju parser. The parser gives an xml file as output. A function called Get is used to obtain the xml file into the variable Parse-tree (line 3). The xml output in Parse-tree is subjected to the proposed APERs, which give the atomic propositions (APs) as output. APs are stored in the AP-list (line 4). Each requirement is subject to all APERs and the AP-list obtained is the union of the APs produced by each of the rules. The output obtained by using the APERs may contain duplicates, which are eliminated by using the function Eliminate_Dup (line 5). AP-list is then subjected to an expert user check, where the AP(s) might be appended, eliminated or revised based on the expert user's domain knowledge (line 6). Some of the APs maybe expressible as a boolean function of other APs.
Therefore, next, a truth table (AP-truth-table) is created, where each row corresponds to an AP from AP-list and each column also corresponds to an AP from AP-list (line 7). Each entry in the table is a Bolean value (true or false). Completing the truth table determines the relationship of each AP with the other APs in the AP-list. The truth table is completed by the expert user (line 8). The list of states for the input requirements are stored in the variable S-list. S-list is initialized to null (line 9). Each truth table entry (A) is defined to be a single state in the transition system (line 10). This heuristic has worked well in practice. S-list is subjected to expert user input (line 12).

The transitions of the TS are computed next. The list of transitions (T) is initialized to a transition between every two states using function 'CreateT' (line 13). The transition list is subjected to expert user input (line 14). A transition system (TS) is constructed using the CreateTS function, which takes the transitions (T) and the list of states (S-list) as input (line

15). This transition system (TS) is then added to the transition system set (TS-set) (line 16). The procedure finally returns a set of transition systems for all the requirements in an application (line 17).

V. Case Study: Generic Insulin Infusion Pump (GIIP)

Insulin pump is a medical device that delivers doses of insulin 24 hours a day to patients with diabetes. It is typically used to keep the blood glucose level in an acceptable range. Overdose of insulin can lead to low blood sugar that can lead to coma/death. Therefore, the insulin pump is a safety-critical device.

Requirement 1.8.2: *When the pump is in suspension mode, insulin deliveries shall be prohibited. Any incomplete bolus delivery shall be stopped and shall not be resumed after the suspension.*

The Generic Insulin Infusion Pump (GIIP) has been proposed [22], which lists a set of safety requirements for insulin pumps. We use these safety requirements for our approach.

As an example, consider requirement 1.8.2 (from [22]) which is needed to address a hazard that may happen in the suspension mode of the pump. Suspension mode can occur when the pump may be in refill or priming or insulin delivery processes. The insulin pump has two type of insulin deliveries: bolus and basal. Bolus is a high insulin rate that is recommended in case of low blood glucose level. From safety requirement 1.8.2, it is clear that the pump should not resume a suspended bolus automatically after returning from suspension since they would be an unexpected amount of insulin.

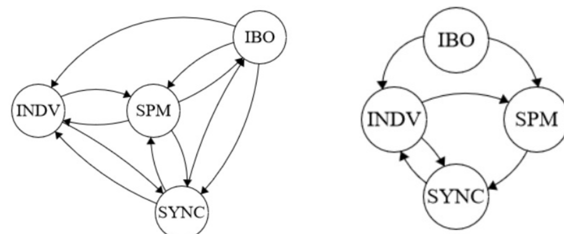
Requirement 1.8.5: *When the pump resumes from suspension, calculations shall be performed to synchronize insulin used and remaining reservoir volume.*

Requirement 1.8.5 is an extension of how the pump should function after returning from the suspension mode. Here two requirements are needed to address one safety hazard. When algorithm 4 is applied on these two requirements, the first step is collecting the APs by using the extraction rules. Applying APER 2 on 1.8.2 gives: ”pump”, ”suspension mode”, ”insulin deliveries”, ”incomplete bolus delivery”, and ”suspension”. Applying APER 2 on 1.8.5 gives: ”pump”, ”suspension”, ”calculations”, and ”synchronize insulin used and remaining reservoir volume”. Next, duplicate APs are to be removed. This eliminates ’pump’ and ’suspension’ from the AP-list. Now, the expert user intervenes for manipulating the AP-list, where APs can be deleted, modified or even inserted based on the expert user’s domain knowledge. This yields the final AP-list as ”suspension mode” (SPM), ”insulin deliveries” (INDV), ”incomplete bolus delivery” (IBO) and ”synchronize insulin used and remaining reservoir volume” (SYNC). Next, the AP-truth-table to define relations between APs is constructed as shown in Table I.

Here, each row represents a state. For example, SPM represents a state where suspension mode is true, IBO is false, INDV is false, and SYNC is also false; which emphasizes that insulin bolus should not be active during suspension. Finally, Procedure 4 applies transitions between every two states as shown in Figure 6a. The expert user will approve or remove some unacceptable transitions. Figure 6b shows the final transition system.

TABLE I. AP-TRUTH-TABLE FOR REQUIREMENT 1.8.2 AND 1.8.5 FROM AP-LIST

APs → ↓	SPM	INDV	IBO	SYNC
SPM	T	F	F	F
INDV	F	T	F	F
IBO	F	T	T	F
SYNC	F	F	F	T



(a) TS with all suggested transitions. (b) TS after removing some transitions.

Figure 6. Finite state machine for pump suspension requirements (1.8.2, 1.8.5).

VI. Results Analysis

Evaluation of the presented approach is performed using the NuSMV model checker. A model checker is a tool that can check if a TS satisfies a set of properties. The properties have to be expressed in a temporal logic. Here, we have used CTL to express the properties. The CTL properties were written manually for each of the requirements that were subjected to our approach. NuSMV was used to check if the TSs synthesized by the presented approach satisfied the CTL properties corresponding to that requirement.

Table II shows the results of applying Procedure 4 on a number of GIIP requirements. The requirement numbers in the table are from [22]. All the final TSs satisfied their corresponding CTL properties. Each requirement or set of requirements (listed in column 1) have been subjected to the extraction rules (column 2), where column 3 shows the total number of APs resulting from each extraction rule. Column 4 gives the number of APs after removing the duplicate APs. In addition, a record of the suggested expert user intervention for adding, removing or modifying the APs is shown in column 5. The final number of APs, states, and transitions are shown in column 6.

As shown in the table, when a requirement is subjected to the APERs, the resultant output from each APER may be different even though the number of APs is the same. For requirements 1.8.2 and 1.8.5, although applying APER1, APER2, and APER3 give the same number of APs, APER1 gives different list of APs from APER2 and APER3.

VII. Conclusion and Future Work

The key ideas of our approach for transforming requirements into transition systems are the following. The extraction rules work on the parse tree to get an initial list of APs. The AP truth table is used to establish relationships between the initial list of APs. For example, an AP may be expressible as a conjunction of two other APs. The initial expert user pruned

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TABLE II. RESULTING TRANSITION SYSTEMS BY APPLYING THE GENERAL ALGORITHM AND APERS ON A SET OF SYSTEM REQUIREMENTS

Req. NO.	APER	Total No. of APs	No. of APs Without DP	User input			Final		
				AP added	AP removed	AP modified	APs	states	transitions
1.1.1	1	10	10	0	6	0	5	4	5
	2	10	10	0	5	0			
	3	10	10	0	6	0			
1.1.3	1	7	7	0	3	2	4	4	4
	2	7	7	0	3	2			
	3	7	7	0	3	1			
1.2.4 , 1.2.6, 1.2.7	1	24	12	3	5	1	10	10	14
	2	24	18	0	8	0			
	3	24	16	2	8	0			
1.3.5	1	11	6	1	3	0	4	4	4
	2	11	8	0	4	1			
	3	11	8	1	5	0			
1.8.2, 1.8.5	1	9	7	1	3	1	4	4	5
	2	9	7	0	3	0			
	3	9	7	0	3	0			
2.2.2, 2.2.3	1	6	6	0	3	1	3	3	4
	2	7	6	0	3	1			
	3	7	6	0	3	2			
3.1.1	1	15	14	0	9	0	5	3	3
	2	14	12	0	7	0			
	3	14	13	0	8	0			
3.2.5	1	10	9	0	7	2	3	3	3
	2	7	7	0	4	1			
	3	7	7	0	4	1			
3.2.7	1	4	4	0	1	0	3	3	3
	2	4	4	0	1	1			
	3	4	4	0	1	0			

list of APs gives insight into the states of the transition system. We have found empirically that having one state for this initial pruned AP list is a good heuristic to compute the states of the transition system. Transitions are applied between every two states and then pruned by the expert user.

Transforming natural language requirements into formal models is quite a hard problem and hard to get right without input from domain expert. Our approach sets up a very structured process, where the tool does lot of the work in analyzing and synthesizing TSs, but also allows for input from domain expert. The proposed methodology has worked very well in practice for the GIIP requirements. All the TSs computed for the requirements satisfied their corresponding CTL properties. For future work, we plan to address requirements with real-time constraints. The corresponding formal model will be timed transition systems.

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