Mapping Safety Properties for Embedded Control Applications to Certifiably Correct Implementations

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Agenda

Motivation

Compactor Scenario

Reconsideration of the model

Case Study

Conclusion
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Conclusion
Example of a system with real-time characteristics

Challenge: Breaking at the right point in time, so that the tires stop between the rolls

Problematic: communication delays and error-prone pose measurement of the car
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- You have to verify and also certify the correct behaviour
- There exists many formal approaches on the verification of embedded control systems [1] [2]
- The physical or technical system is mapped to a context-specific model

BUT ...

- ... verifying safety properties within the model only hold at modeling level
- ... on implementation level, you have to „reverify“

**Goal**
Refinement of the context-specific model, so that the verification of its safety properties also holds at the implementation level.
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- Approach to formulate a formal model for collision avoidance in the context of autonomous driving [5]
- A one-dimensional robotic system between two objects
- One of the objects moves with a constant velocity towards the robotic system

Question
Under which conditions will the robotic system not collide with the moving object?
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Compactor Scenario II

- $\mathcal{W}$: workspace
- $\mathcal{A}$: robotic system
- $\mathcal{B}_f$: static object
- $\mathcal{B}_m$: moving object
- $v_m$: velocity of the moving object $\mathcal{B}_m$
- $d_m$: distance between $\mathcal{A}$ and $\mathcal{B}_m$
- $l_m$: minimal escape distance

\[
\begin{align*}
\mathcal{W} & \\
\mathcal{A} & \quad \mathcal{B}_f \\
\mathcal{B}_m & \\
\end{align*}
\]

\[
\begin{align*}
l_m & \\
d_m & \\
v_m & \\
\end{align*}
\]
Compactor Scenario III

- $t_c$: time to collision
- $t_l/t_r$: last possible time to escape in left/right direction.
- $t_e$: time to escape using the minimal escape route.

$T$ $S$

$-v_{max}$ $v_{max}$

$A$ CS

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Compactor Scenario IV

- $t_d$: time to decide about the minimal escape route
- $t_{la}$: lookahead time

**Constraint**

A collision is avoided, if the following constraint holds:

$$t_d \leq t_c - t_{e} - v_{max} - t_{l} - t_{f} - t_{0}$$

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Compactor Scenario IV

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**Constraint**

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Environment

Sensors
  - current state $s$
  - distance of $A$ to $B_m$
  - velocity $v_{max}$, $v_m$

Program
  - control action (CA)

Actuators
  - velocity

Program output

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How can we map the model to an implementation?

- The measured values of the sensors are used to calculate a correct control action.
- The actuators offer the interface to implement this control action within the environment.
- The important question, which arises is:

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- $t_e = \frac{l_m}{v_{\text{max}}}$
- $t_d$?

Problematic

- The measured values $d_m$, $v_m$ and $d_e$ are error-prone
- The measured values are ageing
- Setting the value $v_{\text{max}}$ to the motors does not necessarily result in an exact movement of $A$ with a velocity $v_{\text{max}}$
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- All these points mentioned before must be considered inside the model, so that the verification of safety properties holds at the implementation level.

- Finally, there are two different categories of refinement to include inside the model:
  1. Errors in values
  2. Deviation in time, e.g., caused by process communications and process scheduling

**Requirement**

There is a need of a dedicated method to describe this kind of refinements.
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Refinement of the model I

- As in [4] and [3] we divide two different entity types to represent the data in our system:
  1. Real-Time Entities, e.g. the current velocity of $B_f$
  2. Observerd Entities, e.g. the measured velocity of $B_f$

- Real-Time Entities are from the view of the technical system or the environment
- Observerd Entities are from the view of the implementation
- Sensors and actuators are the interfaces to transform Real-Time Entities to Observed Entities and vice versa
- A model which uses only the Real-Time Entities exists already
- The challenge is to develop the model from the view of the implementation, using the observed entities
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- First, we need an invariant $I_{RT}$ representing the correctness of a safety property of our system
- Outgoing point of our calculation is the $CA$ inside the implementation
- We divide between the set of ICS and ACS (Avoidable collision states).
- Every state inside ACS matches $I_{RT}$, so this states are safe
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Step 1: Include all time deviations inside the model:

- We have to look into the past, e.g. the age of the measurement of the velocity $v_m$ of $B_f$
- We have to look into the future, e.g. the time until $A$ drives with the velocity $v_{max}$ in the specified direction.
- Using only the worst possible values, e.g. the maximum age of a sensor value, we can calculate a new distance $d_m$ from $A$ towards $B_f$, causes the size of the set of ACS to shrink
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- We have to regard the errors of the sensors, e.g. the deviation of the measured velocity of $B_f$ is $\pm 2.5\%$
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- Using only the worst possible values, e.g. the minimum velocity of $A$, causes the size of the set of ACS to shrink
Concept of the approach III

**Step 2:** Include all measurement errors inside the model:

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Summary

▶ We transformed the Observed Entities back into Real-Time Entities

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Summary
Concept of the approach IV

What is $t_d$?

$t_d$ is the time from the first measurement of a value up to the time, at which the control action takes place inside the environment.
Agenda

Motivation

Compactor Scenario

Reconsideration of the model

Case Study

Conclusion
## Instantiation of the model with example values

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>Deviation</th>
<th>Age of the value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity of the dynamic object</td>
<td>$v_m$</td>
<td>$4 \frac{m}{s}$</td>
<td>$\pm 2,5%$</td>
<td>$[90, 140] \text{ ms}$</td>
</tr>
<tr>
<td>Distance of $A$ towards $B_f$</td>
<td>$d_m$</td>
<td>$8 m$</td>
<td>$\pm 1,1%$</td>
<td>$[50, 90] \text{ ms}$</td>
</tr>
<tr>
<td>Minimal escape distance</td>
<td>$d_e$</td>
<td>$4 m$</td>
<td>$\pm 1,5%$</td>
<td>$[40, 130] \text{ ms}$</td>
</tr>
<tr>
<td>Execution time of the computational system</td>
<td>$\Delta e$</td>
<td>$[15, 31] \text{ ms}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Delay until the drive maneuver takes place</td>
<td>$\Delta a_m$</td>
<td>$[0, 200] \text{ ms}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maximal velocity of $A$</td>
<td>$v_{max}$</td>
<td>$5 \frac{m}{s}$</td>
<td>$\pm 0,1%$</td>
<td>-</td>
</tr>
</tbody>
</table>
Result

Usage of the original model:

\[ t_d \leq \Delta t_c - \max(t_l, t_r) = 1\text{s}. \]

Regarding the age of the measured values:

\[ t_d \leq \frac{dI_m'}{v_m'} - \frac{dI_e'}{v_{max}} = 0.458\text{s} \]

Regarding additionally errors of sensors and actuators:

\[ t_d \leq \frac{odI_m}{ovh_m} - \frac{odI_e}{ovl_{max}} = 0.382\text{s} \]
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- Starting with an invariant condition, the steps can be executed rather mechanically.

- The advantages for the programmer are obvious: Any dependency is comprehensibly documented, verifiable and certifiable respecting the causal order.
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Outlook

- Any of the mentioned steps are error-prone, so that we are working on tool support.
  - Guiding the user by some sort of syntactic view an asking for any parameter.
  - Giving a readable description of all relevant time- and value-dependent deviations.

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Thank you for your attention!
Literature I


Literature II
