From STPA to Safe Behavior Models*

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Abstract. Model checking is a proven approach for checking whether the behavior model of a safety-critical system fulfills safety properties that are stated as LTL formulas. We propose rules for generating such LTL formulas automatically based on the result of the risk analysis technique System-Theoretic Process Analysis (STPA). Additionally, we propose a synthesis of a Safe Behavior Model from these generated LTL formulas. To also cover liveness properties in the model, we extend STPA with Desired Control Actions. We demonstrate our approach on an example system using SCCharts for the behavior model. The resulting model is not necessarily complete but provides a good foundation that already covers safety and liveness properties.

Keywords: STPA · LTL · Behavior Model.

1 Introduction

Verification is an important part of system development to ensure the safety of the system as well as its functionality. One technique to verify a model of a system is *model checking* [5]. The system specifications are translated into Linear Temporal Logic (LTL) formulas and a model checker determines whether the model fulfills them. These formulas may cover safety properties as well as liveness properties. If a formula is not fulfilled, a counterexample is generated by the model checker and the model can be adjusted and checked again. A part of the model checking process is the translation of an LTL formula to a Büchi automaton [10]. This process is computationally expensive [9], which is why significant research focuses on improving this translation [2, 7, 9, 11, 21].

However, creating the LTL formulas and the model of the system in the first place is also non-trivial. Creating models is very time-consuming, which is why many techniques exist to generate them automatically [6, 8, 16, 23, 24]. Additionally, if the safety of the model can already be guaranteed by the construction process, less time is needed to verify it. The creation of the LTL formulas can also be supported. Generating the formulas automatically reduces the time effort and the risk of mistakes in the formulas. If a safety property would be translated wrongly or forgotten, the verification process might overlook flaws in the model of the system.

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In order to determine the safety properties for the system, System-Theoretic Process Analysis (STPA) [18] can be used. STPA is a risk analysis technique that focuses on unsafe interactions between system components and identifies more risks than traditional hazard analysis techniques [19]. In this paper we propose rules to automatically translate the resulting safety properties to LTL formulas ensuring that no property is forgotten and reducing the time effort for creating the formulas. Based on these formulas, we propose a synthesis of a Safe Behavior Model (SBM) as a statechart for the analyzed system.

Contributions & Outline Sec. 2 introduces STPA, the used Statecharts definition, and LTL formulas. Sec. 3 reviews translation rules from STPA to LTL as presented by Abdulkhaleq et al. and the different already existing approaches for the generation of Büchi automaton from LTL formulas. Our main technical contributions, presented in the next three sections, are as follows:

- We expand the translation of the STPA results to LTL formulas (Sec. 4).
- We present an approach to create an SBM based on these formulas (Sec. 5).
- We extend STPA with Desired Control Actions (DCAs), which are needed to not only cover safety properties but liveness properties as well (Sec. 6).

An implementation of the proposed SBM synthesis is presented in Sec. 7. Sec. 8 discusses the approach and finally, Sec. 9 concludes the paper.

2 Background

We give a short introduction of STPA in Sec. 2.1, especially the Unsafe Control Actions (UCAs) for which we propose, in Sec. 4, a translation to LTL formulas. Sec. 2.2 presents the statechart definition used in this paper and Sec. 2.3 explains the LTL operators used in the presented formulas.

2.1 STPA

STPA is a hazard analysis technique for safety critical systems [18]. It focuses on unsafe interactions between system components, unlike traditional techniques such as Fault Tree Analysis (FTA), which focuses on component failures. The STPA process consists of four steps [18]:

1. Define the purpose of the analysis;
2. Model the Control Structure;
3. Identify Unsafe Control Actions (UCAs);
4. Identify Loss Scenarios.

In the first phase, the losses that should be prevented and hazards that lead to these losses are defined. The control structure modeled in the second step consists of controllers, controlled processes, and possibly actuators and sensors. For the controller *control actions* are defined that can be sent to controlled processes, and the controlled processes send *feedback* to the controllers. A controller also has a process model that contains *process model variables* that contain information about the controlled process, the environment, etc.

The third step is the most important one for our contributions. Here, the control actions of the control structure are inspected. The analyst defines *Unsafe Control Actions (UCAs)* by determining in which contexts a control action causes a hazard. The context can be stated informally by describing it, or more formally by using context tables proposed by Thomas [22]. When using context tables, the context is defined by assigning values to the process model variables. For each control action a separate context table is created. Each column represents a process model variable and each row a possible combination of their values called the *context*. Then, for each context the analyst can determine whether the control action is hazardous for any UCA type. The basic UCA types are PROVIDED and NOT-PROVIDED. The first one means that providing the control action leads to a hazard, while the second type states that not providing the control action leads to a hazard. For contexts in which the timing is relevant the types TOO-LATE and TOO-EARLY are used, and for continuous control actions the types APPLIED-TOO-LONG and STOPPED-TOO-SOON must be considered as well. Each of these types further specifies the moment in which (not) sending a control action leads to a hazard.

For these UCAs *controller constraints* are defined, which are the safety properties. In the last STPA step loss scenarios are defined that lead to hazards.

Several tools exist that support the application of STPA, for example Pragmatic Automated System-Theoretic Process Analysis (PASTA) [20]. PASTA is a Visual Studio Code (VS Code) Extension that provides a Domain Specific Language (DSL) with automatic visualization of the defined components and their relationships. PASTA supports the informal definition of UCAs as well as context tables.

2.2 Statecharts

Statecharts are Finite State Machines (FSMs) that are extended with hierarchy, concurrency, and communication [15]. We define a statechart M based on the Extended FSM (EFSM) definition [3] as the 8-tuple $(S, I, O, D, F, U, T, s_0)$, where

- S is a set of *states*,
- I is an n-dimensional space $I_1 \times \cdots \times I_n$ that represents the *input variables*,
- O is an m-dimensional space $O_1 \times \cdots \times O_m$ representing the *output variables*,
- D is a p-dimensional space $D_1 \times \cdots \times D_p$ that represents the *internal variables*,
- F is a set of *enabling functions* f_i with $f_i : D \to \{0, 1\}$ that define the *triggers* of the transitions,
- U is a set of *update functions* u_i with $u_i : D \to D$,
- T is a *transition function* with $T : S \times F \times I \to S \times U \times O$,
- $s_0 \in S$ is the *initial state*.

An *observable trace* is a sequence of in- and outputs: $((x_0, y_0), (x_1, y_1), \dots)$ with $x_i \in I$ input and $y_i \in O$ output in reaction i. In contrast, an *execution trace* also includes the states: $((x_0, s_0, y_0), (x_1, s_1, y_1), \dots)$ with $\forall i \in \mathbb{N} : ((s_i, f_i, x_i), (s_{i+1}, u_i, y_i)) \in T$ [17]. We extend this definition to include the internal variables as well: $((x_0, z_0, s_0, y_0), (x_1, z_1, s_1, y_1), \dots)$ with z_i internal variables at reaction i. In the following we will just use *trace* to refer to an execution trace.

2.3 Linear Temporal Logic

In the following we introduce LTL formulas for EFSM traces based on the definition by Lee and Seshia [17]. The atomic propositions of an LTL formula are:

- true;
- false;
- s, which is true if the statechart is in state s;
- $x = v$, which is true if the variable x has the value v.

Additionally, the boolean operators $\wedge, \vee, \neg$, and $\rightarrow$ can be used. An LTL formula φ applies to an entire trace $t = t_0, t_1, \dots$ and holds for that trace iff φ is true in t_0. If φ holds for all possible traces of a statechart M, φ holds for M. In the following let $t = t_0, t_1, \dots$ be a trace. In order to reason about the entire trace, special temporal operators can be used:

- the *globally* operator $\mathrm{G}\,\varphi$ holds for t when φ holds for every suffix of t;
- the *finally* operator $\mathrm{F}\,\varphi$ holds for t if φ holds for some suffix of t;
- the *next* operator $\mathrm{X}\,\varphi$ holds for t if φ holds for $t_1, t_2, \dots$;
- the *until* operator $\varphi_1 \,\mathrm{U}\, \varphi_2$ holds for t if φ_2 holds for some suffix of t and φ_1 holds until and including when φ_2 becomes true;
- the *release* operator $\varphi_1 \,\mathrm{R}\, \varphi_2$ holds if $\neg(\neg\varphi_1 \,\mathrm{U}\, \neg\varphi_2)$ holds. It states that φ_2 must hold until and including when $\varphi_1 \wedge \varphi_2$ is true for a reaction. If φ_1 never holds, then φ_2 must hold forever.

3 Related Work

Abdulkhaleq et al. already propose an approach for creating LTL formulas based on UCAs [1]. They first define *Refined UCAs (RUCAs)* that contain the control action, the context $CS := \{x_i = v_i \mid x_i \text{ is a process model variable}\}$, and the type. These RUCAs are used to automatically generate *Refined Software Safety Requirements (RSSRs)*, which again are automatically translated into LTL formulas. The proposed LTL formula for a context $cv := \bigwedge_{\varphi \in CS} \varphi$, control action CA, subformula $ca := sent(CA)$, and type PROVIDED is the following:

$$\mathrm{G}(cv \rightarrow \neg ca) \tag{1}$$

It states that every time the context holds, the control action is not allowed to be sent. We will also use this formula for our approach. However, we do not agree with the translations for the types TOO-LATE, TOO-EARLY, and NOT-PROVIDED and hence provide new rules. Additionally, we propose rules for APPLIED-TOO-LONG and STOPPED-TOO-SOON, which is not done by Abdulkhaleq et al.

To verify a model according to an LTL formula, the negated formula is translated to a Büchi automaton, the product with the model is built, and the resulting automaton is checked for emptiness [10]. Since the product automaton grows considerable in size with growing size of the Büchi automaton, much research focuses on optimizing the translation of an LTL formula to a Büchi automaton to reduce the needed memory and translation time [2, 7, 9, 11, 21]. In contrast to these works, we want to synthesize a statechart that can be used as the behavior model of the system. This statechart can then be used to synthesize code.

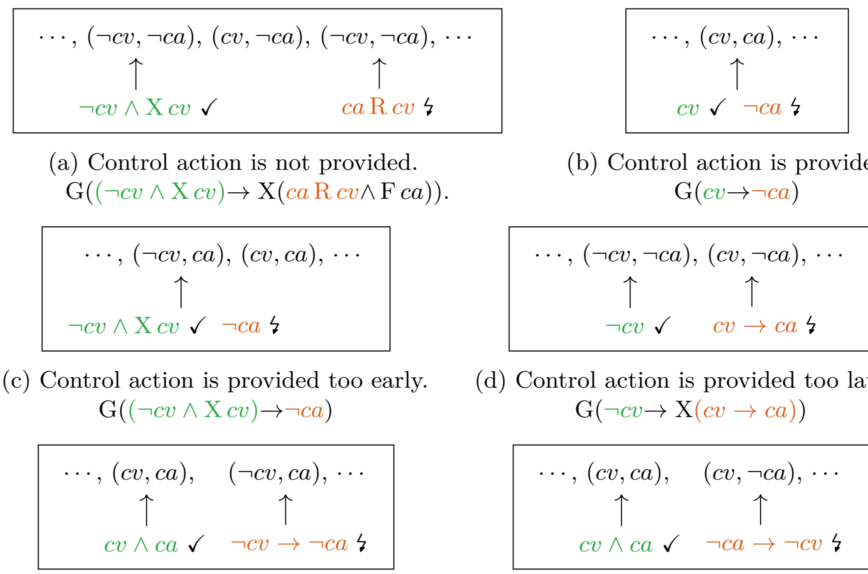
For syntheses of behavior models, Fluent LTL (FLTL) [12] or scenario specifications are used. Scenarios can be specified with Message Sequence Charts (MSCs) describing the interactions between system components and the environment. Syntheses from MSCs to Labelled Transitions Systems (LTS) are presented for example by Uchitel et al. [24] or Damas et al. [6]. Since, LTS cannot distinguish between possible and required behavior Uchitel et al. propose a synthesis from MSCs to Modal Transition Systemss (MTSs) [23].

Krüger et al.'s approach translates MSCs to statecharts [16]. The MSC is translated to a so called *MSC-automaton*. The transitions of this automaton are then translated to intermediate states and transitions. We use STPA instead of MSCs. This has the advantage that the results of a risk analysis that must be done anyway can be used and no additional time is needed to create MSCs. Additionally, this eliminates the problem of *implied scenarios*. Such scenarios occur when scenarios are combined in unexpected ways resulting in unexpected system behavior not covered in the scenario specification [24].

4 STPA to LTL

When using context tables for specifying UCAs, we implicitly have RUCAs and can create LTL formulas that prevent UCAs. The translation rules depend on the type of the UCA: NOT-PROVIDED, PROVIDED, TOO-EARLY, TOO-LATE, APPLIED-TOO-LONG, or STOPPED-TOO-SOON. Abdulkhaleq et al. present rules for the first four types but not for the last two. While we agree with the rule for the PROVIDED type, it is not clear whether the rule for NOT-PROVIDED is correct. This depends on how NOT-PROVIDED should be interpreted, which is discussed in Sec. 4.1. In Sec. 4.2 and Sec. 4.3, we propose more precise rules for TOO-LATE and TOO-EARLY. Additionally, we propose rules for the missing types APPLIED-TOO-LONG in Sec. 4.4 and STOPPED-TOO-SOON in Sec. 4.5.

We define $PM_C := \{PMV_1, \dots, PMV_n\}$ as the process model of a controller C, where $PMV_i := (x_i, \{v_1, \dots, v_m\})$ with $1 \leq i \leq n$ is a process model variable with the name x_i and possible values $v_1, \dots, v_m$. In the following we use an arbitrary UCA with control action CA and context $CS = \{x_i = v_j \mid x_i, v_j \in PMV_i\}$ to explain the translation rules. We define subformulas for the context variables $cv := \bigwedge_{\varphi \in CS} \varphi$, meaning that the context in which CA is hazardous is present, and control action $ca := sent(CA)$, meaning CA is sent. We will use a short form of the trace definition: We use (cv, ca) or $(\neg cv, \neg ca)$ instead of (x, z, s, y), meaning the input and internal variables x and z are set according to cv or $\neg cv$, respectively. The variables that do not occur in cv can have any value, the state s can be any state, and the output y must (not) contain CA. Fig. 1 gives an overview of the traces we prevent with the proposed formulas, as elaborated in the following.



(a) Control action is not provided. $\mathrm{G}((\neg cv \wedge \mathrm{X}\, cv) \rightarrow \mathrm{X}(ca\, \mathrm{R}\, cv \wedge \mathrm{F}\, ca))$.

(b) Control action is provided. $\mathrm{G}(cv \rightarrow \neg ca)$

(c) Control action is provided too early. $\mathrm{G}((\neg cv \wedge \mathrm{X}\, cv) \rightarrow \neg ca)$

(d) Control action is provided too late. $\mathrm{G}(\neg cv \rightarrow \mathrm{X}(cv \rightarrow ca))$

(e) Control action is applied too long. $\mathrm{G}((cv \wedge ca) \rightarrow \mathrm{X}(\neg cv \rightarrow \neg ca))$

(f) Control action is stopped too soon. $\mathrm{G}((cv \wedge ca) \rightarrow \mathrm{X}(\neg ca \rightarrow \neg cv))$

Figure 1: Traces for the different UCA types that are prevented by the proposed formulas. Here, we do not consider the first reaction of a trace.

4.1 Formula for Not-Provided

Stating that not providing a control action is hazardous in a given context can be interpreted in two ways. On the one hand, this could mean that in every reaction where the context holds the control action must be sent to prevent a hazard. On the other hand, it could mean that during the timespan where the context holds continuously the control action must be sent at least once. The rule stated by Abdulkhaleq et al. [1] covers the first interpretation:

$$\mathrm{G}(cv \rightarrow ca)$$

However, this interpretation also already ensures that the control action is not sent too late and is not stopped too soon. That is why we propose a formula for the second interpretation. Let

$$\psi = cv \rightarrow (ca\,\mathrm{R}\,cv \wedge \mathrm{F}\,ca),$$

$$\chi = \mathrm{G}((\neg cv \wedge \mathrm{X}\,cv) \rightarrow \mathrm{X}(ca\,\mathrm{R}\,cv \wedge \mathrm{F}\,ca))$$

then we translate a UCA of type NOT-PROVIDED to the following formula:

$$\psi \wedge \chi \tag{2}$$

In χ the implicant $\neg cv \wedge \mathrm{X}\,cv$ holds in the reactions directly before cv changes from false to true. This means the next reaction is the first time where the context holds, and in this reaction $((ca\,\mathrm{R}\,cv) \wedge \mathrm{F}\,ca)$ should hold. $(ca\,\mathrm{R}\,cv)$ ensures that when cv changes to false, the control action has to have been sent before. Thus, a trace as shown in Fig. 1a would evaluate to false since the context changes to false although the control action was not yet sent. Since $(ca\,\mathrm{R}\,cv)$ evaluates to true when the control action is not sent as long as the context holds indefinitely, we ensure with $\mathrm{F}\,ca$ that eventually the control action will be sent. Hence, the implicand ensures that after the context switches from false to true, the control action is at least sent once while the context holds. However, when a trace starts with cv being true, the implication evaluates to true regardless whether the control action is sent before cv changes to false since the implicant evaluates to false. ψ ensures that also in the first reaction when cv is true, ca must be sent at least once before it changes to false.

4.2 Formula for Too-Late

Abdulkhaleq et al. propose the following formula for UCAs of type TOO-LATE [1]:

$$\mathrm{G}((cv \rightarrow ca) \wedge \neg(cv\,\mathrm{U}\,ca))$$

This formula can only be fulfilled if the first conjunct is fulfilled, namely $cv \rightarrow ca$. This means traces such as $(\dots, (\neg cv, \neg ca), (cv, ca), (cv, \neg ca), \dots)$ evaluate to false although the control action is not provided too late. Hence, this formula covers more than just the TOO-LATE UCA type. Even in cases where $cv \rightarrow ca$ holds, the complete formula evaluates to false for some trace in which the control action is not provided too late. For example, for the trace $((cv, ca), (cv, ca), \dots)$. Since $cvUca$ evaluates to true for this trace, $\neg(cv\,\mathrm{U}\,ca)$ evaluates to false and hence the complete formula evaluates to false.

We argue that we only have to look at the first moment the control action should be provided. The control action should be sent instantly when the context holds. This leads to the following formula:

$$(cv \rightarrow ca) \wedge \mathrm{G}(\neg cv \rightarrow \mathrm{X}(cv \rightarrow ca)) \tag{3}$$

The second conjunct ensures that traces such as shown in Fig. 1d do not occur. The moment the control action should be applied is when the context currently holds and in the previous reaction did not hold. In the formula we capture this in the following way: The control action should be applied in the next reaction if the context currently does not hold and in the next reaction does hold. If the control action is not applied, the formula evaluates to false. The first conjunct of Equation 3, namely $cv \rightarrow ca$, just ensures that the UCA does not occur in the first reaction. If the context already holds in the first reaction we must apply the control action immediately.

4.3 Formula for Too-Early

For the UCAs of type TOO-EARLY Abdulkhaleq et al. propose the following formula [1]:

$$\mathrm{G}((ca \rightarrow cv) \wedge \neg(ca\,\mathrm{U}\,cv))$$

We see here the same problem as before. The first conjunct, namely $ca \rightarrow cv$, ensures that the control action is not sent too early, but this again covers too much. For traces such as $(\dots, (\neg cv, \neg ca), (cv, ca), (\neg cv, ca), \dots)$, where the control action is not sent too early, the formula evaluates to false because of the reaction $(\neg cv, ca)$ and hence the complete formula evaluates to false. Let us examine a trace where the control action is not sent too early and the subformula holds: $((cv, ca), (\neg cv, \neg ca), \dots)$. Since in the first reaction cv and ca hold, the formula $ca\,\mathrm{U}\,cv$ evaluates to true and hence $\neg(ca\,\mathrm{U}\,cv)$ to false, which is why the whole formula is evaluated to false.

We propose a formula that only inspects the moment where cv switches from false to true:

$$\mathrm{G}((\neg cv \wedge \mathrm{X}\,cv) \rightarrow \neg ca) \tag{4}$$

The reaction where the context holds but did not hold in the previous reaction is the first one where the control action is allowed to be sent. Hence, we must ensure that before this reaction, the control action is not sent (see Fig. 1c). The implicant, namely $\neg cv \wedge \mathrm{X}\,cv$, is true if the current reaction is the last one in which cv is false before it switches to true. In such a reaction the control action is not allowed to be sent, which is guaranteed by the implication.

4.4 Formula for Applied-Too-Long

For UCAs of type APPLIED-TOO-LONG we propose the following formula:

$$\mathrm{G}((cv \wedge ca) \rightarrow \mathrm{X}(\neg cv \rightarrow \neg ca)) \tag{5}$$

To ensure an action is not applied too long, we have to inspect the reactions where the control action is already applied while the context holds $(cv \wedge ca)$. In these reactions, we must ensure that the control action is not sent anymore at the latest when the context does not hold any longer. Hence, for each reaction in which cv and ca are true $(cv \wedge ca)$, we must check whether the context still holds in the next reaction $(\mathrm{X}(\dots))$. If it does not, the control action must not be sent, which is guaranteed by the subformula $\neg cv \rightarrow \neg ca$. We are not interested in the traces where the control action is stopped before the context does no longer hold. This is only relevant for UCAs of type STOPPED-TOO-SOON. The formula only evaluates to false for traces such as shown in Fig. 1e.

4.5 Formula for Stopped-Too-Soon

In order to guarantee that a control action is not stopped too soon, we must ensure that after it is sent the first time it is continuously sent until the context does not longer hold. We propose a similar formula as for APPLIED-TOO-LONG:

$$G((cv \wedge ca) \rightarrow X(\neg ca \rightarrow \neg cv)) \tag{6}$$

Again, we are interested in the reactions where the context already holds and the control action is applied ($cv \wedge ca$). In such reactions, the formula ensures that if the control action is not sent anymore in the next reaction, then the context does not hold in the next reaction ($X(\neg ca \rightarrow \neg cv)$). This way traces such as shown in Fig. 1f where the control action is stopped too soon are prevented.

5 STPA to SBM

The LTL formulas generated based on the identified UCAs can be used for model checking the behavior models of the software controllers. Those *Safe Behavior Models (SBMs)* are created manually by the software developers with the help of supporting tools such as Simulink. Abdulkhaleq et al. [1] present an approach to combine the generated LTL formulas with an SBM to create a Symbolic Model Verifier (SMV) model that can be verified using for example NuSmv [4]. This way, the safety of the model is examined. However, creating an SBM in the first place is time-consuming and error-prone.

We now propose an approach for the automatic generation of deterministic SBMs based on the LTL formulas generated for the controller that should be modeled. This way, the developer can work with an initial SBM that already fulfills the LTL formulas that are used for the generation. For this automatic generation we assume that no contradicting UCAs exist. Conflicts have to be solved before applying the generation. Additionally, we assume for simplicity that only one control action is sent at a time and that the initial reaction is used to set up the system such that we do not have to consider subformulas that are only checked on the initial reaction.

The first question we need to answer when generating an SBM from STPA is how we determine the states for the model, which is explained in Sec. 5.1. Afterwards, Sec. 5.2 introduces the determination of the variables in the SBM. Sec. 5.3 - Sec. 5.8 present a translation for each UCA type from the corresponding LTL formula to transitions and possibly states as well as their interaction with the other LTL formula translations. For this we use the previously introduced formulas. Finally, we optimize the constructed SBM (Sec. 5.9) and prove that it fulfills the LTL formulas except the ones for TOO-EARLY (Sec. 5.10).

5.1 States

A straightforward approach to determine the states for the model would be to use each context and control action combination. However, this would blow up the state space, and it is not always necessary to differentiate between states with the same control action but different context. Thus, we start with states that only represent a control action each and an initial state that represents that no control action is sent. Additional states are added during the translation of LTL formulas if necessary. Hence, for a controller C we start with a statechart $M = (S, I, O, D, F, U, T, s_0)$ with $S = s_0 \cup \{s_{CA} \mid CA \text{ is a control action of } C\}$ and $F = U = T = \emptyset$.

5.2 Variables

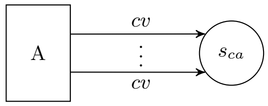
The variables of the statechart are determined based on the process model of the controller C. All process model variables are translated to internal variables, meaning we declare $D = \{x \mid (x, \_) \in PM_C\}$. We infer the type of each input variable from the values it can be assigned. If the values are `true` and `false`, the type of the variable is *boolean*, otherwise it is a *number*. The input variables are composed of the variables that are used for the possible values of the process model variables. Hence, we set $I = \{v \mid v \in V, (\_, V) \in PM_C, v \text{ is variable}\}$. We track the control action that is sent in an additional variable named *controlAction*. Since the chosen control action should be sent to a system component, we declare *controlAction* as an output variable: $O = \{controlAction\}$. The type of this variable depends on the implementation: *string* can be used or an *enum* can be created containing all possible control actions. Two options exist to set the value of this variable in each reaction: Each state can define an entry action setting *controlAction* to the value the state represents, or each transition must set *controlAction* according to the target state. In the following we will use the first option, meaning we can concentrate on the triggers of the transitions.

5.3 Not-Provided Transitions

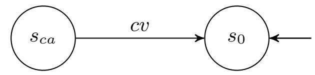
The translation of LTL formulas for UCAs of type NOT-PROVIDED can be seen in Fig. 2a. We cannot automatically determine at which moment in the timespan, where the context holds, the control action should be sent. Thus, we set the moment where the control action must be sent to the first reaction where *cv* holds, which also covers the TOO-LATE type. Since each state in our statechart represents that a specific control action is sent, we must ensure that if the context holds, we go to the state representing the control action. For each formula we add transitions from the states not representing *ca* to the one representing it: $T(s, f_s, i) = (s_{ca}, \emptyset, \emptyset)$ if $f_s(d) = 1$, with $s \neq s_{ca}$, $i \in I$, $d \in D$, and $f_s(cv) = 1$.

5.4 Too-Early Transitions

LTL formulas for the TOO-EARLY UCA type (Equation 4) cannot be translated. In these formulas the context in the next reaction constrains the current control action. Since we cannot see the future, we cannot depict that.



(a) Translation of UCA type NOT-PROVIDED.



(b) Translation of UCA type PROVIDED.

Figure 2: Translation of UCA types PROVIDED and NOT-PROVIDED to statecharts. A is the statechart without the state s_{ca}.

5.5 Too-Late Transitions

The first conjunct of the LTL formula for the TOO-LATE type (Equation 3) is only relevant for the first reaction. Since we assume that the initial reaction is used for setting up the system, we can ignore it. For the second conjunct, we must remember the context in the previous reaction. We could do that by adding new states s_{a_cv} to S, which represent that cv holds and a is sent, for each $a \neq ca$. Then, we could add transitions from s_{a_cv} to s_a that trigger when cv does not hold. The incoming transitions of s_a are split such that the ones where the trigger contains $\neg cv$ remain and the ones containing cv are changed such that they go to s_{a_cv} instead. Since s_a represents that cv did not hold in the last reaction, we could add transitions from s_a to s_{ca} that trigger when cv holds. This way, we would depict the implication $\neg cv \rightarrow \mathrm{X}(cv \rightarrow ca)$. However, the s_{a_cv} states would be unreachable. The only way a transition would go from an arbitrary state to s_{a_cv} would be if a UCA of type not-providing exists for the control action a and context cv. This would be a contradiction to the current inspected formula that ca should not be sent too late in context cv and hence does not occur in a correct analysis. In conclusion, we do not need extra states, we just need to add transitions from states not representing ca to s_{ca} just as done for NOT-PROVIDED.

5.6 Provided Transitions

The translation for UCAs of type PROVIDED is depicted in Fig. 2b. In order to fulfill these formulas, we need contrary transitions to the ones introduced for the NOT-PROVIDED UCA type. We must ensure that if the context holds, the control action is not sent. This is done by adding a transition from s_{ca} to the initial state: $T(s_{ca}, f_s, i) = (s_0, \emptyset, \emptyset)$ if $f_s(d) = 1$, with $i \in I$, $d \in D$, and $f_s(cv) = 1$. However, we must consider that for the same context or a context containing cv a UCA of type NOT-PROVIDED or TOO-LATE may have been defined. In the first case, we already have a transition that leaves s_{ca} when cv holds and we do not have to add another one to the initial state. In the second case, we have to further specify the trigger such that it does not evaluate to `true` if the other transitions evaluates to `true`. Otherwise, the statechart would be non-deterministic.

5.7 Applied-Too-Long Transitions

The formulas for the UCA type APPLIED-TOO-LONG (Equation 5) may already be covered by the previously added transitions. In order to check this, the outgoing transitions of s_{ca} must be inspected. If a transition is triggered for every context $c \neq cv$, the formula is already fulfilled. Otherwise, we need to split s_{ca} into two states by adding s_{ca_cv} to S.

The result of the translation can be seen in Fig. 3. The original transitions to s_{ca} are updated in the following way: If previously $T(s, f_s, i) = (s_{ca}, \emptyset, \emptyset)$ with $f_s(cv) = 1$, we remove that transition and add $T(s, f'_s, i) = (s_{ca\_cv}, \emptyset, \emptyset)$ with $f'_s(x \wedge cv) = 1 \Leftrightarrow f_s(x) = 1$ and $T(s, f'_s, i) = (s_{ca}, \emptyset, \emptyset)$ with $f'_s(x \wedge \neg cv) = 1 \Leftrightarrow f_s(x) = 1$. Hence, the transitions to s_{ca} only trigger when cv does not hold. If cv holds, the transition to s_{ca_cv} is triggered. Additionally, we copy all outgoing transitions of s_{ca} to s_{ca_cv} except the ones going to other duplicate states of s_{ca} and add a transition between the two states that triggers when cv holds: $T(s_{ca}, f_{ca}, i) = (s_{ca\_cv}, \emptyset, \emptyset)$ if $f_{ca}(d) = 1$, with $i \in I$, $d \in D$, and $f_{ca}(cv) = 1$. Now, s_{ca_cv} represents that cv holds and the control action ca is sent.

In order to fulfill the formula, we must still assure that the control action is not sent anymore when the context changes. Hence, we add another transition from s_{ca_cv} to the initial state triggering when cv does not hold: $T(s_{ca\_cv}, f_s, i) = (s_0, \emptyset, \emptyset)$ if $f_{ca\_cv}(d) = 1$, with $i \in I$, $d \in D$, and $f_s(\neg cv) = 1$. In order to avoid non-determinism the trigger may have to be adjusted such that it only evaluates to true when the trigger of the other transitions evaluate to false. This can be done by modifying f_s such that it only evaluates to 1 when $\neg cv$ holds and the triggers of all other transitions do not hold.

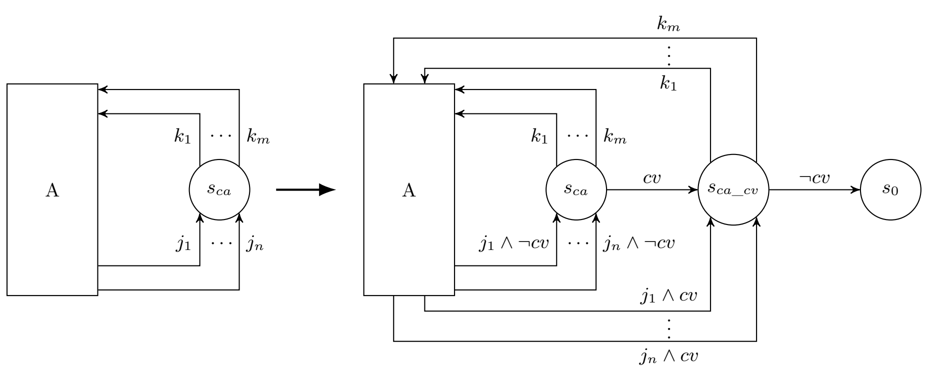


Figure 3: Translation of UCA type APPLIED-TOO-LONG. A is the statechart without the state s_{ca}.

5.8 Stopped-Too-Soon Transitions

LTL formulas for UCAs of type STOPPED-TOO-SOON (Equation 6) are translated in a similar way (Fig. 4). If in s_{ca} no transition is triggered for cv, the formula is already fulfilled. Otherwise, we need to split s_{ca} and its transitions the same way as done for the translation of APPLIED-TOO-LONG, given this is not already done.

The difference to the previous translation is that we do not add a transition to the initial state. Instead, we modify the outgoing transitions of s_{ca_cv} in the following way: If previously $T(s_{ca\_cv}, f_s, i) = (s', \emptyset, \emptyset)$ with $f_s(x) = 1$ and $x \in D$, we replace f_s with f'_s, whereby $f'_s(x \wedge \neg cv) = 1 \Leftrightarrow f_s(x) = 1$, meaning the outgoing transitions can only be triggered if cv does not hold. Another difference is that here we are also interested in the transitions from s_{ca} to duplicates of this state. After all necessary duplicate states are created, these transitions are also copied and modified for the newly created states. With *newly created* we mean that if a duplicate state was already created because of the translation of an APPLIED-TOO-LONG formula, this state does not get transitions to other duplicate states even if for the same context a STOPPED-TOO-SOON formula exist.

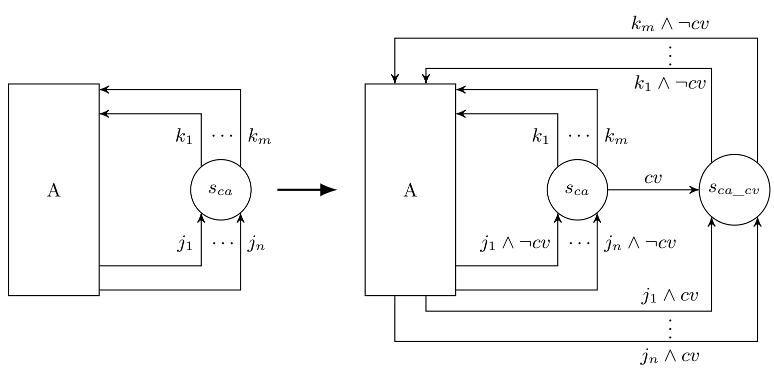


Figure 4: Translation of UCA type STOPPED-TOO-SOON. A is the statechart without the state s_{ca}.

5.9 Optimization

After application of the proposed translation rules, the statechart can be further optimized. When translating UCAs of type APPLIED-TOO-LONG or STOPPED-TOO-SOON we modify the trigger for the incoming transitions to the original state. This may lead to triggers that always evaluate to false. Transitions with such triggers can be deleted, which can lead to unreachable states that can be deleted as well.

5.10 Construction Proof

We cannot translate TOO-EARLY formulas into corresponding transitions, and thus cannot ensure that these formulas are fulfilled. However, we can ensure other formulas are fulfilled, as stated in the following theorem.

Theorem 1. *For an SBM created with the proposed construction rules, no trace exists that violates one of the LTL formulas, except possibly the ones for the type TOO-EARLY.*

Proof. Let $\varphi = \varphi_0 \wedge \cdots \wedge \varphi_i$ be the LTL formula the SBM should fulfill, where $\varphi_0, \ldots, \varphi_i$ are the formulas used to create the SBM. Let $t = t_0, t_1, \ldots$ be a trace that does not fulfill φ, which means at least one subformula is not fulfilled. Then there exists a φ_j with $0 \leq j \leq i, j \in \mathbb{N}$ that is not fulfilled by t. We show that the generated statechart cannot produce a trace $r = r_0, r_1, \ldots$, which violates φ_j. φ_j can have five possible forms, one for each UCA type except TOO-EARLY. We assume the statechart can produce a trace r with $r = t$.

Case PROVIDED (Equation 1)**.**

φ_j is of form $cv \to \neg ca$. This means t_x, t_{x+1} exist with $output(t_{x+1}) = ca$ and cv holds in reaction $x + 1$.

If $output(t_x) = ca$, according to the construction rules a transition from s_{ca} to s_0 exists that triggers when cv holds. Hence, $state(r_{x+1}) = s_0$ and $output(r_{x+1}) = \emptyset \neq \{ca\} = output(t_{x+1})$ and therefore $r \neq t$.

If $output(t_x) \neq ca$, a transition from $state(r_x)$ to $state(r_{x+1})$ must exist that is triggered when cv holds, and $output(r_{x+1}) = ca$. Such a transition only exists if there exists φ_k with $0 \leq k \leq i, k \in \mathbb{N}$ of the form $cv \to ca$, which would mean φ is not satisfiable and hence is forbidden.

Case NOT-PROVIDED (Equation 2)**.**

φ_j is of form $\mathrm{G}((\neg cv \wedge \mathrm{X}\, cv) \to \mathrm{X}((ca \,\mathrm{R}\, cv) \wedge \mathrm{F}\, ca))$.

Case 1**.**

A sequence $t_x, \ldots, t_y$ exists with $output(t_{x+1}), \ldots, output(t_{y-1}) \neq ca$, cv does not hold in reaction x, cv holds in reactions $x + 1$ till $y - 1$ and cv does not hold in reaction y. Then either $state(r_x) = s_{ca}$ must hold or according to the construction rule a transition from $state(r_x)$ to s_{ca} must exist that triggers when cv holds.

In the latter case, since cv holds in reaction $x + 1$, $state(r_{x+1}) = s_{ca}$ must hold. In the first case, according to construction rules we only leave the state ca if an LTL formula exists, which states that providing ca is forbidden or which states that providing another control action is necessary. Both occurrences are a contradiction. Thus, $state(r_{x+1}) = s_{ca}$.

Hence, in both cases $output(r_{x+1}) = ca \neq output(t_{x+1})$ holds.

Case 2**.**

A reaction t_x exists with $output(t_z) \neq ca$ for all $z > x$, cv does not hold in reaction x, and cv holds for every reaction after x. In this case, the same argument applies as for the other case. Either we are already in s_{ca} and do not leave it because cv holds, or a transition from $state(r_x)$ to s_{ca} must exist that triggers when cv holds. Hence, since cv holds in reaction $x+1$, it must hold $state(r_{x+1}) = s_{ca}$. Thus, $output(r_{x+1}) = ca \neq output(t_{x+1})$.

Case TOO-LATE (Equation 3).
φ_j is of form $cv \to ca \wedge \mathrm{G}(\neg cv \to \mathrm{X}(cv \to ca))$. This means t_x, t_{x+1} exist with $output(t_{x+1}) \neq ca$, cv does not hold in reaction x, and cv holds in reaction $x+1$. According to the construction rule a transition from all states to s_{ca} exists that triggers when cv holds. Since we defined the triggers of transitions uniquely to avoid non-determinism, no other transition exists that could fire. Hence, $state(r_{x+1}) = s_{ca}$ and thus $output(r_{x+1}) = ca \neq output(t_{x+1})$.

Case APPLIED-TOO-LONG (Equation 5).
φ_j is of form $\mathrm{G}((cv \wedge ca) \to \mathrm{X}(\neg cv \to \neg ca))$. This means a sequence t_x, t_{x+1} exist with $output(t_x) = output(t_{x+1}) = ca$, cv holds in reaction x, and cv does not hold in reaction $x+1$. According to the construction rule and since $output(t_x) = ca$, it must hold $state(r_x) = s_{ca\_cv}$. Since cv does not hold in reaction $x+1$, the transition to s_0 or another state that does not send ca is triggered. This leads to $output(r_{x+1}) \neq ca = output(t_{x+1})$.

Case STOPPED-TOO-SOON (Equation 6).
φ_j is of form $\mathrm{G}((cv \wedge ca) \to \mathrm{X}(\neg ca \to \neg cv))$. This means t_x, t_{x+1} exist with $output(t_x) = ca$, $output(t_{x+1}) \neq ca$, and cv holds in reaction x and $x+1$. According to the construction rule and since $output(t_x) = ca$, it must hold $state(r_x) = s_{ca\_cv}$. Since $output(t_{x+1}) \neq ca$, an outgoing transition must have been triggered and thus $state(t_{x+1}) \neq s_{ca\_cv}$. According to the construction, an outgoing transition can only be triggered if cv does not hold, which is a contradiction to the statement that cv holds in reaction $x+1$.

6 Desired Control Actions

The behavior model that is generated with the translation presented in the last section fulfills the LTL formulas and hence is safe. However, a system should not only be safe but also should fulfill its system goals, which is typically not implied by the safety properties alone and thus not part of the proposed model generation. However, it turns out that we can apply the machinery presented so far to achieve that aim as well.

To address the issue, we propose to extend STPA with *Desired Control Actions (DCAs)*. A DCA determines in which context a control action should (not) be sent to fulfill the system goal. In contrast to UCAs, DCAs have only two types: PROVIDED and NOT-PROVIDED. The analysts applying STPA already have to look at each context to determine whether UCAs exist. During that process, they can declare DCAs for contexts where (not) providing a control action is desired to achieve the system goal.

These DCAs can be translated to LTL formulas just as done for the UCAs. The difference is that for DCAs of type PROVIDED Equation 2 must be used and for DCAs of type NOT-PROVIDED Equation 1. For a UCA of type NOT-PROVIDED the formula must ensure that the control action is provided, and for a UCA of type PROVIDED the formula must ensure that the control action is not provided. Conversely, for a DCA of type NOT-PROVIDED the formula must ensure that the control action is not provided, and for a DCA of type PROVIDED the formula must ensure that the control action is provided.

When using these LTL formulas that represent DCAs together with the ones that prevent UCAs to generate the SBM, the resulting model will not only be safe but additionally fulfills the specified system goals.

7 ACC Example

We implemented the proposed SBM generation in the open source tool PASTA [20] to demonstrate the approach. As an example we analyzed an Adaptive Cruise Control (ACC) with stop and go functionality [25]. In PASTA the analyst can state abstract values for process model variables, which can be used to define UCAs. In order to infer the process model variable types, the user can define the value ranges for each abstract value. The keywords *true* and *false* can be used to indicate boolean variables. *MIN* and *MAX* can be used to state that there is no lower or upper bound respectively. In value ranges that contain two values, '[' and ']' are used to indicate that the range should include the first or last value respectively, while '(' and ')' indicate that the value should be excluded.

Consider for example the variable *speed* with the values *desiredSpeed*, *lessThanDesiredSpeed*, and *greaterThanDesiredSpeed* for the ACC as used by Abdulkhaleq et al. [1]. The value ranges for these values are the following:

$$\begin{aligned} desiredSpeed &= [desiredSpeed] \\ lessThanDesiredSpeed &= [MIN, desiredSpeed) \\ greaterThanDesiredSpeed &= (desiredSpeed, MAX] \end{aligned}$$

If no value ranges are defined, we create an enum type that contains the values. This way the context in an UCA can be translated to variables used in the behavior model. For example a UCA with context *speed=lessDesiredSpeed* is translated to *speed* < *desiredSpeed* when generating the LTL formula.

The DCAs can be defined the same way as the UCAs. Rules can be defined for control actions and DCA types. In the *contexts* field the DCAs are defined stating the context in which the control action should (not) be provided.

The user can select a controller for which the model should be generated, which triggers the generation of the SBM as a Sequentially Constructive Statechart (SCChart). An SCChart can contain several states, transitions with priorities, and input, output and internal variables [13]. The resulting SBM contains a state for each control action and an initial state as described in Sec. 5. The process model variables are translated to internal variables, where the type is inferred from the value ranges. Additionally, an enum is created that contains the control actions as values and the `controlAction` variable has the type of that enum. The input variables are the ones that are used in the value ranges.

The UCAs and DCAs are translated to LTL formulas following the proposed translation rules. *cv* is created by connecting the elements in the *context* field of the UCA/DCA with the $\land$ operator. For *ca* the control action stated in the UCA/DCA is translated to the corresponding enum value *caEnum*, and we define $ca \Leftrightarrow controlAction = caEnum$. The formulas are added as *LTL Annotations* to

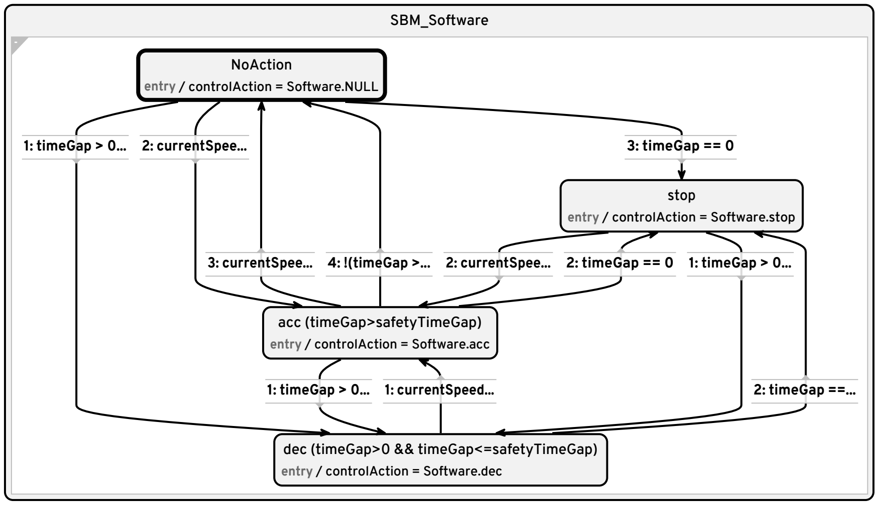


Figure 5: Automatically generated SBM for the ACC example.

the SCChart and translated as described in Sec. 5. In each created state an *entry* action is defined to set *controlAction* to the value represented by the state.

For the ACC example the resulting SBM is shown in Fig. 5. It contains four states: the initial one in which no control action is sent, a state in which the vehicle stops, a state in which the vehicle accelerates, and one in which the vehicle decelerates. The names of the accelerating and decelerating state differ from the other two because they were generated based on a UCA with type APPLIED-TOO-LONG and STOPPED-TOO-SOON respectively. The original states, which were just labeled `acc` and `dec` were deleted since they were not reachable. The `stpa` file and the resulting textual SCChart are shown in the Appendix.

8 Discussion

The resulting SBM for the ACC example fulfills all generated LTL formulas. Hence, safety properties as well as liveness properties are fulfilled. However, the proposed synthesis is not necessarily complete. Calculations of internal values, e. g. `timeGap`, cannot be automatically inferred. The user has to modify the resulting SBM by adding another region and stating the calculation. This way the calculations are performed concurrently to the behavior of the system.

The same applies to the initialization of values. Variables that are of type *int* get 0 as initial value, but in the ACC example the variable `currentSpeed` should be set to some initial speed of the vehicle. Additionally, `currentSpeed` must be updated in each reaction. For that the user must state how the speed changes based on the sent control action or an additional input is needed, whose value is assigned to `currentSpeed`. A complete ACC SBM is shown in the Appendix.

It would be possible to modify STPA such that this missing information can be extracted automatically. The analyst could state the effect of a control action in its definition, and the definition of the process model variables can be extended to also include initial values and calculations. However, we think that this is out of scope for the safety analyst and should be done by a system developer. The needed information may not be known by the analyst and does not influence the analysis. Additionally, it would not save time to just outsource the initialization and calculation of variables to the analyst.

When the missing information is added to the SBM, the model depicts the desired and safe behavior since the behavior is not changed by the added information. The SBM created manually by Abdulkhaleq et al. for the ACC is very similar to our generated one. It contains the same four states but these are further encapsulated by a superstate. This superstate is connected to another state that models whether the ACC is off or on. Since the controller in the analysis has no variable for stating the status of the ACC, this is not considered in our SBM generation. Even if it is considered we would not generate a superstate for the four already generated states. In future work we will work on integrating an option to define which superstates are required such that the internal behavior can be generated automatically.

In conclusion, the generated SBM is not fully complete and can be further improved. However, it already gives the system developers a solid foundation for an SBM, and since risk analysis has to be done either way, the synthesis saves time. Generating the safety properties directly based on a safety analysis could also reduce failures or missing formulas.

9 Conclusion and Future Work

We presented a synthesis of an SBM from STPA. The first part of the synthesis translates the UCAs from STPA to LTL formulas. In the second part an SBM is generated by using each control action defined in the analysis as a state and translating the LTL formulas to corresponding transitions. We extended STPA by DCAs to model the desired behavior as well. They are stated just like the UCAs and hence can be translated to LTL formulas and to transitions in the same way.

The synthesis is implemented in PASTA and creates an SCChart as the SBM. As an example an ACC was used, which resulted in a similar SBM as created manually by Abdulkhaleq et al. The resulting SBM is not complete because initialization and calculation of variables must be added manually. However, it provides a good foundation and covers safety as well as liveness properties.

In the future we want to allow the definition of explicit state variables in the process model of a controller. For each value of this variable a superstate can be created. The behavior inside each superstate can be generated by using the presented approach with the corresponding UCAs. An open question in this approach is how to automatically generate the transitions between the superstates. One approach could be to extend STPA even more to define the transitions between the states, but this again may be out of scope for the safety analyst.

Appendix

The analysis we have done for the example ACC system is shown in Lst. 1. It is an `stpa` file created in PASTA. Executing the generation of the SBM for this file results in the SCChart file shown in Lst. 2. The textual SCChart is annotated with the LTL formula we generated and used for the synthesis of the model. Generally, SCCharts are realized with a text-first approach [14]. This means, the SCChart is defined textually in an editor and the corresponding visualization is generated automatically.

```
Losses
L1 "The ACC robot crashes the robot ahead"

Hazards
H1 "The ACC software does not keep a safe distance from the vehicle
     robot ahead." [L1]

ControlStructure
ACC {
    Software {
        processModel {
            currentSpeed: [desiredSpeed=[desiredSpeed], lessDesiredSpeed
                 = [MIN, desiredSpeed),
                 greaterDesiredSpeed=(desiredSpeed, MAX]]
            timeGap: [lessSafetyTimeGap=(0, safetyTimeGap],
                 greaterSafetyTimeGap=(safetyTimeGap, MAX], zero=[0]]
        }
        controlActions {
            [acc "Accelerate", dec "Decelerate", stop "Fully Stop"] ->
                 Robot
        }
    }
    Robot {
        feedback {
            [speed "Speed"] -> Software
        }
    }
}

ContextTable
// acceleration
RL1 {
    controlAction: Software.acc
    type: provided
    contexts: {
        UCA1 [timeGap = lessSafetyTimeGap] [H1]
    }
}
RL2 {
    controlAction: Software.acc
```

```
    type: applied-too-long
    contexts: {
        UCA2 [timeGap = greaterSafetyTimeGap] [H1]
    }
}
RL3 {
    controlAction: Software.acc
    type: provided
    contexts: {
        UCA3 [timeGap = zero] [H1]
    }
}
// deceleration
RL4 {
    controlAction: Software.dec
    type: too-late
    contexts: {
        UCA4 [timeGap = lessSafetyTimeGap] [H1]
    }
}
RL5 {
    controlAction: Software.dec
    type: stopped-too-soon
    contexts: {
        UCA5 [timeGap = lessSafetyTimeGap] [H1]
    }
}
RL6 {
    controlAction: Software.dec
    type: not-provided
    contexts: {
        UCA6 [timeGap = lessSafetyTimeGap] [H1]
    }
}
// stop
RL7 {
    controlAction: Software.stop
    type: too-late
    contexts: {
        UCA7 [timeGap = zero] [H1]
    }
}
RL8 {
    controlAction: Software.stop
    type: not-provided
    contexts: {
        UCA8 [timeGap = zero] [H1]
    }
}
```

```
DCAs
R1 {
    controlAction: Software.acc
    type: provided
    contexts: {
        DCA1 [currentSpeed = lessDesiredSpeed, timeGap = greaterSafetyTimeGap]
    }
}
R2 {
    controlAction: Software.acc
    type: not-provided
    contexts: {
        DCA2 [currentSpeed = greaterDesiredSpeed]
    }
}
```

Listing 1: ACC example analysis in PASTA.

```
@LTL G ((timeGap > 0 && timeGap <= safetyTimeGap) -> (controlAction != Software.acc)), "UCA1"
@LTL G ((timeGap > safetyTimeGap && controlAction == Software.acc) -> (X ((!(timeGap > safetyTimeGap)) -> controlAction != Software.acc))), "UCA2"
@LTL G ((timeGap == 0) -> (controlAction != Software.acc)), "UCA3"
@LTL ((timeGap > 0 && timeGap <= safetyTimeGap) -> (controlAction == Software.dec)) && G ((!(timeGap > 0 && timeGap <= safetyTimeGap)) -> (X ((timeGap > 0 && timeGap <= safetyTimeGap) -> (controlAction == Software.dec)))), "UCA4"
@LTL G ((timeGap > 0 && timeGap <= safetyTimeGap && controlAction == Software.dec) -> (X((controlAction != Software.dec) -> (!(timeGap > 0 && timeGap <= safetyTimeGap))))), "UCA5"
@LTL G ((timeGap > 0 && timeGap <= safetyTimeGap) -> (controlAction == Software.dec)), "UCA6"
@LTL ((timeGap == 0) -> (controlAction == Software.stop)) && G ((!(timeGap == 0)) -> (X((timeGap == 0) -> (controlAction == Software.stop)))), "UCA7"
@LTL G ((timeGap == 0) -> (controlAction == Software.stop)), "UCA8"
@LTL G ((currentSpeed > desiredSpeed) -> (controlAction != Software.acc)), "DCA1"
@LTL G ((currentSpeed < desiredSpeed && timeGap > safetyTimeGap) -> (controlAction == Software.acc)), "DCA2"
scchart SBM_Software {

enum Software{acc, dec, stop, NULL}
int timeGap
input int safetyTimeGap
int currentSpeed
input int desiredSpeed
ref Software controlAction
```

```
initial state NoAction {
    entry do controlAction = Software.NULL
}
if timeGap > 0 && timeGap <= safetyTimeGap go to dec_timeGapGreaterThan0AndtimeGapLessOrEqualTosafetyTimeGap
if currentSpeed < desiredSpeed && timeGap > safetyTimeGap go to acc_timeGapGreaterThansafetyTimeGap
if timeGap == 0 go to stop

state stop {
    entry do controlAction = Software.stop
}
if timeGap > 0 && timeGap <= safetyTimeGap go to dec_timeGapGreaterThan0AndtimeGapLessOrEqualTosafetyTimeGap
if currentSpeed < desiredSpeed && timeGap > safetyTimeGap go to acc_timeGapGreaterThansafetyTimeGap

state acc_timeGapGreaterThansafetyTimeGap "acc (timeGap > safetyTimeGap)" {
    entry do controlAction = Software.acc
}
if timeGap > 0 && timeGap <= safetyTimeGap go to dec_timeGapGreaterThan0AndtimeGapLessOrEqualTosafetyTimeGap
if timeGap == 0 go to stop
if currentSpeed > desiredSpeed go to NoAction
if !(timeGap > safetyTimeGap) go to NoAction

state dec_timeGapGreaterThan0AndtimeGapLessOrEqualTosafetyTimeGap "dec (timeGap > 0 && timeGap <= safetyTimeGap)" {
    entry do controlAction = Software.dec
}
if currentSpeed < desiredSpeed && timeGap > safetyTimeGap && !(timeGap > 0 && timeGap <= safetyTimeGap) go to acc_timeGapGreaterThansafetyTimeGap
if timeGap == 0 && !(timeGap > 0 && timeGap <= safetyTimeGap) go to stop
}
```

Listing 2: Automatically generated textual SCChart based on the ACC analysis. The LTL formulas are here highlighted as done in Fig. 1 with the implicant in green and the implicand in orange.

Fig. 6 shows the visualization of the generated textual SCChart. As mentioned in Sec. 8 this model is not complete yet. We have to define the calculation of `timeGap` and the effect of each control action manually. Fig. 7 shows an SCChart where we have added these missing information. We declared `during` actions in each state to model the effect of the corresponding control action and defined an additional region in which `timeGap` is calculated.

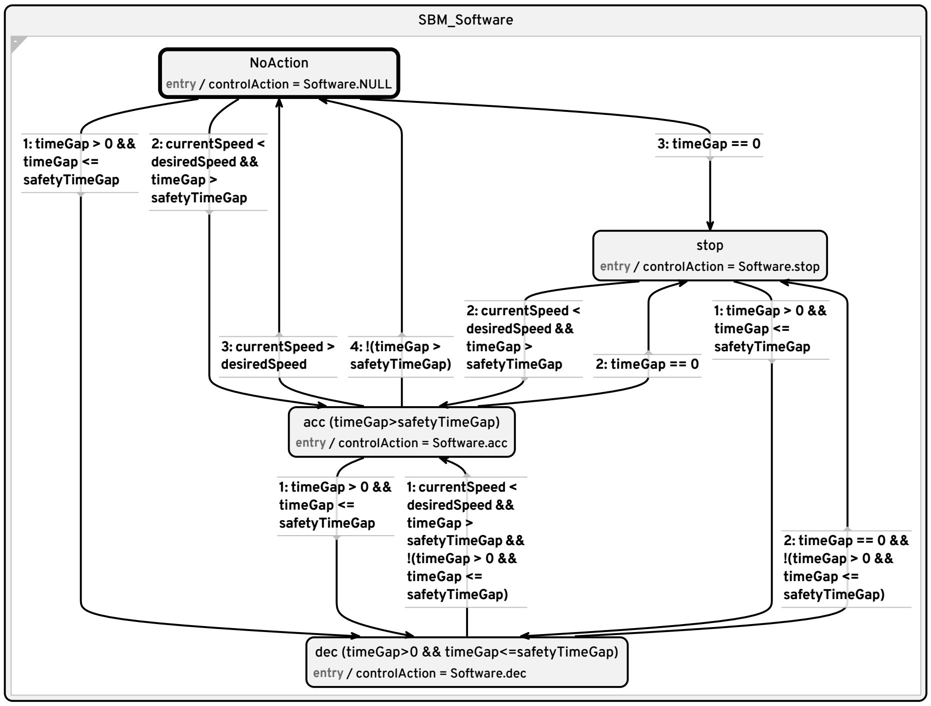


Figure 6: The ACC SBM as an SCChart with complete transition labels.

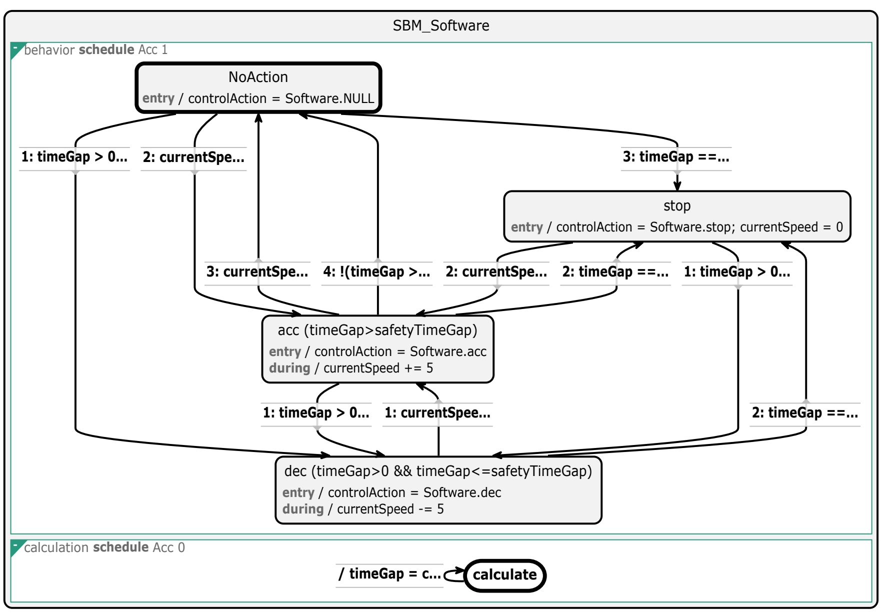


Figure 7: The ACC SBM containing the missing information.

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