Reconciling a component and process view

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Abstract—In many cases we need to represent on the same abstraction level not only system components but also processes within the system, and if for both representation different frameworks are used, the system model becomes hard to read and to understand. We suggest a solution how to cover this gap and to reconcile component and process views on system representation: a formal framework that gives the advantage of solving design problems for large-scale component systems.

I. INTRODUCTION

Component-based software engineering is one of the largest fields of software and system engineering, however, in many cases we need to represent on the same abstraction level not only system components and the data flows between them but also processes within the system. Even if the common practice to model parts of a system is to use the component view, the representation of system behaviour by modelling processes within the system becomes more and more important: nowadays the process view and the data flow representation are a typical part of the development of interactive or reactive systems. Having a process view, we can abstract from several aspects of the data flows by focusing on the control flow within the system, which gives us the advantage of comprehensible representation even in the case of large-scale systems. However, if we need to have both, process and component, views on the system to get a comprehensive system model, the gap between these views can reduce to zero the benefit of having both kinds of representation. To cover this gap, we present a formal model of processes which is compatible with the component view: modelling both components and processes within the same framework, we not only increase the readability of a system model but also can easier ensure consistency among these different views on a system.

On the one hand, this concept can also be related to the IEC 61499 standard developed as a technology for distributed automation systems with the decentralised and distributed control logic (cf. [1], [2]). This standard is oriented on the development of reusable modules for industrial control applications, and purposes to use function blocks as the basic constructs. Each function block corresponds to an abstract representation of a functional unit of software, where local data and the behavioural specification are encapsulated within an event-data interface. In IEC 61499, modular components have an event signal interface (representing a control flow) and data ports (representing a data flow), and are coupled in a hierarchical manner to arrange more complicated, compositional blocks. Thus, the suggested approach can be seen as a formalisation of the main parts of the IEC 61499 standard, however, due to suggested syntax, we can also switch from an event-based specification to a time-triggered one – in both cases we have a trigger of some kind, the difference solely is whether the trigger is an explicit data/control signal or an information about the current time in a system. On the other hand, specifying a process view on a system, it is desirable to have a possibility of a flexible translation from/to a common Petri Net notation (cf. e.g., [3], [4]), which allows to focus on the control flow analysis within a system and is mainly recognised as a modelling language for process representation. Our approach enables schematic translation between the suggested process view representation and the Petri Net language.

II. RELATED WORK

Component-based software engineering utilises a well-defined composition theory to enable the prediction of such properties as performance and reliability. This is one of the largest fields of software and system engineering. There are many approaches on component-based development covering different aspects and focusing on requirements, quality, timing properties etc. (cf. e.g., [5], [6], [7]). Several component-based prediction approaches, e.g. Palladio [8], CB-SPE [9], ROBO-COP [10] derive the benefits of reusing well-documented component specifications (cf. also a survey in [11]). In our approach we focus on the questions of combination of component/data flow and process views, to reuse most of the advantages of both representations and to avoid gaps in having these representations as unconsolidated ones.

There is a large variety of approaches on process representation which have a lot of similarities as well as differences in many aspects such as (co-)algebraic view, composition types, kinds of structuring, representation of time, separation of different kinds of flow, etc. An informal way to represent processes is used in the UML (Unified Modeling Language, [12]): the concept of activity diagrams supports the specification of control flow in terms of choice, iteration, and concurrency. However, there is a number of approaches, e.g., [13], which aim to formalise the UML semantics in different ways. A co-algebraic view on process modelling gives, e.g., the coordination language Reo [14] a channel-based modelling language that introduces various types of channels and their composition rules. By composing Reo channels, we can specify connectors to realise some behavioural protocols. The main concepts used in this language are the service synchronisation and the data flow constraints.

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Many process description techniques are also based on the ideas of Petri Nets [3], [4]. For example, YAWL (Yet Another Workflow Language, cf. [15]) was developed by taking Petri Nets as a starting point and adding new mechanisms on the workflow patterns. A number of architecture description languages (ADLs) have been developed to specify compositional views of a system on an abstract level, e.g., the TrustME ADL [16], which combines software architecture specification approaches with ideas of design-by-contract. This approach allows capturing of complex behavioural interaction patterns, synchronous and asynchronous, between large-scale components of software and systems architectures.

Other approaches formalise work flows using the concept of process algebras [17]. The most famous of them are Bergstra’s Algebra of Communicating Processes [18], Hoare’s approach on Communicating Sequential Processes (CSP) [19], Milner’s Calculus of Communicating Systems (CCS, cf. [20]), and variants thereof. This kind of techniques do not provide the high level of abstraction which is very important in the early phases of system development. Nevertheless, general ideas of process algebras influence many other methods, and there are works aimed to solve the problem with abstract view, e.g., by adding graphical notations like in [21].

III. FORMAL MODEL OF PROCESSES

From the large collection of process description techniques, we chose the process language described in [22] as the most suitable for our purpose to embed the process view into the component representation: this process language combines the concept of (de)activating processes via control points, firstly introduced in Petri Nets, with the idea of separation of data and control flow to enable a proper composition of processes. A process is understood there as “an observable activity executed by one or several actors, which might be persons, components, technical systems, or combinations thereof”: it has one entry (activation, start) point and one exit (end) point, what also perfectly fits to the main ideas of the IEC 61499 standard: an entry point is a special kind of input channel that activates the process (the functional block in IEC 61499), where an exit point is a special kind of output channel that is used to indicate that the process (computation in the fictional block) is finished. Our approach allows us to model elementary and composed processes in a formal way, to argue about properties of composed systems, and easily switch from the process view to a classical component view. The hierarchical definition of a process gives many advantages for analysis, the formal model of a process permits its formal verification, and, moreover, provides a formal interpretation for the behaviour of a process as a special kind of a component.

Formal specification frameworks should include predefined templates and special alerts helping to avoid the omission of assumptions about the systems environment. For this reason we specify every component in terms of an assumption and a guarantee: whenever input from the environment behaves in accordance with the assumption, the specified component is required to fulfill the guarantee. Even the application of specification templates can make the model development more understandable and more appropriate for safety-critical and large-scale component systems [23]. The main ideas presented in this paper are mostly language-independent, nevertheless we prefer to present them using an algebraic language FOCUS [24] inspired by FOCUS [25], a framework for formal specification and development of interactive systems. Another advantage is a well-developed theory of composition.

We specify for any process P its entry and exit points by Entry(P) and Exit(P) respectively, and represent a process P (elementary or composed) by the corresponding component specification PComp, thus, [P] = PComp. For any process P with syntactic interface (IP > OP), where IP and OP are sets of input and output data streams respectively, we can specify 

\[ I_P = \{ \text{Entry}(P) \} \cup I_P \text{ and } O_P = \{ \text{Exit}(P) \} \cup O_P. \]

A process can be defined as an elementary or a composed one, where the composition of any two processes P1 and P2 can be sequential P1; P2, alternate P1 ⊕ P2 or parallel P1 || P2, and for any process P we can define repetitively composed process \( P \circ lpspec \), where lpspec denotes a loop specifier. We treat a process as a special kind of a component that has additionally two extra channels (one input and one output channel) which are used only to activate the process and to indicate its termination, i.e., to represent the entry and exit points of the process.

The formal correlation between the definition of processes and components are presented below, separately for elementary and composite processes. Composite specifications of processes (as well as of components) are built hierarchically from elementary ones using constructors for composition, and can be represented in the graphical or textual style.

In this paper we use the following operators to present examples of process/component specifications:

\[ \{ \} \text{ an empty stream} \]
\[ \{ x \} \text{ one element stream consisting of the element } x \]
\[ ft. l \text{ the first element of an untimed stream } l \]
\[ s^t \text{ the } t \text{th time interval of the stream } s \]
\[ \text{msg}_n(s) \text{ } s \text{ can have at most } n \text{ messages at each time interval} \]

A. Model of an elementary process

An elementary process corresponds to an elementary specification that has one special input channel start of type Event consisting of one element * as well as one special output stop of the same type (input and output points of the process that corresponds to the signals process is started and process is finished). Using the syntax proposed in this paper, we specify the type of these channels only implicitly, and need to have the following extensions of a component to model a process:

- Each input channel (except the activation signal channel) c has a corresponding buffer (local variable) cBuf of size one (one element buffer), which value will be taking into account, when starting the process.
- If the process is inactive, there are no values on its output channels.
The component gets a local variable active of type Bool to represent whether the process is in active phase.

We suggest the following framework for process specification. Assume a process P has n input channels x₁, . . . , xₙ and m output channels y₁, . . . , yₘ (cf. Figure 4 for a general specification and Figure 2 for the corresponding component specification). Data types of input and output streams are denoted by M₁, . . . , Mₙ and MO₁, . . . , MOₘ respectively. In the local-section of the specification we introduce all the local variables used by the process as well as the buffer variables used to store the values of the latest inputs while the process is inactive. The initial values of buffers for the input channels x₁, . . . , xₙ are denoted by BufInit₁, . . . , BufInitₙ. A process can also have a number of parameters which can be listed in parenthesis.

The specification section initProcess differs from the section init in the following sense: everything that is defined within the init section must be initialised only once, in the beginning, where everything that is defined within the initProcess section must be initialised every time the process is (re)started, i.e. every time the value of the local variable active is triggered from false to true (in a process specification this trigger is used implicitly, where in a component specification we specify these changes directly).

To increase readability, we label all transitions in the state transition diagram: dealing with specifications or real systems, where a diagram could be hardly readable due to its size and a large number of state transitions, we need to use another representation style. Each table line (in the case of a diagram, each transition) can be specified as a single formula in the gar-part of the specification, the rewriting scheme is straightforward. In addition, we distinguish two types of the transition labels by coloured representation: inputs and constraints on the current local variables’ values are marked blue, outputs and changes of local variables’ values are marked green.

The asm-part of the specification must contain all the assumption about the environment, i.e. all the properties of input streams which are necessary for the correct system behaviour. The gar-part of the specification contains the description of system behaviour: the behaviour of any process in its active phase. The condition of the process finishing is defined by the relation PrEnding over the received input values.

The relation PrCalcF describes the calculations of the output and buffer values for the case PrEnding holds, however, sometimes we can use the same predicate for both cases. By the relation PrCalc we represent here all the calculations of the output and local values for the current step/time unit and of the buffer values for the next step – they have to be performed during the time process is active. In some cases we need to extend this predicate by calculations of some other local variables of the process.

Below we have presented a general specification of a process P following by the corresponding component specification PComp. The 1st and 2nd formulas in the component specification are almost equal to the formulas in the process specification: the constraints on the variable active are now added explicitly. The behaviour of any process in its inactive phase is defined in the component specification by the formulas 3, . . . , 6 + 2n. It is the same for any process, and is therefore omitted in process specifications. The only exception is the formula 4: initialisation of the values of local variables:

```
process P [start, stop] (Parameters) timed
in  x₁ : M₁; . . . , xₙ : Mₙ
out y₁ : MO₁; . . . , yₘ : MOₘ
local x₁Buf ∈ M₁; . . . , xₙBuf ∈ Mₙ
init x₁Buf = BufInit₁; . . . , xₙBuf = BufInitₙ

initProcess InitValuesReqForEveryProcessRestart

asm SomeAssumptions

gar
1 PrEnding(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf') → ex₁' = (⋆) ∧ PrCalcF(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf', y₁', . . . , yₘ')
2 ¬PrEnding(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf') → ex₁' = (⋆) ∧ PrCalc(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf', y₁', . . . , yₘ')
```

Fig. 1. Specification of a process P

```
PCComp(Parameters) timed
in start : Event; x₁ : M₁; . . . , xₙ : Mₙ
out stop : Event; y₁ : MO₁; . . . , yₘ : MOₘ
local active : Bool; x₁Buf ∈ Mₙ; . . . , xₙBuf ∈ Mₙ
init active = false; x₁Buf = BufInit₁; . . . , xₙBuf = BufInitₙ

asm SomeAssumptions

gar
1 active = true ∧ ¬PrEnding(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf') → ex₁' = (⋆) ∧ PrCalcF(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf', y₁', . . . , yₘ') ∧ active' = false
2 active = true ∧ ¬PrEnding(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf') → ex₁' = (⋆) ∧ PrCalc(x₁', . . . , xₙ', x₁Buf', . . . , xₙBuf', y₁', . . . , yₘ') ∧ active' = true
3 active = false ∧ ex₁' = (⋆) → ex₁' = (⋆) ∧ active' = true ∧ y₁' = (⋆) ∧ . . . ∧ yₘ' = (⋆)
4 active = false ∧ ex₁' ≠ (⋆) → InitValuesReqForEveryProcessRestart ∧ ex₁' = (⋆) ∧ active' = true ∧ y₁' = (⋆) ∧ . . . ∧ yₘ' = (⋆)
5 active = false ∧ x₁' ≠ (⋆) → xₙBuf' = ft.x₁'
6 active = false ∧ x₁' = (⋆) → xₙBuf' = xₙBuf

5+2n active = false ∧ x₁' ≠ (⋆) → xₙBuf' = ft.x₁'
6+2n active = false ∧ x₁' = (⋆) → xₙBuf' = xₙBuf
```

Fig. 2. Specification of a component, representing the process P
if it is required for every restart of a process, the corresponding constraints should be moved to the initProcess section.

It is easy to see that a process and a classical component specification have a very similar structure and syntax, and one can easily change from one view to the other without any effort and learning a new language. The same also holds for composed processes and components.

We suggest to represent PrCalc by a state transition diagram or the corresponding state transition table (also combining it with the representation of PrCalcF), because a graphical specification is, in general, more readable than a plain text one. Here is applicable the idea of mode automata, which have a long history motivated by real-time design practices and methods used in industry in connection with statecharts. Maraninchi et al. [26] capture the notion of modes formally for a practical extension of the real-time synchronous language Lustre and include elements of the well-known I/O-automata. Mode automata define synchronous mode automata as a hybrid between data-flow and transition systems, and in our case we need only a part of their approach: a process in our framework has only two modes, Active and Inactive, that correspond two possible values of the variable active. To argue about a mode of a process P at time interval t we use the predicate active(P, t) introduced below.

In the stream representation we say that streams x₁, . . . , xₙ are disjoint (denoted by disjoint(x₁, . . . , xₙ)) iff on every time interval i only one of these streams contains messages, i.e.

∀ t ∈ N, i ∈ [1..n] : xᵢ(t) ≠ ∅ → ∀ j ≠ i, j ∈ [1..n] : xⱼ(t) = ∅

We can extend this idea to the operation over components and processes (as a special kind of components). A component C is active on output stream x ∈ O(C) on the time interval t if on this time interval the stream x is nonempty

active(x)(C, t) = ∃ x ∈ O(C) : x(t) ≠ ∅

and it is active only on output stream x on the time interval t if on this time interval all other its output streams are empty

active[x](C, t) = ∃ x ∈ O(C) : x(t) ≠ ∅

i.e., ∃ x ∈ O(C) : x(t) ≠ ∅ → ∀ y ≠ x, y ∈ O(C) : y(t) = ∅.

Thus, a component C is active on the time interval t if at least one of its output streams is nonempty on this time interval:

active(C, t) = ∃ x ∈ O(C) : active(x)(C, t)

and respectively a component C is restrictively active with a lower/lower bound rb on the time interval t, rb ≤ ||O(C)||, on this time interval any k of its output streams are nonempty, where

- for lower bound, active[rb](C, t), rb ≤ k, i.e. the situation where all of streams are nonempty is allowed, and
- for upper bound, active[rb](C, t), k ≤ rb, i.e. the situation where all of streams are nonempty is allowed,
- (exact) bound active[rb](C, t), k = rb, i.e. an exact number of streams should be active.

active[rb](C, t) = \{ x ∈ O(C) : active(x)(C, t) \} ≥ rb

active[rb](C, t) = \{ x ∈ O(C) : active(x)(C, t) \} ≤ rb

active[rb](C, t) = \{ x ∈ O(C) : active(x)(C, t) \} = rb

If ∀ t : active[1](C, t) we have the case where all the output streams of the component C are disjoint.

In a similar way we specify predicates over a set S of components to express that on the time interval t some of the components from this set are active:

activeS(S, t) = ∃ C ∈ S : active(C, t)

activeS[rb](S, t) = \{ C ∈ S | \exists x ∈ O(C) : active(x)(C, t) \} ≥ rb

activeS[rb](S, t) = \{ C ∈ S | \exists x ∈ O(C) : active(x)(C, t) \} ≤ rb

activeS[rb](S, t) = \{ C ∈ S | \exists x ∈ O(C) : active(x)(C, t) \} = rb

activeS[rb](S, t) = \{ C ∈ S | \exists x ∈ O(C) : active(x)(C, t) \} = rb

B. Composition of processes

Assume P and Q be any two processes. The sets of input and output channels are defined for processes P and Q as well as for the the corresponding components PComp and QComp, i.e. the component representation of these processes, PComp = [P] and QComp = [Q], as follows:

Entry(P) = entP Entry(Q) = entQ
Exit(P) = extP Exit(Q) = extQ
I_P = i₁, . . . , i_m I_Q = x₁, . . . , x_k
O_P = o₁, . . . , o_n O_Q = y₁, . . . , y_z

A general graphical representation of composition is presented on Figure 3. All the channels representing entry and exit points of a process (as well as connectors to merge and to split the streams over these channels) are drawn in orange. The details of auxiliary component specifications are omitted in this paper, cf. the technical report [27]. Having this representation we can analyse properties of composed processes by applying a well-developed composition theory, elaborated by Broy [28].

Among other factors, the purported representation gives a basis for a straightforward analysis of the worst case execution time (WCET) of the composed processes, e.g., it is easy to see that

wcet(P ∪ Q) = wcet(P) + wcet(Q),
wcet(P ⨿ Q) = wcet(P),
wcet(P ∥ Q) = max\{wcet(P), wcet(Q)\} + wcet(∈),
wcet(∈) + wcet(+) = wcet(X) denotes the WCET of the process X. Consequently, on some abstraction level the the WCET of the components ∈, @ and + can be treated as 0.
Sequentially composed process $P;Q$ (cf. Figure 3a) is the simplest variant of the process composition, which requires no additional auxiliary components:

$$
[P(i_1, \ldots, i_m, o_1, \ldots, o_n); Q(x_1, \ldots, x_k, y_1, \ldots, y_z)] = P\text{Comp}(\text{ent}P, i_1, \ldots, i_m, \text{ext}P, o_1, \ldots, o_n) \land Q\text{Comp}(\text{ext}P, x_1, \ldots, x_k, \text{ext}Q, y_1, \ldots, y_z)
$$

The entry and exit points are defined in this case by $\text{Entry}(P; Q) = \text{ent}P$ and $\text{Exit}(P; Q) = \text{ext}Q$.

Repetitively composed process (cf. Figure 3b) can be realised in two versions, an autonomous and a non-autonomous one. For both cases, the special component $\text{Delay}$ can be defined in many ways to fulfill the required restart-properties, however, in most cases it should represent either a timer or a counter of some kind. The important point is here that it should be \textit{strict causal}, i.e. to have at least one time unit delay, to prevent Zeno runs [29] for the case the process $P$ is only weak causal.

In the autonomous version, the entry and the exit points are undefined, because the process is started by itself and repeated after the time specified by the $\text{Delay}$ component:

$$
[P(i_1, \ldots, i_m, o_1, \ldots, o_n) \circ \text{lpspec}] = P\text{Comp}(\text{ent}D, i_1, \ldots, i_m, \text{ext}D, o_1, \ldots, o_n) \land \text{Delay}(\text{ext}D, \text{ent}D)
$$

In the non-autonomous version, the $\text{Delay}$ component should be specified in more sophisticated way to model not only a delay but also react to the start signals from outside, as well as to define whether the process can be restarted before it was completed. Thus, $\text{Entry}(P \circ \text{lpspec}) = \text{ent}P$ and $\text{Exit}(P \circ \text{lpspec}) = \text{ext}P$.

Simultaneously composed process $P || Q$ (cf. Figure 3c) requires an auxiliary components to join the output control streams, and and assumes that the processes $P$ and $Q$ can be activated next time only in the case when both of them are completed, $\text{Entry}(P; Q) = \text{ent}P$ and $\text{Exit}(P; Q) = \text{ext}PQ$:

$$
[P(i_1, \ldots, i_m, o_1, \ldots, o_n) || Q(x_1, \ldots, x_k, y_1, \ldots, y_z)] = P\text{Comp}(\text{ent}P, i_1, \ldots, i_m, \text{ext}P, o_1, \ldots, o_n) \land Q\text{Comp}(\text{ent}P, x_1, \ldots, x_k, \text{ext}Q, y_1, \ldots, y_z) \land @(\text{ext}P, \text{ext}Q, \text{ext}PQ)
$$

The connector $@$ models the following behaviour: the exit point of $[P || Q]$ must be activated iff both processes, $P$ and $Q$ have terminated either simultaneously or one after another. Its local variables $x\text{Ready}$ and $y\text{Ready}$ indicate whether the corresponding process have already terminated. If one of these processes terminates first, the component sets the corresponding variable to true to indicate that the component is waiting for the termination of the second process. Only when another process terminates (or if $P$ and $Q$ terminate in the same time unit), the component produces the exit-message and set both variables to false.

Alternate process $P \oplus Q$ (cf. Fig. 3d, $\text{Exit}(P \oplus Q) = \text{ext}PQ$ and $\text{Entry}(P \oplus Q) = \text{ext}PQ$) requires two connectors: $@$ to choose which of the processes should be started (at which process should be sent the activation signal), and $+$ to merge the output control flow:

$$
[P(i_1, \ldots, i_m, o_1, \ldots, o_n) \oplus Q(x_1, \ldots, x_k, y_1, \ldots, y_z)] = P\text{Comp}(\text{ent}P, i_1, \ldots, i_m, \text{ext}P, o_1, \ldots, o_n) \land Q\text{Comp}(\text{ent}Q, x_1, \ldots, x_k, \text{ext}Q, y_1, \ldots, y_z) \land @(\text{ext}PQ, \text{ent}P, \text{ent}Q) \land +(\text{ext}P, \text{ext}Q, \text{ext}PQ)
$$

We omit the technical details of the specifications of these connectors in this paper.

IV. CONCLUSIONS AND FUTURE WORK

This paper introduces a formal model of processes that is compatible with the component/ data flow view. This approach reflects general constrains of the IEC 61499 standard and can be seen as a formal representation of its main ideas. Moreover, it allows to swap from an event-based specification to a time-triggered one. To present our theory of process modelling, we discussed how a process can be represented by a component as well as which properties have the different kinds of composition operators.

This approach is based on human factor analysis within formal methods [23, 30], allows to have short and at the same time readable specifications, and is appropriate for the case the switching to another language is required as well as for application of the specification and proof methodology [31] aligned on the future proofs already during specification phase.
to make them simpler and appropriate for application not only in theory but also in practice.

Future research direction comprises extension of the presented approach by parameterised contracts and reliability as well as timing analysis to concurrent systems, combining the results introduced in this paper with analysis of the WCET of a specified process as discussed in [32] as well as with prior work in this direction [33], where timing analysis to concurrent systems of both WCET in industry-strength tools for large software systems in distributed control, and of sampled performance in large-scale runs, were analysed.

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