Components for Embedded Software — The PECOS Approach

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1 Introduction

This paper presents a domain specific composition language called CoCo. The CoCo language has been developed in the context of the PECOS project[1] which aims at enabling component–based technology for a certain class of embedded systems called "field devices".

CoCo is used in PECOS for the specification of components and for the composition of components to build entire field device applications. Besides this, CoCo allows the specification of architectural styles and system families and it supports compositional reasoning.

The sequel of the paper is organized as follows: Section 2 gives a brief introduction to the application domain of field devices. In section 3, the PECOS component model is presented. Section 4 addresses the different aspects of the CoCo language mentioned above. Section 5 summarizes the ideas presented in this paper and points out future work.

2 Case study description

ABB's Instruments business unit develops a large number of different field devices, such as temperature–, pressure–, and flow–sensors, actuators and positioners. A field device is an embedded hard real–time system. Field devices use sensors to continuously gather data, such as temperature, pressure or rate of flow. They process this data, and react by controlling actuators like valves or motors. A typical field device may contain a 16–bit microprocessor with only 256KB of ROM and 40KB of RAM.

Fig. 1. Pneumatic positioner TZID

The software for a typical field device, such as the TZID pneumatic positioner shown in Fig. 1, is monolithic, and it has to be developed separately for each kind of field device. This results in a number of well–known problems: There is no or little code reuse and the software is hard to maintain, extend or customize. This is made even worse by the use of hard–coded, cyclic execution schedules.

The goal of the PECOS project is to develop a model-centric CBSE process for embedded component software. This includes the definition of a component model, composition language and development environment, which support reuse of components and device architectures and provide support for (semi–)automatic schedule generation.

2.1 Example Application

We will use the following example throughout this paper to illustrate the PECOS component model and composition language. Part of the PECOS case study is concerned with setting a valve at a specific position between open and closed. Fig. 2 illustrates three connected PECOS components that collaborate to set the valve position; the desired position is determined by other components not shown here. In order to set and keep the valve at a certain position, a control loop is used to continuously monitor and adjust the valve.

- The ModBus component works as an interface to a piece of hardware called the frequency converter, which determines the speed of the motor. The frequency to which the motor should be set is obtained from the ProcessApplication component. ModBus outputs this value over a serial
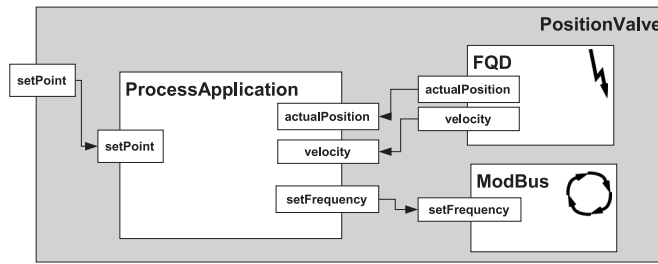
Fig. 2. FQD control loop

line to the frequency converter using the Mod-Bus protocol.

- The FQD (Fast Quadrature Decoder [2]) component is responsible for capturing events from the motor. This component abstracts from a micro–controller module that does FQD in hardware. It provides the ProcessApplication with both the velocity and the position of the valve.
- The component ProcessApplication obtains the desired position of the valve (Set–Point) and reads the current state of the valve from the FQD component. This information is then used to compute a frequency for the motor. Once the motor has opened the valve sufficiently, ascertained by the next reading from the FQD, the motor must be slowed or stopped. This repeated adjustment and monitoring constitutes the control loop.

Besides the tight resource situation, there are additional key issues concerning the field device domain: (1) **Cyclic behavior** — each component is responsible for a single piece of functionality, which is repeatedly executed (with a specified cycle time) and must not take longer than a specified worst–case execution time. (2) **Data–flow–oriented interaction** — components communicate by sending or receiving data. The interface of a component consists of a set of data ports. (3) **Threading** — some components are passive (i.e., cyclically invoked by a scheduler), while others (like FQD) have their own thread of control in order to react on asynchronous events or to perform long computations in the background.

3 A Component Model for Embedded Software

In order to apply component–based software development to embedded systems software, we must be

precise about what we mean by a *component*. In particular, we must take care to specify how components are *structured* and *composed*, which *properties* of components are important to capture and reason about, and how a composition of components can be interpreted at *run–time*.
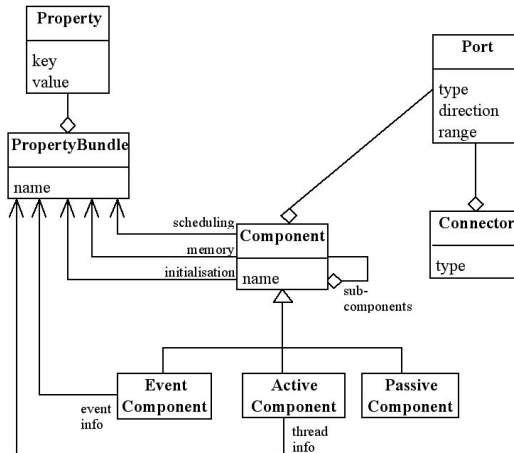

Fig. 3. A Component Model for Embedded Software

Here we briefly present a meta–model that reflects an architectural style [10] for embedded systems software. We also sketch how compositions of components can be interpreted by means of Petri nets.

3.1 Model Elements

Fig. 3 illustrates the key elements of the component model. *Components* have interfaces defined by a number of *ports*, and may be hierarchically composed. So–called *leaf components* are treated as black boxes, and are directly implemented in some host programming language. Composite components, on the other hand, are built by connect-

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ing the *ports* of other, existing components (leaf or composite), and expressing which ports of the constituent components are *exported* as ports of the composite (See Fig. 4.)

Ports are shared variables that allow components to communicate with each other. Connected ports and exported ports therefore represent the *same* variable. Connectors may only connect ports of compatible *type*, *direction* and *range*.

The model expresses three kinds of components relevant for embedded systems.

Fig. 4. A Composite Component

Active Components (e.g., *ModBus* in figure 2) have their own thread of control. Active components are used to model ongoing or long–lived activities that cannot complete in a short cycle–time. A complete system composed of components is always modeled as a composite active component. Composite active components *schedule* their constituent components in order to meet the deadlines imposed by the real–time constraints.

Passive Components (e.g., *ProcessApplication*) have no own thread of control. They are used to encapsulate a piece of behavior that executes synchronously and completes in a short cycle time. Passive components are scheduled by the nearest active parent that contains them.

Event Components (e.g., *FQD*) are components whose functionality is triggered by an event. They are typically used to model hardware elements that periodically generate events. Typical examples are timers, used to keep track of deadlines, or devices that emit events encoding status information, such as the current rotation speed of a motor, the current temperature, and so on.

All three kinds of components can be composite. Components are characterized by their *properties*, which encode information such as timing and memory usage.

3.2 Execution model

In addition to the static structure described above, the PECOS model has an execution model that describes the behavior of a Field Device. By using Petri nets [12] to represent the execution model, we intend to reason about real–time constraints and automatically generate real–time schedules for software components.

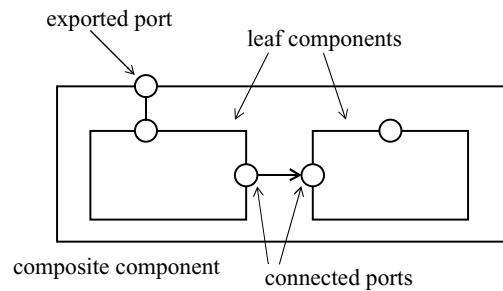The execution model deals with the following two issues: **Synchronization** — how to synchronize data–flow between components (esp. between components that live in different threads of control) and **Timing** — how to make sure that component's functionality is executed according to cycle times and required deadlines.

A composition of components has as many threads of control as there are active components. Each active component is responsible for scheduling the passive components under its control. We formalize the execution semantics by means of a Petri net interpretation. The details of this formalization, however, are beyond the scope of this paper. They are described in [7, 5].

4 The CoCo Language

In this section we introduce the component composition language CoCo. It is the syntactical representation of the component model described in section 3, enhanced with additional features.

The language is intended to be used for 1) the specification of components, 2) the specification of entire field device applications as compositions of components 3) the specification of architectures and system families. In addition, CoCo supports reuse of components and architectures and supports compositional reasoning. Last but not least, CoCo serves as input for scheduler computation and code generation.

In the sequel, we present these different aspects of the language. First, we describe how developers can specify components in terms of their interfaces. Then, we describe how components are composed to build composite components and show how CoCo supports the specification of system families. Finally, we sketch how CoCo specifications can be used for reasoning about functional and non–functional properties of a system.

4.1 Specifying Components in CoCo

Components represent units of computation and are the major means of structuring a CoCo system. CoCo supports all component types of the component model. For example, Figures 5 and 6 show a CoCo specification of our recurring example. There we see an active component (marked with the keyword `active`), an event component (keyword `event`) and two passive components.

In analogy to the OO model, components play the role of classes. That means, they define a type and scope in the same sense as OO classes do. Components can be instantiated that is, one can create an instances of a component with a unique identity. But in contrary to object instances, components can not be instantiated dynamically at run–time, but all instances are statically known.

```
event component FQD {
  output float actualPosition;
  output float velocity;
  property cycleTime = 100;
  property execTime = 10;
}

active component ModBus {
  input float setFrequency;
  property cycleTime = 100;
  property execTime = 10;
}

component ProcessApplication {
  input float setPoint;
  input float actualPosition;
  input float velocity;
  output float setFrequency;
  property cycleTime = 100;
  property execTime = 20;
}
```

Fig. 5. The FQD control loop components specified in CoCo

Programming in CoCo is data–flow–oriented. **Ports** (e.g., `setPoint`) denote data flow into or out of a component and are the only means of using a component. Ports are assigned both a data flow direction (input, output, or in–/output) and a data type. A component's interface does not contain any functions that my be called, but one may think of a component as a piece of functionality that is executed cyclically (passive component) or in response to a certain event (event component) in order to compute output values depending on the current input values and/or the internal state of the component. The actual behavior, however, is not specified at the level of CoCo specifications but hidden in the implementation of the component.

The only information available about this implementation is the worst–case execution time it takes to perform the computation (property `execTime`) and the interval between these computations (property `cycleTime`). These values are specified in CoCo as component properties.

Properties serve to attach functional and non–functional features to a component, such as init values for ports, memory consumption and worst–case execution time. They can be structured in so–called *property bundles*. These bundles group properties that semantically belong together, such as scheduling information (worst–case execution time, cycle time). Properties can be used by tools to inspect the component in different phases of the development process (e.g., when generating a scheduler). Properties can be set on a per–component basis and a per–instance basis.

4.2 Composing Components with CoCo

Components are composite when they contain instances of other components (see for example the component `PositionValve` in Fig. 6). In PECOS, an entire application, such as a field device, is modeled as a composite component. Instances of components have a component type and a unique name within the scope of the enclosing component. All instances are created at system start–up, that is there is no "new" statement to dynamically create instances during run–time but all possible instances are known at compile–time. This allows for a number of checks at compile–time as well as for automated scheduler generation.

```
component PositionValve{
  ModBus mb;
  FQD fqd;
  ProcessApplication pa;

  input float setPoint;

  connector c1 (setPoint, pa.setPoint);
  connector c2 (fqd.actualPosition,
                    pa.actualPosition);
  connector c3 (fqd.velocity, pa.velocity);
  connector c4 (pa.setFrequency, mb.setFrequency);
}
```

Fig. 6. The FQD (Fig. 2) control loop itself specified in CoCo

Connection of components is achieved through the use of **connectors** (e.g., connector `c1` in component `PositionValve`). Connectors connect a list of ports defined either in the current component (like

port `setPoint` in connector `c1`) or by one of the contained instances (that is, instances in the same scope). Different connectors that share a common port represent the same connection. A special case of this rule is at the border of composite event and active components: as theses components execute in their own thread of control, data only bypasses their borders during a synchronization step.

4.3 Specifying software families with CoCo

Components serve to specify concrete pieces of a system. But it is often desirable to be able to specify architectural styles or families of components or families of entire applications (devices). CoCo provides the concept of **abstract components** for this purpose. By means of abstract components one can specify a template of a system that can later be filled in with concrete components. Abstract components do not have a representation in the model as they do not contribute to the run–time behavior of field device software. They are merely a technique to simplify specification and to enable the reuse of designs.

```
abstract component PecosControlLoop{
  role AbstractProcessApplication PecosPA;
  role AbstractControlDevice PecosCtrl;
  role AbstractFeedBackDevice PecosFdbck;
  input float setPoint;

  connector setPoint(setPoint, PecosPA.setPoint);
  connector feedback1(PecosPA.actualPosition,
                      PecosFdbck.actualPosition);
  connector feedback2(PecosPA.velocity,
                      PecosFdbck.velocity);
  connector control(PecosPA.setFrequency,
                    PecosCtrl.setFrequency);
}
[...]
component PositionValve is PecosControlLoop{
  ProcessApplication pa is PecosPA;
  ModBus mb is PecosCtrl;
  FQD fqd is PecosFdbck;
}
```

Fig. 7. Using abstract components to specify system families

Besides the elements known from normal components, abstract components can define so–called roles. **Roles** are typed variation points or holes in a (micro–)architecture. Fig. 7 shows the specification of an architectural style for control loops.

We assume that a `PecosControlLoop` should always have an instance of sub–type of `AbstractProcessApplication` that plays the role `PecosPA` in our valve controller architecture.

`AbstractProcessApplication` again is an abstract component that defines a certain interface (i.e., ports, properties) every process application component has to conform to. Thus, roles serve as placeholders for instances. These placeholders can also be connected by connectors as if they were normal instances. This way a developer is able to specify an entire family of applications that share a common architecture in terms of the components involved and their data–flow dependencies. To create a specific member of this family, a component has to implement the respective abstract component. Implementing an abstract component means that all roles defined by this abstract component have to be bound to suitable instances and that all connectors, instances, ports, and properties defined in this abstract component become now part of the implementing component. In our example the role `PecosPA` is bound to an instance of component `ProcessApplication`. The component `ProcessApplication` on the other hand is required to implement the abstract component `AbstractProcessApplication`.

4.4 Composition checking

In this section we briefly sketch how compositions can be reasoned about.

In order to make a composition valid, certain rules must be followed. There are simple syntactic rules and rules originating from the static semantics of CoCo which are checked by the composition language compiler.These rules express requirements, that emerge from the component model. Examples for such rules are "if a component implements an abstract component, it must bind all roles" or "all mandatory ports must be bound", etc.

In addition we allow the specifaction and checking of company-, product-line- or product-specific semantic rules. We employ first-order predicate logic for this purpose. The PECOS composition tool is able to generate a database of Prolog facts out of a composition specification. These facts describe the whole system, together with all included components, their ports, properties, and connections. Semantic rules are formulated as Prolog queries (or in the form of Horn clauses) and are checked against the generated facts.

For example, Fig. 8 shows the Prolog facts, which have been generated for the CoCo specifications of Fig. 5. An example query is shown in Fig. 9. It defines the Prolog rule `validScheduleInfo` which checks, if every component has got the `execTime` and `cycleTime` properties specified.

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```
% Component FQD
component('FQD', 'event').
property('FQD', 'optional', 'cycleTime', '100').
property('FQD', 'optional', 'execTime', '10').
port('FQD', 'optional', 'output', 'float',
 'actualPosition').
port('FQD', 'optional', 'output', 'float',
 'velocity').

% Component ModBus
component('ModBus', 'active').
property('ModBus', 'optional', 'cycleTime', '100').
property('ModBus', 'optional', 'execTime', '10').
port('ModBus', 'optional', 'input', 'float',
 'setFrequency').

% Component ProcessApplication
component('ProcessApplication', 'passive').
property('ProcessApplication', 'optional',
 'cycleTime', '100').
property('ProcessApplication', 'optional',
 'execTime', '10').
port('ProcessApplication', 'optional', 'input',
 'float', 'setPoint').
port('ProcessApplication', 'optional', 'input',
 'float', 'actualPosition').
port('ProcessApplication', 'optional', 'input',
 'float', 'velocity').
port('ProcessApplication', 'optional', 'output',
 'float', 'setFrequency').
```

Fig. 8. The Prolog facts for the components of Fig.5

```
hasProperty(X, Y):-
component(X, Z1),
property(X, Z2, Y, Z3).
hasExecTime(X):-
hasProperty(X, execTime).
hasCycleTime(X):-
hasProperty(X, cycleTime).
scheduleInfo(X):-
hasExecTime(X),
hasCycleTime(X).
validScheduleInfo:-
forall(component(X), scheduleInfo(X)).
```

Fig. 9. Example Prolog query

Other examples for this type of rules are fulfillment test of specific requirements for debugging, release versions of the software, dependencies between components, platform specific property settings, such as in "...in this product line, a particular type of components must always be used together with another particular component type...´´.

4.5 Code Generation: from CoCo to C++ and Java

As already mentioned, the behaviour of a PECOS component is not specified in CoCo, but it is directly implemented in a target language. Therefore, a system specified in CoCo is mapped into a class hirarchy in the target language. This hirarchy corresponds directly to the hirarchical component structure of the CoCo specification: Components map to

classes, component instances map to statically initialized instance variables, and connectors represent shared instance variables in the enclosing object. Ports map to set– and get–methods that read from or write to these shared instance variables, as determined by the connectors.

This code generation from CoCo specifications needs to pay special attention to efficiency — measured both in execution time and in memory consumption, because of the requirements imposed by the field device domain. More information on these issues can be found in the relevant PECOS deliverable [9].

5 Related work

Several approaches to the composition of software from components have been proposed in the literature. An important contribution to this topic stems from the field of software architecture systems [3, 10, 4]. A recent survey is given in [6]. Architecture systems introduce the notion of components, ports, and connectors as first class representations. However, most of the approaches proposed in the literature do not take into account the specific properties of software systems for embedded devices.

In [8] van Ommering *et.al.* introduce a component model that is used for embedded software in consumer electronic devices. Koala components may have several "provides" and "requires" interfaces. Each of this interfaces defines "ports" in the sense of methods. In order to generate efficient code from Koala specifications, partial evaluation techniques are employed. However, Koala does not take into account non-functional requirements such as timing and memory consumption. Koala lacks a formal execution model and automated scheduler generation is not supported.

In [11] a framework for dynamically reconfigurable real-time software is presented. It is based on the concept of so called Port Based Objects. The framework provides only a limited form of specifying a component (e.g., only rudimentary scheduling information is given, predefined port types). Furthermore the architecture is limited i.e., there is no support for composite components. The verification of a composition regarding non-functional properties such as memory consumption and schedulability is lacking too.

6 Summary

In this paper, we have presented the domain specific composition language CoCo as part of the PECOS

project. The two main characteristics of the language are its data–flow oriented composition style and the support for non–functional properties (most importantly timing information as input for schedule generation).

The different purposes of CoCo have been presented: it serves for defining component interfaces and composite[2] components. Furthermore, it has been shown, how CoCo allows to define system architectures in the form of abstract components. Finally, it has been indicated, how compositional reasoning is supported and how the mapping from CoCo to C++ and Java is handled.

In order to prove the usefulness of the CoCo language, ABB is currently carrying out a number of case–studies. One of these has been sketched in section 2.

In order to facilitate the application of the PECOS approach, tool support for CoCo has been developed. A first prototypical implementation of a development environment has been carried out which groups together a CoCo editor, the code generator for C++ and Java as well as the Prologe fact generator. Currently, a more sophisticated implementation in form of an Eclipse [1] plug–in is under develpment which will integrate further project management facilities like ressource and version control.

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[2] As we have seen, entire PECOS applications are a special case of those.