Formal $\text{FOCUS}^{ST}$ Specification of CAN

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November 21, 2018

Abstract

This paper presents a formal specification of the Controller Area Network (CAN) protocol using $\text{FOCUS}^{ST}$ framework. We formally describe core components of the protocol, which provides a basis for further formal analysis using the Isabelle/HOL theorem prover.

1 Introduction

Controller Area Network (CAN) protocol is one of the standard communication protocols used in automotive systems. CAN was developed by Robert Bosch GmbH [3] and is a part of the ISO 11898 standard [10].

In this paper, we present a formal specification of this protocol using $\text{FOCUS}^{ST}$ framework. $\text{FOCUS}^{ST}$ was introduced as an extension of the $\text{FOCUS}$ language, see [4, 24]. Similarly to $\text{FOCUS}$, specifications in $\text{FOCUS}^{ST}$ are based on the notion of streams, and a formal meaning of a specification is exactly this external input/output relation. However, in the original $\text{FOCUS}$ input and output streams of a component are mappings of natural numbers to single messages, whereas a $\text{FOCUS}^{ST}$ stream is a mapping from natural numbers to lists of messages within the corresponding time intervals. Moreover, the syntax of $\text{FOCUS}^{ST}$ is particularly devoted to specify spatial (S) and timing (T) aspects in a comprehensible fashion, which is the reason to extend the name of the language by $^{ST}$.

The $\text{FOCUS}^{ST}$ specification layout was then discussed in [20]. Here, we present only a small subset of that we applied to specify the CAN protocol:

- $\langle \rangle$ denotes an empty stream;
- $\text{dom.s}$ yields the list $[1...#s]$, where $#s$ denotes the length of the stream $s$;
- $\text{rng.s}$ converts the stream $s$ into a set of its elements : $\{s.j \mid j \in \text{dom.s}\}$;
- The predicate $\text{msg}_n(s)$ is true iff the stream $s$ has at every time interval at most $n$ messages.
Figure 1: Logical architecture of a CAN-based system

2 Specification of a CAN-based system

Figure 1 presents the specification $SystemArch$, which describes a logical architecture of a CAN-based system. We define the following the data types for this specification: $AMessage$ represents the data type of messages, which are sent by one automotive application to another:

\[
\text{type } AMessage = msg(id : \mathbb{N}, data : Data)
\]

$Message$ will denote the CAN-internal messages, and $Req$ will be a simple request type to denote the CAN requests to the system bufferes.

\[
\text{type } Message = N | Data
\]

\[
\text{type } Req = N
\]

The core system requirements are defined by the following specification $CAN$, where the assumption is that all data streams $as_i$ (which CAN receives from the automotive application components via the corresponding buffer components) satisfy the $msg_i(as_i)$ predicate, i.e., all these streams must have at every time interval at most one message. The guarantee part of this specification has two predicates that define

1. all data streams $ar_i$ (which CAN sends to the the corresponding automotive application components) satisfy the $msg_i(ar_i)$ predicate,

2. the data transmission is correct as per the predicate $MessageTransmission$. 


Note, that in contrast to the FocusST specification of FlexRay [6, 7, 8, 21, 23], where the correct transmission means the transmission according the FlexRay scheduling tables, in the case of CAN the correct transmission is specified according the priority relations, see below.

We also defined the following auxiliary functions to specify the MessageTransmission predicate:

- **TakeIds** takes as an input a finite list of type AMessage and returns the corresponding finite list of the identifiers.

- **CollectElements** describes collection of all data received by CAN at a particular time interval.

- **MinNatList** finds the smallest element in a finite list of natural numbers.
TakeIds

\( AMessage^* \rightarrow N^* \)

1. \( TakeIds(\langle \rangle) = \langle \rangle \)
2. \( TakeIds(\langle x \rangle \triangleright y) = \langle id(x) \rangle \triangleright TakeIds(y) \)

CollectElements

\( N \times \cdots \times M^* \times M^* \rightarrow M^* \)

1. \( CollectElements(0, s_1, \ldots, s_n) = \langle \rangle \)
2. \( CollectElements(i + 1, s_1, \ldots, s_n) = \)
   
   \( \text{if } s_{i+1} = \langle \rangle \) 
   
   \( \text{then } CollectElements(i, s_1, \ldots, s_n) \)
   
   \( \text{else } s_{i+1} \triangleright CollectElements(i, s_1, \ldots, s_n) \)

fi

MinNatList

\( N \times \cdots \times N^* \rightarrow N \)

1. \( MinNatList(a, \langle \rangle) = a \)
2. \( MinNatList(a, \langle x \rangle \triangleright y) = \)
   
   \( \text{if } a \leq x \) 
   
   \( \text{then } MinNatList(a, y) \)
   
   \( \text{else } MinNatList(x, y) \)

fi

We specify a CAN-buffer in \textit{Focus}^{ST} as a component \textit{Buffer}, see below. This component has two input streams (data from an automotive application and requests from CAN). The only assumption on the inputs is that the data stream from an automotive application must have at most one message per each time unit. The output stream will also have at most one message per each time unit. In the even time intervals, the buffer’s output stream will be empty, where in the even time intervals it will send the stored data to the CAN component.
Buffer timed

\begin{align*}
\text{in} & \quad \text{a AMessage; \; r : Req} \\
\text{out} & \quad \text{as : AMessage} \\
\text{local} & \quad \text{buf, b \in AMessage} \\
\text{init} & \quad \text{buf = \langle \rangle; \; b = \langle \rangle} \\
\text{asm} & \quad \text{msg}_1(a) \\
\text{gar} & \quad \text{msg}_1(as) \\
\forall t \in \mathbb{N} : \\
\text{2} & \quad \text{even}(t) \rightarrow as^t = \langle \rangle \\
\text{3} & \quad \text{odd}(t) \rightarrow as^t = b \\
\text{4} & \quad r^t = \langle \rangle \rightarrow b' = b \land buf' = \text{newbuf} \\
\text{5} & \quad r^t \neq \langle \rangle \land buf = \langle \rangle \rightarrow b' = a^t \land buf' = \langle \rangle \\
\text{6} & \quad r^t \neq \langle \rangle \land buf \neq \langle \rangle \rightarrow b' = \text{ft.newbuf} \land buf' = \text{rt.newbuf} \\
\text{where newbuf = if a}^t = \langle \rangle \text{ then buf else PrAdd(buf, ft.a}^t) \text{ fi}
\end{align*}

The auxiliary function \text{PrAdd} specifies the buffer update according to the priorities of the messages. A lower value of the identifier means a higher priority.

\text{PrAdd}

AMessage \times AMessage \rightarrow AMessage

\begin{align*}
\text{1} & \quad \text{PrAdd}(\langle \rangle, a) = \langle a \rangle \\
\text{2} & \quad \text{PrAdd}(x \sim y, a) = \\
& \quad \text{if } id(a) < id(x) \\
& \quad \text{then } \langle a \rangle \sim (x) \sim y \\
& \quad \text{else } (x) \sim \text{PrAdd}(y, a) \\
& \quad \text{fi}
\end{align*}
3 Specification of a CAN component

Figure 2 presents the specification CANArch, which describes a logical architecture of a CAN protocol component. Each system node will be coordinated using the corresponding Controller component, where the communication between controllers will go through the Wire component.

![Diagram of CANArch and Wire components](image)

Figure 2: Logical architecture of a CAN component

The Wire component has two assumptions on the input streams:

- all streams $w_{si}, 1 \leq i \leq n$ (CAN messages sent by Controller components, where $n$ is the number of controllers, i.e., the number of CAN nodes in the system) must have at most one message per each time interval;
- at each time interval, if one of the streams $w_{si}, 1 \leq i \leq n$ is nonempty and carries an element of type $N$ then all other streams $w_{sj}, 1 \leq j \leq n, j \neq i$ must be either empty or carry an element of type $N$;
- at each time interval, if one of the streams $w_{si}, 1 \leq i \leq n$ is nonempty and carries an element of type $Data$ then all other streams $w_{sj}, 1 \leq j \leq n, j \neq i$ must be either empty or carry an element of type $Data$;
A Controller component is also composite, the specification of its logical architecture is presented in Figure 3. Controller consists of three sub-components:

- **Encoder** that converts the automotive application messages into CAN messages,
- **Decoder** that ensures the reverse transformation, where CAN messages are decoded into the automotive application messages,
- **LogicalLayer** that ensures that CAN bus behaves correctly.
The Encoder component assumes that its input stream of type AMessage can have at most one message per time interval. As soon as this component receives a message, it forwards its identifier to the logical level it the same time interval and sends the actual data part in the next time interval. If we specify this behaviour simply by

\[ \forall t \in \mathbb{N} : \]
\[ (1) \quad as^t = \langle \rangle \rightarrow ms^t = \langle \rangle \]
\[ (2) \quad as^t \neq \langle \rangle \rightarrow ms^t = \langle id(as^t) \rangle \wedge ms^{t+1} = \langle data(as^t) \rangle \]

We will have many contradictions. Thus, assume that \( as^t \neq \langle \rangle \) and \( as^{t+1} = \langle \rangle \). From (1) we can conclude that \( ms^{t+1} = \langle \rangle \). However, from (2) it follows that \( ms^{t+1} = \langle data(as^t) \rangle \). Also, in the case \( as^t \neq \langle \rangle \) and \( as^{t+1} \neq \langle \rangle \), we would have \( ms^{t+1} = \langle data(as^t) \rangle \) because \( as^t \neq \langle \rangle \), and at the same time \( ms^{t+1} = \langle id(as^{t+1}) \rangle \) because \( as^{t+1} \neq \langle \rangle \). Thus, we have to use a state variable to ensure the correct modelling. Let us call this variable \( e \). A simple Boolean type will be enough to specify the correct behaviour: the true value will denote the state of active encoding process, where the false value (which will be also the initial value for \( e \)) would mean that no encoding is currently performed.
The aim of the Decoder component is to build an output message of type AMessage out of two consequently received input messages, where the first input message must be of type N and the second input message must be of type Data. This property is specifies as the following predicate:

\[
\text{MsgCANFormat}_{s \in \text{Message}} =
\]

\[
\forall t \in \mathbb{N} : \\
\begin{array}{ll}
1 & s^t \neq \langle \rangle \land ft.s^t \in \mathbb{N} \rightarrow \\
 & s^{t+1} \neq \langle \rangle \land ft.s^t \in \text{Data} \\
2 & s^t \neq \langle \rangle \land ft.s^t \in \text{Data} \rightarrow \\
 & t > 0 \land s^{t-1} \neq \langle \rangle \land ft.s^{t-1} \in \mathbb{N} \\
\end{array}
\]

Thus, the Decoder component assumes that at each time interval it can receive at most one message, and if the message is non-empty and of type N, the next time interval will of the input stream will contain data. We will use a local variable \(d\) of type \(\mathbb{B}\)ool to denote that the decoding process is in progress:

\[
\text{Encoder} \quad \text{timed} =
\]

\[
\begin{array}{ll}
\text{in} & as : \text{AMessage} \\
\text{out} & ms : \text{Message} \\
\text{local} & e \in \mathbb{B} \\
\text{init} & e = \text{false} \\
\text{asm} & 1 \text{msg}_1(as) \\
\text{gar} & 1 \text{msg}_1(ms) \\
\forall t \in \mathbb{N} : \\
2 & (e = \text{false} \land as^t = \langle \rangle) \rightarrow \\
 & (ms^t = \langle \rangle \land e' = \text{false}) \\
3 & (e = \text{false} \land as^t \neq \langle \rangle) \rightarrow \\
 & (ms^t = \langle \text{id}(as^t) \rangle \land ms^{t+1} = \langle \text{data}(as^t) \rangle \land e' = \text{true}) \\
4 & e = \text{true} \rightarrow (ms^t = \langle \text{data}(as^{t-1}) \rangle \land e' = \text{false}) \\
\end{array}
\]
the true value will denote the state of active decoding process, where the false value (which will be also the initial value for $d$) would mean that no decoding is currently performed.

The LogicalLayer component assumes that both its input stream of type $Message$ can have at most one message per time interval and fulfil the property $MsgFormat$. All three its output streams also should have at most one message per time interval, where the $mr$-stream that goes to the Decoder component should in addition fulfil the property $MsgFormat$. 
LogicalLayer —— timed ——

in  $ms, wr : Message$

out $mr, ws : Message; r : Req$

local $lid ∈ \mathbb{N}$

init $lid = 0$

asm

1 $msg_1(ms)$
2 $msg_1(mr)$
3 $MsgFormat(ms)$
4 $MsgFormat(mr)$

gar

1 $msg_1(ws)$
2 $msg_1(r)$
3 $msg_1(mr)$
4 $MsgFormat(mr)$
5 $∀ t ∈ \mathbb{N}: mr^t = wr^t$

\textit{tiTable LLTable}

\textit{tiTable LLTable:} $∀ t ∈ \mathbb{N}$

|   | $ms$ | $wr$ | $ws$ | $r$ | $lid'$ | Assumption |
|---|------|------|------|-----|--------|------------|
| 1 | $\langle \rangle$ | $y$ | $\langle \rangle$ | $\langle \rangle$ | $lid$ |            |
| 2 | $x$ | $y$ | $\langle \rangle$ | $\langle \rangle$ | $ft.x$ | $x \neq \langle \rangle, ft.x ∈ \mathbb{N}$ |
| 3 | $x$ | $\langle \rangle$ | $\langle \rangle$ | $\langle \rangle$ | $lid$ | $x \neq \langle \rangle, ft.x ∈ Data$ |
| 4 | $x$ | $y$ | $x$ | $\langle req \rangle$ | $lid$ | $x \neq \langle \rangle, ft.x ∈ Data, y \neq \langle \rangle, ft.x = lid$ |
| 5 | $x$ | $y$ | $\langle \rangle$ | $\langle \rangle$ | $lid$ | $x \neq \langle \rangle, ft.x ∈ Data, y \neq \langle \rangle, ft.x \neq lid$ |

**Remark:**
The 3rd line of the table \textit{LLTable} will never be used by the specification \textit{LogicalLayer} because of the assumptions and the properties of the specification \textit{Wire}. 
4 Related work

4.1 CAN

There have been very few formal approaches targeting analysis of CAN protocol. A formal method for analysis of automotive systems (also CAN-based) was discussed in [5]. A frame packing algorithms for automotive applications was introduced in [12].

Van Osch and Smolka proposed a finite-state method for analysis of the CAN bus protocol. Saha and Roy presented a formal specification of the time triggered version of CAN Protocol, see [11].

4.2 Focus$^{ST}$

Focus$^{ST}$ approaches presented in [16, 17, 27] aims to apply the engineering psychology achievements to the design of formal methods, focusing on the specification phase of a system development process. Its core ideas originated from the analysis of the Focus framework and also led to an extended version of the framework, Focus$^{ST}$.

Another approach based on Focus$^{ST}$, allows analysis of component dependencies [19]. This was later extended to framework for formal analysis of dependencies among services [25].

Model-based analysis of temporal properties using Focus$^{ST}$ was presented in [22]. The authors also demonstrate how to implement on Focus$^{ST}$ basis time-triggered and event-based view on systems with temporal properties.

Spatio-temporal models for formal analysis and property-based testing were presented in [1, 2] by Alzahrani et al. The authors aimed to to apply property-based testing on Focus$^{ST}$ and TLA models with temporal properties.

Zamansky et al. [28, 28] reviewing some recent large-scale industrial projects in which formal methods (including Focus$^{ST}$) have been successfully applied. The authors also covered some aspects of teaching formal methods for software engineering, including Focus$^{ST}$, cf. [26, 13].

5 Conclusions

This paper presents a formal specification of the Controller Area Network (CAN) protocol using Focus$^{ST}$ framework. We formally describe core components of the protocol, which provides a basis for further formal analysis using the Isabelle/HOL theorem prover [9] using the Focus on Isabelle methodology [14, 18, 15].
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