Towards Feature-Oriented Requirements Validation for Automotive Systems

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***Abstract*—In the modern automotive industry, feature models have been widely used as a domain-specific requirements model, which can capture commonality and variability of a software product line through a set of features. Product variants can thus be configured by selecting different sets of features from the feature model. For feature-oriented requirements validation, the variability of feature sets often makes the hidden flaws such as behavioral inconsistencies of features, hardly to avoid. In this paper, we present an approach to feature-oriented requirements validation for automotive systems w.r.t. both functional behaviors and non-functional properties. Our approach first starts with the behavioral specification of features and the associated requirements by following a restricted use case modeling approach, and then formalizes such specifications by using a formal yet literate language for analysis. We demonstrate the applicability of our approach through an industrial application of a Vehicle Locking-Unlocking system.**

***Index Terms*—feature-oriented requirements modeling; model-based requirements validation; eTASM; RUCM; software product lines; systems functional behaviors and non-functional properties**

I. Introduction

With the growing maturity and standardization of the automotive domain, requirements specifications for automotive systems tend to center around the concept of feature models. Feature models [1] are proposed to capture the commonality and variability within a software product line by using features, between which there are relations and constraints. Further, a feature [2], [3] is a logical unit of functionality comprehensible to end-users, which consists of the requirements (i.e., the feature requirement hereafter) associated with the feature and the corresponding behavioral specification (i.e., the feature behaviors hereafter). A product can be configured by selecting a set of features (i.e., the feature set hereafter) from a feature model. The validity of a feature set refers to two situations: 1) one is from the structural perspective, i.e., the selected features should conform to the constraints defined by the feature model and, 2) the other is from the functional perspective, i.e., no undesirable behaviors exist between two or more (as integrated) feature behavioral specifications. In order to increase the confidence of the validity of the feature set, several feature-oriented requirements validation techniques [3], [4], [5], [6], [7], [8] have been developed. However, it is well recognized that with the increasing size of feature models, the inherent variability of the feature sets leads to an inevitable issue that the hidden flaws of features are difficult to avoid [9]. Especially, the feature interaction problem (referring to the situation that two or more features exhibit unexpected behaviors) cannot be detected when the features are used in isolation.

As the unexpected behaviors can result in uncertainties and even hazards of automotive systems, adequate efforts on detecting the unexpected feature interactions thereby must be applied in the early stages of the pertaining development process. In the literature, there are many examples [7], [10], [11] where the process starts with translating the natural language specification (NLS) of a feature into a formal language specification (FLS) of the feature behaviors, and then the requirements validation is performed based on the generated formalisms. To our best knowledge, the main drawbacks of using NLS lie in: 1) ambiguities in the NLS cause imprecise definitions and even wrong understanding of the feature behaviors and, 2) the direct translation from the NLS to a FLS tends to be very costly and, 3) the NLS hinders to a large extent the possibility of performing automatic feature-oriented requirements validation.

To challenge the feature interaction problem and make up for the deficiency in the current practice, in this paper we propose a model-based approach to feature-oriented requirements validation. To be specific, our approach firstly specifies features by using an informal yet restricted natural language (from scratch) without losing ease of use, and then formalizes a set of executable models based upon the aforementioned intermediate specifications to perform the requirements validation. The approach is comprised of four steps as follows:

- **Feature Specification** specifies the behaviors and requirements of features by following the restricted use case modeling (RUCM) approach [12], which adopts a generic use case template and several restriction rules to reduce ambiguity and facilitate further analysis.
- **Feature Behaviors Formalization** formalizes the feature behaviors in terms of a formal yet literate specification using the extended Timed Abstract State Machine (eTASM) language [13], which generates executable models for analysis.
- **Feature Requirements Formalization** models the fea-

ture requirements by using the Observers technique [13] in eTASM for validation purpose.

- **Feature Validation** performs three kinds of model-based validation checking to detect the hidden flaws in the selected features, including *Logical Consistency Checking*, *Coverage Checking*, and *Model Checking*.

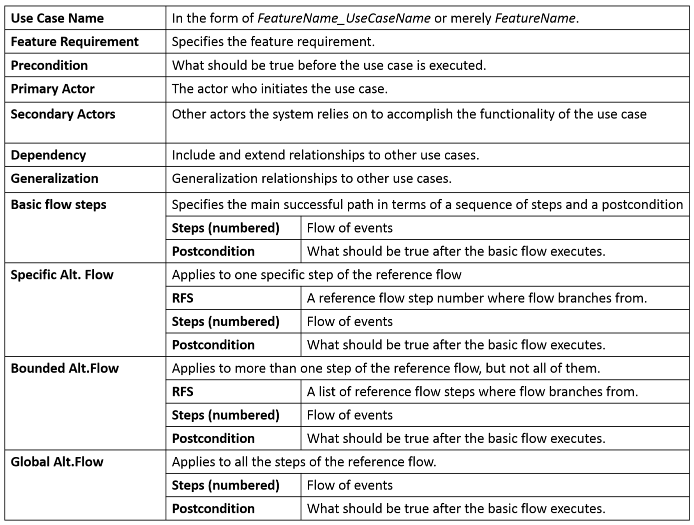
We also demonstrate the applicability of our approach through an illustration application, and the remainder of this paper is organized as follows: An introduction to the background knowledge is presented in Section II. Section III introduces the illustration application i.e., the Vehicle Locking-Unlocking (VLU) system. Our approach to feature-oriented requirements validation is described and illustrated by using the VLU system in Section IV. Section V discusses the related work, and finally concluding remarks and future work are drawn in Section VI.

II. Background

In this section, we briefly introduce the RUCM approach [12] and the formal specification language eTASM [13] used in our approach for a better understanding.

A. Restricted Use Case Modeling

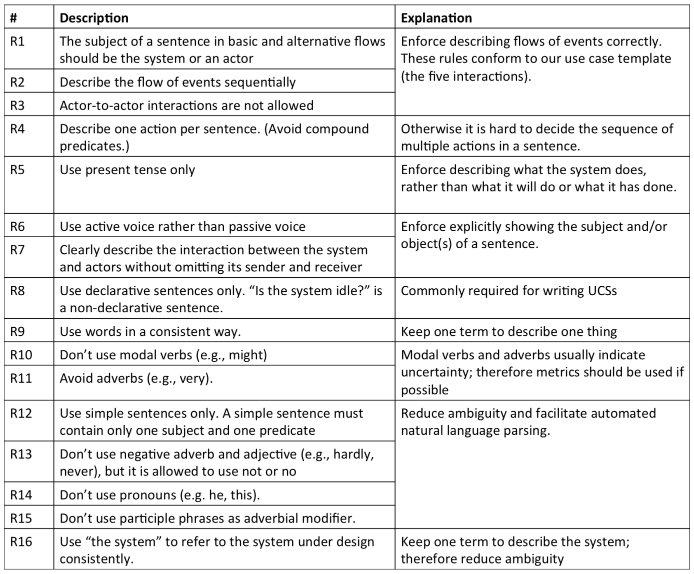
The restricted use case modeling (RUCM) [12] is a use case modeling approach that extends the UML [14] use case diagram by proposing a use case template and 26 restriction rules for reducing ambiguity and easing automated analysis. In our work, we specify features by populating the proposed use case template and following the restriction rules. In order to meet our needs, we make two slight modifications to the template. First, for the purpose of traceability, the use case name is required to follow the form of *FeatureName_UseCaseName* or merely *FeatureName*. Second, the *Basic Description* entry is replaced by *Feature Requirement* which specifies the requirement that the feature is associated with. Figure 1 shows the modified template and the brief explanation for each entry.



Use Case Name	In the form of *FeatureName_UseCaseName* or merely *FeatureName*.	
Feature Requirement	Specifies the feature requirement.	
Precondition	What should be true before the use case is executed.	
Primary Actor	The actor who initiates the use case.	
Secondary Actors	Other actors the system relies on to accomplish the functionality of the use case	
Dependency	Include and extend relationships to other use cases.	
Generalization	Generalization relationships to other use cases.	
Basic flow steps	Specifies the main successful path in terms of a sequence of steps and a postcondition	
	Steps (numbered)	Flow of events
	Postcondition	What should be true after the basic flow executes.
Specific Alt. Flow	Applies to one specific step of the reference flow	
	RFS	A reference flow step number where flow branches from.
	Steps (numbered)	Flow of events
	Postcondition	What should be true after the basic flow executes.
Bounded Alt.Flow	Applies to more than one step of the reference flow, but not all of them.	
	RFS	A list of reference flow steps where flow branches from.
	Steps (numbered)	Flow of events
	Postcondition	What should be true after the basic flow executes.
Global Alt.Flow	Applies to all the steps of the reference flow.	
	Steps (numbered)	Flow of events
	Postcondition	What should be true after the basic flow executes.

Fig. 1. The modified use case template of RUCM.

The feature behaviors are specified via use case flows, which are composed of one basic flow and one or more alternative flows. The basic flow specifies the main execution path in terms of a sequence of steps and a postcondition. Alternative flows specify execution branches when deviations occur somewhere in the reference flow that can be the basic flow or an alternative flow. There are three types of alternative flows: a specific alternative flow refers to a specific step in the reference flow; a bounded alternative flow refers to more than one step in the reference flow; a global alternative flow refers to all steps in the reference flow. RUCM defines 16 restriction rules to constrain the use of natural language, as shown in Figure 2. A set of keywords are also defined in the other 10 rules to specify control structures. For example, the keyword VALIDATES THAT (as shown in Figure 4) is used for condition checking. In particular, if the condition evaluates to be true, the current flow continues, otherwise an alternative flow will be executed. The detailed description of all the restriction rules and keywords are provided in [12].



#	**Description**	**Explanation**
R1	The subject of a sentence in basic and alternative flows should be the system or an actor	Enforce describing flows of events correctly. These rules conform to our use case template (the five interactions).
R2	Describe the flow of events sequentially	
R3	Actor-to-actor interactions are not allowed	
R4	Describe one action per sentence. (Avoid compound predicates.)	Otherwise it is hard to decide the sequence of multiple actions in a sentence.
R5	Use present tense only	Enforce describing what the system does, rather than what it will do or what it has done.
R6	Use active voice rather than passive voice	Enforce explicitly showing the subject and/or object(s) of a sentence.
R7	Clearly describe the interaction between the system and actors without omitting its sender and receiver	
R8	Use declarative sentences only. “Is the system idle?” is a non-declarative sentence.	Commonly required for writing UCSs
R9	Use words in a consistent way.	Keep one term to describe one thing
R10	Don’t use modal verbs (e.g., might)	Modal verbs and adverbs usually indicate uncertainty; therefore metrics should be used if possible
R11	Avoid adverbs (e.g., very).	
R12	Use simple sentences only. A simple sentence must contain only one subject and one predicate	Reduce ambiguity and facilitate automated natural language parsing.
R13	Don’t use negative adverb and adjective (e.g., hardly, never), but it is allowed to use not or no	
R14	Don’t use pronouns (e.g. he, this).	
R15	Don’t use participle phrases as adverbial modifier.	
R16	Use “the system” to refer to the system under design consistently.	Keep one term to describe the system; therefore reduce ambiguity

Fig. 2. The rules of RUCM to constrain the use of natural language.

B. The Extended TASM Language

eTASM [13] is a formal language for the specification of safety-critical systems, which extends the Timed Abstract State Machine (TASM) language [15] with the Observer and Event constructs. eTASM inherits the easy-to-use characteristic from TASM, which is a literate specification language understandable and usable without extensive mathematical training. An eTASM model consists of three parts – an environment, a set of machines, and a set of observers. The environment defines the set and the type of machine variables which machines can monitor or control, and the set of named resources which machines can consume. An machine consists of a set of monitored variables (which can affect the machine execution), a set of controlled variables (which machines can modify), and a set of machine rules. The set of rules specify the machine execution logic in the form of "if *condition* then *action*", where *condition* is an expression depending on the monitored variables, and *action* is a set of updates of the controlled variables. We can also use the rule "else then *action*" which is enabled merely when no other rules are enabled. A rule can specify the annotation of the time duration and resource consumption of its execution. The duration of a rule execution can be the keyword *next* that essentially states the fact that time should elapse until one of the other rules is enabled. The observers will monitor the events triggered by the execution of machines, and each observer represents one correctness property of interests that should be satisfied by the proposed system. In the eTASM language, four types of events can be triggered: The *ChangeValueEvent* type is triggered by a specific eTASM environment variable whenever its value is updated, the *ResourceUsedUpEvent* is triggered by the case whenever the resource of the application is consumed totally, and the *RuleEnableEvent* and *RuleDisableEvent* are triggered whenever the corresponding eTASM rule is enabled or disabled, respectively. An observer is made up of an ObserverEnvironment, a Listener, and an Observation. The ObserverEnvironment defines a set of observer variables and an EventsFilter that filters out irrelevant event types to the observer. The Listener specifies the expected events sequence following the syntax and semantics of *regular expression*. The Observation indicates the monitoring result, i.e., whether the correctness property monitored by the observer is satisfied.

eTASM describes the basic execution semantics as the computing steps with time and resource annotations: In one step, it reads the monitored variables, selects a rule of which *condition* is satisfied, consumes the specified resources, and after waiting for the duration of the execution, it applies the update set instantaneously. During the execution, eTASM triggers events whenever possible. The events sequence is monitored by observers. Once an expected sequence is observed, the corresponding monitoring result will be concluded. As a specification language, eTASM supports the concepts of parallelism (which stipulates that eTASM machines are executed in parallel) and hierarchical composition (which is achieved by means of auxiliary machines which can be used in other machines). There are two kinds of auxiliary machines - *function* machines that can take machine variables as parameters and return an execution result, and *sub* machines that can encapsulate machine rules for reuse purpose [15]. Communication and interaction between machines can be achieved by defining corresponding environment variables.

III. Illustration Application

In this section, we describe a simplified Vehicle Locking-Unlocking (VLU) system, as a running example to illustrate our approach in this work. The proposed VLU system aims to replace the mechanical key, as a control access to a vehicle, and it follows a common pattern in feature-oriented requirements specification: The basic functionality is encapsulated as an individual feature, and additional/optional enhancements are specified as features that provide the increments in functionality. Specifically, such features are Central Locking (CL), Auto-lockout (AUL) and Anti-lockout (ANL). Figure 3 shows the features of the VLU system in the form of technical feature model tree which is presented in EAST-ADL [16].

Central Locking (a basic feature) locks and unlocks all the doors of the vehicle upon receipt of a command from the user key fob.

Auto-lockout (an optional feature) locks all the doors of the vehicle when a timeout expires after the vehicle has stopped. It provides a theft protection in case that the driver forgets locking the doors manually.

Anti-lockout (an optional feature) enables unlocking of the doors while a key is in ignition after the vehicle has stopped, of which purpose is to prevent the driver from being locked out of the vehicle.

In simple applications such as the one above, it is possible to manually analyze the interactions between features for requirements validation. However, the real-world systems often have a large number of complex features, making the pertaining manual analysis extremely time-consuming and error-prone. The main motivation for our approach is to provide a semi-automatic technique for feature-oriented requirements validation for automotive systems, by performing undesirable feature interaction analysis. In the rest of the paper, we will use the aforementioned simplified application to illustrate our approach for features modeling, features specification, and auto-detection of undesired interactions.

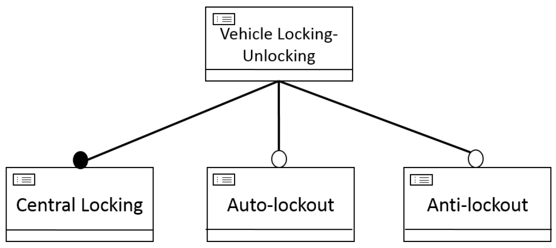


Fig. 3. The technical feature model tree of the VLU system.

IV. The Approach to Feature-Oriented Requirements Validation

In this section, we will introduce our approach that addresses the issue of formalizing and validating feature-oriented requirements specifications. In general, our approach is conducted in four steps as follows:

- **Step 1: Feature Specification** specifies the behaviors and requirements of features by using the RUCM use cases, which facilitates the further analysis.
- **Step 2: Feature Behaviors Formalization** formalizes the feature behaviors using the eTASM machines, which are executable analysis models.
- **Step 3: Feature Requirements Formalization** formalizes the feature requirements by using the eTASM Observer technique.

TABLE I
THE IDENTIFIED USE CASES AND CORRESPONDING FEATURE REQUIREMENTS.

Feature	Use case name	Feature requirements
Central Locking	CL_Lock	The system shall lock the doors
	CL_Unlock	The system shall unlock the doors
Auto-lockout	Auto-Lockout	The system shall automatically lock the doors after 20 seconds, when the vehicle has stopped
Anti-lockout	Anti-Lockout	The system shall anti-lock the doors if the key is in ignition and the vehicle has stopped

- **Step 4: Feature Validation** performs three types of checking by using model-based analysis techniques, to detect the hidden flaws in feature specifications.

We will go into details about each step by introducing the adhering sub-steps and show a running example to illustrate our approach. Specifically, Section IV-A introduces feature specification using the RUCM use cases. Section IV-B and Section IV-C discuss modeling of the behaviors and requirements of features respectively. Section IV-D presents the analysis and results of feature validation of the VLU system.

A. Feature Specification

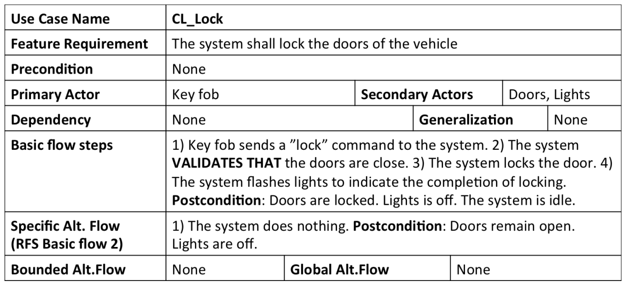
The Feature Specification step describes the features of a system in a restricted natural language, which can facilitate the further transformation from an informal specification to the formal one, for the purpose of validation. In this step, each feature will be specified by following the RUCM approach, and there are two sub-steps in our work as follows:

- **Step 1.1: Use Cases Identification**: Since a feature captures a set of cohesive functionalities in the form of requirements and corresponding behaviors, it is therefore necessary to split the functionalities and identify the possible use cases based on the expert's understanding of the feature.
- **Step 1.2: Use Cases Specification**: Use cases are specified by filling the RUCM template using a restricted natural language. In order to facilitate the further analysis, some predefined restriction rules must be followed.

In the VLU system, there are three selected features i.e., *CL*, *AUL* and *ANL* (as introduced in Section III). The specification of features, as an example, is illustrated by applying the proposed steps to the *CL* feature. To be specific, since the *CL* feature describes two opposite functionalities, two use cases can be thereby identified in terms of *CL_Lock* and *CL_Unlock*, as shown in Table I. Figure 4 and Figure 5 describe the filled use case templates of *CL_Lock* and *CL_Unlock*, respectively.

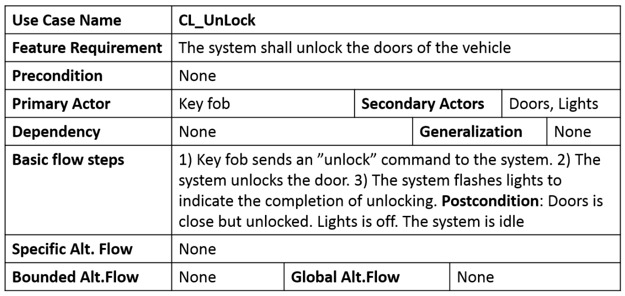
B. Feature Behaviors Formalization

This step is to analyze the specified RUCM templates and formalize the corresponding feature behaviors by using eTASM models which are executable simulation models for analysis. The Feature Behaviors Formalization step contains four sub-steps:



Use Case Name	**CL_Lock**		
Feature Requirement	The system shall lock the doors of the vehicle		
Precondition	None		
Primary Actor	Key fob	**Secondary Actors**	Doors, Lights
Dependency	None	**Generalization**	None
Basic flow steps	1) Key fob sends a "lock" command to the system. 2) The system **VALIDATES THAT** the doors are close. 3) The system locks the door. 4) The system flashes lights to indicate the completion of locking. **Postcondition**: Doors are locked. Lights is off. The system is idle.		
Specific Alt. Flow (RFS Basic flow 2)	1) The system does nothing. **Postcondition**: Doors remain open. Lights are off.		
Bounded Alt.Flow	None	**Global Alt.Flow**	None

Fig. 4. The CL_Lock use case of the CL feature.



Use Case Name	**CL_UnLock**		
Feature Requirement	The system shall unlock the doors of the vehicle		
Precondition	None		
Primary Actor	Key fob	**Secondary Actors**	Doors, Lights
Dependency	None	**Generalization**	None
Basic flow steps	1) Key fob sends an "unlock" command to the system. 2) The system unlocks the door. 3) The system flashes lights to indicate the completion of unlocking. **Postcondition**: Doors is close but unlocked. Lights is off. The system is idle		
Specific Alt. Flow	None		
Bounded Alt.Flow	None	**Global Alt.Flow**	None

Fig. 5. The CL_Unlock use case of the CL feature.

- **Step 2.1: System Constituents Identification** extracts the relevant system constituents referred in the RUCM use cases and specifies them in eTASM machines.
- **Step 2.2: Constituents Interaction Identification** identifies the interactions between different system constituents referred in the RUCM use cases and specifies them in eTASM environment variables.
- **Step 2.3: Machine Rules Specification** analyzes the possible states of identified machines and specifies feature behaviors by using a set of eTASM machine rules.
- **Step 2.4: Property Annotation** adds non-functional property annotations to the relevant eTASM machines.

1) System Constituents Identification: The identification of the system constituents from the use cases is of importance in the process to formalize the behaviors of the proposed system and model the scenarios for model-based validation. In order to do so, we recommend the following two tasks:

- *External Constituents Identification*: Use case actors are considered as external constituents which interact with the proposed system. The external constituents will be modeled to simulate the execution scenarios.
- *Internal Constituents Identification*: Each use case is considered to be an internal constituent, making up the proposed system. The internal constituents will be modeled to simulate the proposed system.

In this step, a list of eTASM machines w.r.t. the identified constituents is defined for the VLU system, as shown in Table II.

2) Constituents Interaction Identification: Two types of interaction between the sending constituent (i.e., sender) and receiving constituent (i.e., receiver) are considered in our

TABLE II
THE eTASM MACHINES IDENTIFIED FOR THE VLU SYSTEM.

Machine	Quantity	Category	Brief Description
KEY_FOB	1	External	model the key fob's behavior
LIGHT	1	External	model the light's behavior
DOORS	1	External	model the behavior of doors
IGNITION	1	External	model the behavior of ignition
VEHICLESPEEDSENSOR	1	External	model the behavior of vehicle speed sensor
CL_LOCK	1	Internal	lock doors
CL_UNLOCK	1	Internal	unlock doors
AUTO_LOCKOUT	1	Internal	lock doors when timeout expires
ANTI_LOCKOUT	1	Internal	anti-lock doors if key is in ignition

approach:

- *Data Transmission Interaction (DTI)* represents that data (such as the state information and various sensor values) are transferred from the sender to the receiver, which are modeled as eTASM environment variables. The variables are named as *sender_datatype* which denotes the transferred data. Line 2 in Figure 7 shows an example.
- *Data Modification Interaction (DMI)* represents that the data of the receiver is directly changed by the sender, which are modeled via directly modifying the value of the receiver's environment variable. The variables are named in the form of *receiver_datatype*, which denotes the modified data. One example can be found in Lines 9 and 10 in Figure 7.

Since RUCM requires the interaction between a system and an actor to be clearly described without omitting some information about its sender and receiver, it is therefore easy to identify interactions between constituents from the use case models. Figure 6 shows the identified interactions in our VLU system, which are twelve interactions. Further, the solid lines represent DTIs, and the dashed lines represent DMIs.

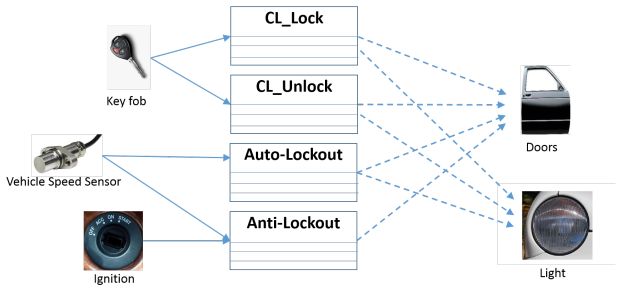


Fig. 6. The identified interactions between constituents in the VLU system.

3) Machine Rules Specification: The restricted use case flow sentences (e.g., in basic and/or alternative flows) can to a large extent facilitate the transformation from use case models to analysis models [17]. Based on the sentences specified in use case flows, we recommend the following sub-steps to specify the eTASM machine rules:

- *Identification of possible states of the corresponding constituent*: The possible states of a constituent can be identified via analyzing the adjectives and verbs in the use case flows. A user-defined type is used to represent the possible states, and a state variable is defined to denote the current state of the constituent.
- *Identification of the transition conditions of states*: The conditions of a certain machine rule are given, according to the pertaining values of the state variables and the transition conditions.
- *Identification of the actions when the system enters a specific state*: The actions of machine rules are specified, based on the behaviors of a constituent and the next possible state.

In our VLU application, there are five external constituents and four internal constituents under consideration, as shown in Table II. The KEY_FOB machine simulates the behaviors of a user's key fob. This machine has two possible states *lock* and *unlock*, in which the *lock/unlock* state denotes that the lock/unlock command is sent to the proposed VLU system. The LIGHT machine simulates the behaviors of the vehicle light, which has two states i.e., the *flashed* state and the *off* state. The *flashed* state denotes that the light flashes for several times. The DOORS machine simulates the behaviors of the vehicle doors, which has three possible states *open*, *close* and *locked*. The IGNITION machine simulates the behaviors of the vehicle ignition, which has two possible states *haskey* and *nokey*. The VEHICLESPEEDSENSOR machine simulates the behaviors of the vehicle speed sensor, which has two possible states *still* and *running*.

The CL_LOCK machine, as shown in Figure 7, models the CL_Lock use case. The machine has two possible states in terms of *idle* and *lockdoor*. The Rule *ReceiveCommand* represents that the system receives the lock command from the key fob. The Rule *Locking* represents that the system locks the doors. The Rule *Idle* keeps the machine alive and represents the system is idle. The CL_UNLOCK machine has similar rules, which will not be introduced for simplicity.

The AUTO_LOCKOUT machine, as shown in Figure 8, models the behaviors of the Auto-Lockout use case. The Rule *Timeout* represents that when the vehicle stops and the doors are close, the feature will be activated upon the timeout expires (i.e., 20s in our case). The Rule *Autolock* represents that the system is to automatically lock the doors. The Rule *Timer* represents the timer measuring time intervals. Rule *Idle* keeps the machine alive and represents that the timer will be reset either when the doors are open or when the vehicle starts running.

```
R1:ReceiveCommand{
  if cllock_state = idle and keyfob_cmd = lock then
    cllock_state := lockdoor;
    keyfob_cmd := NONE;
}
R2:Locking{
  t:=locking_time;
  if cllock_state = lockdoor then
    door_state := locked;
    light_state := flashed;
    cllock_state := idle;
}
R3:Idle{
  t := next;
  else  then
    skip;
}
```

Fig. 7. The eTASM main machine models the CL_Lock use case.

```
R1:Timeout{
  if aul_state = idle and door_state = close and
    vehicle_state = still and timer = 20 then
    aul_state := timeout;
    timer   := 0;
}
R2:Autolock{
  t:=locking_time;
  if aul_state = timeout then
    door_state := locked;
    light_state:= flashed;
    aul_state := idle;
}
R3:Timer{
  t := 1;
  if aul_state = idle and door_state = close and
     vehicle_state = still and timer < 20  then
    timer := timer + 1;
}
R4:TimerReset{
  t := next;
  else  then
    timer := 0;
}
```

Fig. 8. The eTASM main machine models the Auto-Lockout use case.

The ANTI_LOCKOUT machine, as shown in Figure 9, models the behaviors specified in the Anti-Lockout use case. The Rule *HasKey* represents that when the vehicle stops, the feature will be activated if the key is in ignition. The Rule *Antilock* represents that the system is to unlock the doors after activated. The Rule *Idle* keeps the machine alive and represents that the system is idle.

4) Property Annotation: Validation of non-functional requirements in this stage relies on the estimates of the pertaining non-functional properties of the proposed system. This step can be carried out in the following ways:

- The properties are determined based upon the non-functional requirements specified in the use cases.
- The properties are determined by using the experience or analysis of existing systems (in which estimates can be obtained by using existing well-known analysis methods, e.g., Worst-Case Execution Time (WCET) analysis [18], [19] for time duration of rules).

We annotate the aforementioned eTASM models with time durations, as shown in Figures 7, 8, and 9. The annotation terms *locking_time* and *unlocking_time* are either a specific value or a range of values.

```
R1:HasKey{
  if anl_state = idle and ignition_state = haskey and
     vehicle_state = still then
    anl_state := antilock;
}
R2:Antilock{
  t:=unlocking_time;
  if anl_state = antilock then
    door_state := close;
    anl_state := idle;
}
R3:Idle{
  t := next;
  else  then
    skip;
}
```

Fig. 9. The eTASM main machine models the Anti-Lockout use case.

C. Feature Requirements Formalization

Our approach proceeds with the formalization of feature requirements by using the eTASM Observer technique, which consists of four sub-steps as follows:

- **Step 3.1: Listener Specification** specifies the possible events sequence which represents the proposed system's observable functional behaviors and/or non-functional properties required by the feature requirements, and the corresponding actions taken on observer variables when the sequence is caught by a Listener.
- **Step 3.2: Observation Specification** formalizes a predicate depending on the observer variables. If the predicate of the Observation holds, i.e., evaluates to be true, it implies that the property satisfaction of the feature is achieved, as it can be observed in the proposed system.
- **Step 3.3: Events Filtering** identifies the interesting events and filters out the irrelevant events by specifying *EventsFilter*.
- **Step 3.4: Traceability Creation** links a specific Observer to the textual requirements. The link is used for requirements traceability from the formalization to natural language requirements in order to perform coverage checking.

In the VLU system, there are four feature requirements, i.e., *CL_Lock*, *CL_Unlock*, *Auto_Lockout* and *Anti_Lockout*. The specification of an observer is illustrated by applying the proposed steps to the *ANL* feature requirement. To be specific, the *ANL* feature requirement states "The system shall anti-lock the doors if the key is in ignition and the vehicle has stopped", and the interesting events sequence consists of three parts. The first part "ANTI_LOCKOUT→Haskey→RuleEnableEvent" denotes that the event is triggered when the Rule *HasKey* of the ANTI_LOCKOUT machine is enabled, modeling the behavior that the key is in ignition. The second part "[^(AUTO_LOCKOUT→Autolock→RuleEnableEvent | CL_LOCK→Locking→RuleEnableEvent)]*" represents an arbitrary number of events that are not triggered by the enabling of either the Rule *Autolock* of the AUTO_LOCKOUT machine or the Rule *Locking* of the CL_LOCK machine. Both of these two rules model the behavior that the doors are locked. The last part "ANTI_LOCKOUT->Idle->RuleEnableEvent" represents the event that is triggered when the Rule *Idle* of the ANTI_LOCKOUT machine is enabled, which models the situation in which the key is removed. If the events sequence is detected, the Observation "ov == true" evaluates to be true, which indicates the situation in which after the key is in ignition, the doors are not locked before the key is removed, i.e., the *ANL* feature requirement is satisfied in the eTASM model.

```
ObserverVariables:{
  Boolean ov := false;
}
EventsFilter:{
  filter out: ChangeValueEvent, ResourceUsedUpEvent,
              RuleDisableEvent;
}
Listener:{
  listening ANTI_LOCKOUT→Haskey→RuleEnableEvent
            [ˆ(AUTO_LOCKOUT→Autolock→RuleEnableEvent|
               CL_LOCK→Locking→RuleEnableEvent)]
            ANTI_LOCKOUT→Idle→RuleEnableEvent then
    ov := true;
}
Observation:{
  ov == true;
}
```

Fig. 10. The observer for the ANL feature requirement.

D. Feature Validation

Validation of the formalized requirements aims at increasing the confidence of the validity of selected features. In this work, we assume that there is a semantic equivalence relation between the RUCM use cases and eTASM models. This is built upon the fact that the eTASM models are derived, by following the proposed modeling steps as well as our thorough understanding of the VLU system. The validation goal is achieved by following several analysis steps, based on the use of the derived eTASM models which may help to pinpoint flaws that are not trivial to detect. Such validation steps in our approach are:

- **Step 4.1: Logical Consistency Checking**. The term of logical consistency can be intuitively explained as "free of contradictions in the specifications". In our work, the logical consistency checking is performed on the executable eTASM models, by using our developed tool TASM TOOLSET. Furthermore, there are two kinds of inconsistency flaws to discover. One kind of flaws is that two rules in the same machine are enabled simultaneously, which is usually caused by the fact that there exist unpredictable behaviors in the specification of the corresponding feature. The other is that different values are assigned to the same variable simultaneously by different machines, which is usually caused by the fact that there exist hidden undesirable feature interactions in the specifications of the corresponding features.
- **Step 4.2: Coverage Checking**. The coverage checking corresponds to checking whether the feature requirements can be observed in the integrated feature specifications, which is an important activity of requirements completeness checking. To perform the coverage checking, all the feature requirements are translated into observers which monitor the execution of the features specifications, i.e., the derived eTASM models. If an *Observation* cannot hold, it indicates that although the features specifications satisfy their individual requirements in isolation, there are behavioral inconsistencies in the integrated feature specification.
- **Step 4.3: Model Checking**. The eTASM machines can be easily translated into timed automata through the transformation rules defined in [15]. The transformation enables the use of the UPPAAL model checker to verify the various properties of the eTASM model. This type of checking aims at verifying whether the eTASM model is free of deadlock and whether an expected property specified in a feature requirement is satisfied by the eTASM model. It is necessary to stress that the essential difference between *Model Checking* and *Coverage Checking* is whether a property is exhaustively checked against a model or not. Although a sound property checking is desired, in some cases *Model Checking* will encounter state explosion problem, which limits its usefulness in practice.

We follow the aforementioned validation steps to check the validity of the selected features of the VLU system. First, we use the TASM TOOLSET to perform *Logical Consistency Checking* on the formalized eTASM model. Two inconsistencies are detected, one of which is that the Rule *Autolock* of the AUTO_LOCKOUT machine and the Rule *Antilock* of the ANTI_LOCKOUT machine update the *door_state* variable simultaneously with different values. An analysis of the inconsistency reveals: When the key is in ignition, the ANL feature will keep the doors unlocked. Meanwhile, if the autolock timeout expires, the AUL feature will try to lock the door. Since no rules are explicitly specified in the selected features to handle this situation, undesirable behaviors will occur. The other inconsistency is detected in a similar situation where the Rule *Locking* of the CL_LOCK machine and the Rule *Antilock* of the ANTI_LOCKOUT machine update the *door_state* variable simultaneously with different values. In this work, we correct such inconsistencies by assigning a higher priority (as an extra condition of the corresponding rule) to the Rule *Antilock*, which guarantees that it will be executed at first when both of two rules are enabled at the same time. Note that there are some other methods that can be used to remove the discovered inconsistencies, which are however out of the scope of this paper.

After the removal of the inconsistencies, we proceed to *Coverage Checking*. The TASM TOOLSET is applied, and the result has shown that the observations of all eTASM observers are met. Therefore, the integrated features specifications satisfies the feature requirements, from the *Coverage Checking* perspective.

On the note about *Model Checking*, we first translate the eTASM model into timed automata, and then check the deadlock property as well as the feature requirements via UPPAAL. The corresponding results are: 1) *Deadlock free* is *satisfied* and, 2) the *CL_Lock feature requirement* is *satisfied* and, 3) the *CL_Unlock feature requirement* is *satisfied* and, 4) the *AUL feature requirement* is *satisfied* and, 5) the *ANL feature requirement* is *satisfied*. As a result, the satisfaction of deadlock-free and feature requirements has been achieved.

In summary, our approach has found *two* behavioral inconsistencies in the integrated features specifications. Although the VLU system is not complex, it is enough, as an illustrative example, to show how to perform feature-oriented requirements validation by following our proposed approach.

V. Related Work

Kimbler et al. [20] introduce a user-oriented approach to feature interaction analysis. It aims first at creating use case models to describe different possible ways of using the system services, and then building service usage models which simulate the dynamic relations between services. This work is quite similar with our idea, however its focus is in the telecommunication domain. Moreover, we use the RUCM approach to facilitate the transformation from use case models to subsequent formalisms. Eriksson et al. [21] propose a software product line use case modeling approach i.e., PLUSS to modeling SPL. The difference between their work and ours is the purpose of using use cases. PLUSS aims to utilize use cases to capture variants of SPL, while our approach utilizes use cases to specify behavioral specifications of features. The white paper of EAST-ADL [16] mentions that use cases can be used to specify features but no more details were given. In this work, we have provided a set of steps to specify features and perform requirements validation.

Amyot et al. [10] propose an approach to detecting feature interactions of telecommunication systems, by using Use Case Maps (UCMs) for designing features, and LOTOS for the formal specification of features. Sampath et al. [22] present a formal specification and analysis method for automotive features in the early stages of software development process. This method starts with an empty specification, and then incrementally adds clauses to the specification until all the feature requirements are satisfied. Arora et al. [7] propose a method and algorithms for identifying and resolving feature interactions in the early stages of the software development life-cycle. The work uses *State Machines* to model the behavior of independent features, context diagrams to integrate independent features, and Live Sequence Charts to capture the interactions of features.

VI. Conclusions and Future Work

In this paper, we have proposed a novel approach to feature-oriented requirements validation by using the RUCM approach and the eTASM language. Our approach 1) specifies the behaviors and requirements of features in the RUCM use cases and, 2) transforms such RUCM use cases to the formal yet literate eTASM models and, 3) performs the requirements validation by using the TASM TOOLSET and the model checker UPPAAL. Our illustration application using a Vehicle Locking-Unlocking (VLU) system has shown that our approach can achieve the goal of feature-oriented requirements validation via *Logical Consistency Checking*, *Coverage Checking*, and *Model Checking*.

As inspired by Scandurra et al. [17] showing the promise of rule-based transformation from RUCM use cases to analysis models, we will in the future combine the proposed modeling approach with such rule/pattern-based algorithms, to achieve a fully automatic transformation between the RUCM use cases and eTASM models. We are also interested in integrating our approach and related tools for the development of correct-by-construction systems (e.g., developed by EAST-ADL language) in a seamless and cost efficient way. Another part of future work also includes a wider industrial validation of our approach, as well as the improvement of our current TASM TOOLSET.

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