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ABSTRACT

The main aim of this paper is to present the possibilities offered by UML for developing process control systems. The proposed approach applies modified Harmony SE methodology and is based on the combined use of UML profile for system engineering SysML, IEC 61499 standard and FIPA standard protocols. The basic development phases are illustrated by UML models of a simple process control system. Finally some conclusions are made.

Keywords: object-oriented modeling, control system, UML, SysML, IEC 61499.

INTRODUCTION

One of the trends in the domain of control systems is associated with the significant growing of the software used, its volume and complexity, the need to integrate this software into physical systems and to ensure its integrity, security, reliability, interoperability and portability. The response to these new challenges is the so-called Model Driven Engineering (MDE) [1] or its counterpart in the field of architectures - Model Driven Architecture (MDA) [2]. The approaches of MDE and MDA consist in transformation of different platform independent models towards executable applications. The transition from approaches based on a directly code creation to model-driven software development poses the modeling as one of the first most important aspects in the field of engineering.

UML [3] supports MDE and MDA as a general purpose modelling language and an open standard. It does not specify a methodology for software or system design but aims to provide an integrated modelling framework covering structural, functional and behaviour descriptions. UML notations support the development of various diagrams that reflect different aspects of the system in order to capture the full complexity in the phases of detailed analysis and system design. In the last years there has been an increasing striving to use UML in control, automation, and industrial enterprise engineering. There are many working groups whose research activities are directed to filling the gap between the state of the art in software engineering and the state of the practice in the control domain. They use different approaches and techniques in order to extend the object-oriented software development and especially UML for the development of real time systems. The main drawbacks of all these extensions are connected with the difficulties in modelling and analysis of the closed loop systems. In order to overcome these drawbacks, UML profile for System Engineering (SysML) is used in this work [4].

The paper is organized in four parts. After the introduction, the second part gives a short overview of the object-oriented approaches for development of control systems is given and different extensions of UML for modeling of hard real time systems are presented and analyzed. In the third part the suggested approach for development of agent-based control systems is described. The last part of the paper illustrates the approach with modeling of simple process control system for water level feedback control. Finally some conclusions are made.
OVERVIEW OF SOME OBJECT-ORIENTED APPROACHES FOR DEVELOPMENT OF CONTROL SYSTEMS

In recent years we have witnessed an increased interest in the use of object-oriented approaches in the field of software development which is associated with a reduction of its complexity, achievement of modularity, portability, interoperability and reusability, as well as provision of opportunities for modifications and extensions [5, 6].

The main challenges towards real-time UML are connected with the creation of different mechanisms to handle real-time features such as: models of physical time, timing specifications, timing facilities, modeling and management of physical resources and concurrency. Another important issue is the development or use of means for early verification and validation of the designed systems in respect not only to their functionality but also in respect to the non-functionality requirements.

There are many different proposals for extending UML to support the design and analysis of control systems and they can be grouped in 2 main abstract classes shown in Fig.1. The first class of real-time (RT) extensions is connected with the combination of standard UML capabilities with those of other real-time frameworks, languages and methods, covering different real time features of the designed systems. One very large subclass of RT extensions of UML is connected with the filling the gap of the lack of well-defined formal semantic and ensuring of capabilities for formal verification of designed UML models. In general, these extensions can be separated into two major categories. The second class of extensions follows the idea of Douglas and Selic that the behaviour of complex real-time control systems can be fully described by using the standard capabilities of UML. It is subdivided in two classes applying the following extension strategies [7, 8]:

- Creating UML profiles (standard and specific) on the base of stereotypes, constraints and tagged values.
  - The 3 built-in extension mechanisms can be used separately or together.
- Changing UML meta-model by explicitly adding new meta-classes and other meta-constructs;

The detailed description and analysis of the different suggestions may be found in [15]. The presented in Fig. 1 UML extensions for real time are expanded with the MARTE (Modeling and Analysis of Embedded Real Time Systems) profile which enjoys currently a wide popularity. MARTE is a specification of OMG and is based on a SPT (Schedulability, Performance and Time) profile using standard notations and semantics of UML [9, 10]. This UML profile is an independent methodology offering a compatible set of standard notations and semantics to design custom hardware and software applications. MARTE defines a framework for annotation of non-functional properties into UML models of embedded systems by adding various extensions like:

- the ability to add models and resources for real-time;
- to cover modeling and support of non-functional properties;
- to define the concepts of modeling and implementation of hardware and software platforms;

![Fig. 1. UML extensions for real time.](image-url)
• to define the concepts of allocation of applications on a platform;
• to ensure support for quantitative analysis.

The MARTE profile consists of three packages named MARTE Foundation, MARTE Design Model and MARTE Analysis Model, shown in Fig. 2. With MARTE profile the designers have possibilities to ensure the definition of time requirements and constraints by two time types - logical and chronometric using additional stereotypes.

Fig. 2. MARTE profile.

An important UML profile, not considered in Fig. 1, is the general-purpose modeling language for system engineering, SysML, that is the core of the proposed approach. It reuses a subset of the last UML2.x versions and provides additional extensions through stereotypes, diagram extensions and model library in order to model a wide range of system engineering problems as for example specifying requirements, structure, behaviour, allocations and constraints on system properties to support engineering analysis. The system structure design is supported by four types of diagrams Block Definition Diagram (BDD), Internal Block Diagram (IBD) reinforced by Parametric Diagram (ParD), and Package Diagrams (PacD). The Behaviour Diagrams incorporate four diagrams too, namely: Activity Diagram (AD), Sequence Diagram (SD), State Machine Diagram (SMD), and Use Case Diagram (UCD) shown in Fig. 3. The Requirements Diagrams (RD) which can be presented in a graphical, tabular or tree structure format, are used to specify different constructs for system requirements and to cover the relationships between them. In SysML two kinds of requirements are used – functional and performance, as they specify the capabilities or the conditions which must be performed or satisfied by the system [4].

SHORT DESCRIPTION OF THE PROPOSED APPROACH

The success of UML in unifying many different object-oriented approaches led to the idea of applying UML to the design of Multi Agent Systems (MAS). From a software perspective, agent-based systems are a specialization of object-oriented systems but UML does not provide enough means to comprise all agents related modeling aspects like autonomy, pro-activity and cooperation. The software agents have their own thread of control, localizing not only code and state but their invocations as well [11]. In an open and distributed, agent-based, integrated control environment, the need of standard mechanisms and specifications are vital for ensuring the interoperability of the autonomous agents.

The approaches in the area of distributed control systems existing until now are based only on UML/ SysML or on the combined use of UML and IEC-61499 standard, as described above. In the approach using UML/SysML profile the SysML stereotypes define new modeling constructs by customizing the existing UML constructs with new properties and constructs in order to create a framework which is a dynamic evolutionary

Fig. 3. SysML Diagrams [4].
environment, providing traceability and consistency. A SysML specification would be a much better start for the system development than a specification in natural language. But there is a fundamental difference between UML and SysML in the sense that UML models for software systems are intended to employ the same concepts during the complete development phases, reflecting the final software. Through the encapsulated objects in UML 2.0 and the hierarchical structure which they gain using SysML profile the OO systems get near to agent-based systems. For the software development processes Harmony SE based methodology is used [12]. The task flow development process includes: Requirements Analysis; System functional analysis; Architecture design; Hardware/Software design specification.

The methodology described above is used to model the internal structure of control system and to define how this system can be mapped to physical entities. However the standards used are not enough to model the communications between Human Machine Interface (HMI) and the distributed controllers. For this reason FIPA [13] reference model is suitable to be used. The FIPA modeling standard for development of multi-agent systems uses Activity Diagram as a part of AUML. In an accord with Lind, we adopted SysML Activity Diagram to model an agent interaction protocol without introducing any new modeling elements [14]. The approach uses the existing UML concepts only and requires no additional modeling elements which enables UML users to understand the notation without learning a completely new type of diagram [15].

CASE STUDY

The suggested approach will be illustrated in this part with a simple example of water level control in a tank as shown in Fig. 4.

According to the suggested approach the first two stages in the control system design refer to the definition of the system requirements through Requirements Diagram (Fig. 5-1) and the system functionality definition using Use Case Diagram (Fig.5-2) that captures the interactions between the system and its users as well as the requirements refinements to the distributed control application. The static composite structure of the closed loop control system consisting of HMI, “ControlSubSystem”, “TankSubSystem” and communication bus, and their connections are presented by BDD (Fig. 5-5).

The third development stage includes modeling of the internal structure of the system blocks included in the overall static structure using BDDs and IBDs. The IBD (Fig. 5-4) of “TankSubSystem” is presented which is composed different types of equipment such as input valve, output valve, tank and sensor. Each part is defined uniquely through its attributes and operations. The attributes characterizing “Valve_in” and “Valve_out” are respectively input/output pressure (Pin/Pout), input/output flow rate (Qin/Qout), Cin/Cout for density of liquid and Sin/Sout for coefficient of input/output valve. The connections are modeled as flow ports. In order to present the dynamical behaviour of the plant, the elements of “TankSubSystem” are described by their transfer functions as operations. The model view browser as planned according the suggested approach is presented in Fig.5-3.

The controller assuming to use a simple PID algorithm to control the level in the tank is modeled as “system blocks” and is decomposed in tree main “parts”: The controller internal structure covers the system hierarchy described through the composition relationships and it is modeled through IBD as shown in Fig. 6-1. It contains “PID_Calc”, “Derivative” and “Integral” which are interconnected via flow ports. “Derivative” and “Integral” provide derivative and integration function respectively for inputs of real data. “PID_Calc” encapsulates PID algorithm and calculates new output values which are proportional to a weighted summation of the error, the derivative error and the integral of the error. The parts are uniquely presented through attributes.
and operations. All parts in IBDs are modeled by parts of “BasicFunctionBlock” stereotype.

The communication interfaces are defined by different types of ports according to IEC-61499 and UML2.x standards. Contract-based ports are used in order to define contracts which specify the precise allowable inputs and outputs of the system components. The contract-based ports between the parts of the controller as shown in Fig. 6 have two types of interfaces: provided (Fig. 6-3) and required (Fig. 6-2). The provided interface characterizes the requests from the environment and the required one – the request from the port. Because the ports are connected to other ports which are exactly “reversed” and to ports providing and requiring the same set of interfaces, the explicit contracts are used.

There are two roles in FIPA “request when” protocol: a sender and a receiver, which are linked via implicit communication channels. In a protocol context the communication messages are grouped representing the sender – receiver direction. This interaction protocol is modeled through activity diagram as behaviour of interface used and is illustrated in Fig.6-4. The diagram is customized through the introduction of stereotype <<role>> associating swim lanes with roles. Additional stereotypes according to MARTE profile are defined in the structure of the activity diagram in order to model the different time characteristics and constraints of the system.

According to FIPA reference model a class of “ACLMessage” stereotype is defined for representing Agent Communication Language messages. Sending and receiving activities in this diagram allow the agents to exchange messages based on the communication protocols. The main benefits of using FIPA Agent Interaction protocol is that it contains unified agreements on the methods used for initiation and termination of protocol data units (message), formatting and encoding data, synchronization of senders and receivers, and
detection and correction of transmission errors. The protocol specification consists of the following parts: service specification, assumption on the environment, precise message format for (syntax), procedure rules for data exchange (grammar) and a vocabulary of messages used with their meaning (semantics).

CONCLUSIONS

The main benefits of using the approach proposed can be summarized as follows: it provides comprehensive consistency in the syntax and underlying semantics; increases the potential and likelihood of reuse; supports the whole software development life cycle in the field of process control - from the requirements definition to the software implementation. Including the main features of SysML, based on extended activity diagrams, parametric diagrams, flow ports and items, the proposed approach opens the possibilities for modeling a continuous system and for support the development in field of process control. Another main advantage of using the UML/MARTE profile is the possibility for analysis of the designed system and for a detailed design of the hardware and software platform of the modeled application.
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