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ScienceDirect

Procedia CIRP 60 (2017) 273 – 278

www.elsevier.com/locate/procedia

27th CIRP Design 2017

Enhanced Sequence Diagram for Function Modelling of Complex Systems

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Abstract

This paper introduces a novel method referred to as Enhanced Sequence Diagram (ESD) to support rigorous functional modelling of complex multidisciplinary systems. The ESD concept integrates an exchanges based functional requirements reasoning based on a coherent graphical schema, integrated with the system operational analysis based on a sequence diagram. The effectiveness of the method to support generic function modelling of complex multidisciplinary systems at the early conceptual design stages is discussed in conjunction with an electric vehicle powertrain example, followed by an assessment of potential impact for broader application of the method in the industry.

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference

Keywords: Systems engineering, sequence diagrams, functional requirements, complex multidisciplinary systems.

1. Introduction

The complexity of technical systems such as the automotive vehicles has increased significantly in order to address evolving customer needs and environmental concerns. From a product development process viewpoint, the introduction of new technologies and control features amplify the need for integrated function modelling of complex multidisciplinary systems with a strong focus on interactions between systems from different engineering disciplines. This challenge is further compounded by the prevalence of software based features controlling the enhanced functionality of the systems of systems.

From an engineering design perspective, many functional reasoning schemes have been proposed (see [1] for a comprehensive review). Many of the well-established schemes, including Stone and Wood [2], Ulrich and Eppinger [3] and Ullman [4], have essentially evolved from an electro-mechanical perspective, and are rooted in the Pahl & Beitz [5] flow based thinking, i.e. represent the functional model of a system in terms of the flows of material, energy and information through the system. Several other researchers (e.g. Umeda et al. [6], and Goel et al. [7]) have determined functional requirements of systems in relation to the linkage between function and the intended behavior and structure of the system. However, it has been recognized that these functional modelling schemes are somewhat limited in supporting the design analysis of complex multidisciplinary systems, which require top-down solution neutral analysis and synthesis of the architecture across multiple interconnected functional flows integrated according to the operating concept of the system across the whole lifecycle. A specific limitation of such functional models is the capture of the time domain requirements corresponding to the sequence of events associated with the system operation modes and use cases, within a “global” functional model of the system.

Systems engineering approaches have evolved from the need to address the overall integration of operational and functional models within a system-of-systems context, with strong trace-ability, inter-operability and re-use properties. In particular Model Based Systems Engineering (MBSE) makes use of formal modelling methods to support functional analysis of complex systems. System Modelling Language (SysML), which emerges as a prevalent MBSE system modelling environment, provides a graphical semi-formal descriptive “language” for system modelling, focused on capturing functional requirements from the operational concept of the system across its lifecycle use cases. Each use case can be analyzed and described in detail using tools such as sequence diagrams, activity diagrams or state machine diagrams at the

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference
doi:10.1016/j.procir.2017.01.053

designer's discretion (Friedenthal et al. [8]). Several modelling languages exploit SysML diagrams, e.g. Harmony (Hoffman [9]) and Object-oriented analysis and design (Booch et al. [10]). A strength of the MBSE framework is that it combines an abstract graphical representation of the operations and functional model of a system with a detailed simulation model (either exchanges or transactions based – e.g. using state charts or state machines, or transformations based in conjunction with physical simulation environments such as Modelica, Simulink, etc). This provides strong support for system analysis, but essentially relies on the availability of models of the system of appropriate maturity (fidelity and resolution) for the known or assumed system architecture.

The current paradigm of automotive systems development, taking for example challenges like autonomous driving, requires modelling of complex systems for largely unknown scenarios, for which models are not available. Similarly, the introduction of enhanced control features on existing systems (e.g. advanced driver assist systems – ADAS, or advanced on-board diagnostics systems for powertrain control for dynamic emissions management), require structured and systematic approaches for generic functional analysis to support "solution neutral" analysis in early concept phase, which can then be implemented in different system architectures during the analysis and design development phase. Such generic function modelling framework needs to consistently and concurrently capture: (i) the sequence based functional requirements (to implement the desired operational concept); as well as (ii) the exchanges based functional requirements (i.e. the behaviors that deliver the transactional and transformative functionality required to deliver the sequence). The MBSE framework uses tools such as activity and sequence diagrams that adequately capture the sequence of events, but does not support equally well a rigorous exchanges based abstract functional modelling based on flow based thinking in a solution neutral manner.

The research presented in this paper addresses these limitations by introducing a novel functional modelling method referred to as Enhanced Sequence Diagram (ESD). The ESD concept introduces an exchanges / flow based functional requirements reasoning and schema integrated with the system operational analysis based on a sequence diagram, to provide a rigorous generic functional modelling framework of a complex multidisciplinary system. The organization of the paper is as follows: section 2 gives an overview of the background literature on flow-based and sequence-based function modelling approaches, focusing in particular on a critique of the current approach to sequence diagrams; section 3 introduces the proposed schema and methodology for ESD, followed by an illustrative application example in section 4, based on an electric vehicle powertrain; the paper concludes with a discussion and conclusions section.

2. Critical review of flow and sequence based function modelling approaches

2.1. Flow-based function modelling

Integrated Function Modelling framework [13] follows a task-oriented approach in function modelling of a system, by representing the flows of functions through the system with respect to causality, i.e. the first function is connected to the second function, and so on. Pahl & Beitz [5] have introduced a concise taxonomy for the flows through a system in terms of energy, material and signal (information), commonly underpinning functional chains in the task-oriented approaches. The overall function of an engineered system is articulated in verb-noun format and represented in a black box with input-output flows of energy, material and signal. Function structures are created by decomposing into sub-functions, with associated black boxes describing what the elements of the system might do in order to fulfil the overall function. Sub-functions are linked with arrows denoting the flows of material, energy and information. Function chains (e.g. material flow) are created to combine into a single functional structure model, achieving the overall function. The basic principles of the function modelling approach proposed by Pahl & Beitz have been widely adopted in engineering design literature (see [13] for detail).

Functions can also be conceptualized and represented in relation to state transitions, e.g. based on the general principles of the statecharts [14]. Figure 1 illustrates a state based representation of function in which a state is denoted by a box and a function is represented by an arrow [15]. The function is defined in relation to the requirement to achieve the transfer or transformation between the input and output states of the flow or operand. A systematic approach for function modelling underpinned by a state-based representation of the flows through a complex system, introduced as a System State Flow Diagram (SSFD) by Campean et al. [15], has been further described by Yildirim [16]. The essence of the reasoning that underpins this function modelling framework is illustrated in Figure 2. This is based on the Object-Attribute-Function framework of Sickafus [17], in which a function is conceptually defined in terms of a "triad"; i.e. the System of Interest (SoI), conceptualized as an object described by its attributes with their input values, must interact with another object (or "actor", denoted as "Object 2" in Figure 2), with certain properties (attributes / values), in order to achieve the desired function - transition to the output state, described in terms of the desired attribute (output) values of the operand.

2.2. Sequence-based function modelling

Sequence diagrams are based on the Message Sequence Charts (MSC) of the Specification and Description Language (SDL) (Weilkiens [18]). The SDL provides the basis of Unified Modelling Language (UML) and thus SysML, which are widely accepted in both academia and industry [19]. In engineering applications SysML is considered as "the most popular tool for model-based development of multidisciplinary systems" [20]. Of UML interaction diagrams (i.e. sequence diagram, communication diagram, timing diagram and interaction overview diagram), SysML uses sequence diagram in the representation of scenarios of interaction for a particular functionality (use case) of a system. In addition to UML and SysML, sequence diagrams are used in other languages too. For example, Soft Domain Driven Design uses sequence diagrams in behavior modelling [11], while UML sequence diagrams are used in object-oriented analysis and design [12].