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Pattern-based integration of system optimization in mechatronic system design

Wenqiang Yuan[a], Yusheng Liu[a,*], Jianjun Zhao[b,**], Hongwei Wang[c]

[a] State Key Lab. of CAD&CG, Zhejiang University, 38 Zheda Road, Hangzhou 310058, P.R. China
[b] School of Mechanical Science & Engineering, HUST, Wuhan 430074, P.R. China
[c] School of Engineering, University of Portsmouth, Portsmouth PO1 3DJ, UK

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ABSTRACT

Model-Based Systems Engineering (MBSE) is a promising methodology for the design of complex mechatronic systems. There are some tools developed to support MBSE in complex system design and modeling. However, none of them has got the functionality of supporting system optimization. This work is precisely motivated by this gap and aims to develop effective methods to support automatic system optimization for MBSE. Specifically, a pattern-based method is proposed to support the integration of system optimization into mechatronic system design. In such a method, optimization problems, their solving methods and computation results are formally defined in each pattern based on the System Modeling Language (SysML). In addition, a model description scheme termed an optimization profile is proposed based on SysML to include the components for formalizing different kinds of optimization problems and optimization methods. After an optimization profile is created for an optimization problem, system optimization methods can be chosen automatically from the pattern library based on a semantic similarity evaluation. Then, optimization results are provided to users to support decision-making and the pattern library is updated using the relevant information obtained in this process. A system design example is used to demonstrate the feasibility and effectiveness of proposed methods.

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1. Introduction

The design of mechatronic systems is increasingly complicated as it involves considerations of constraints from multiple domains such as mechanical, control, electrical and software [1]. The Model-Based Systems Engineering (MBSE) has been widely accepted by mechatronic system designers ascribed to its key advantages [2]. With the help of the standard system modeling languages such as SysML [3], a mechatronic system can be represented as diagram-based models used to describe its requirements, structure and behavior. To verify the system design results, some research has been done on the integration of system simulation and system design [4,5]. Based on simulation results, system designers can compare the behavior of a system to see whether the given requirements have been met. However, it is not a trivial issue to obtain an optimal system design solution by solely using the simulation-based verification process.

Generally, the system optimization process plays an imperative role for mechatronic system design [6,7]. It can improve the design solutions and decrease the production cost to some extent. To the authors' knowledge, although there are some researches about the integration between system design and system optimization, there are some deficiencies. Firstly, there should be a complete and compatible representation method to facilitate the integration between system design and system optimization. Secondly, the engineering semantics information is an important issue for real mechatronic systems and must be considered and represented during the integration process. Thirdly, how to select the most appropriate optimization method is a key problem although there are lots of mature optimization methods.

To the best of the authors' knowledge, it retains an open problem in mechatronic system design to implement effective transfer of information between design models, optimization models and optimization algorithms. To support automatic system optimization during the system design process [8,9], two problems need to be solved. The first one is the automatic identification of design parameters for establishing a formalized optimization model. The second one is on how to find feasible optimization methods for specific problems effectively and efficiently. Additionally, it is also necessary to establish the correlations between the parameters in the design models and the variables in the optimization models.

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* Corresponding author. Tel.: +0086-571-88206681; fax: +0086-571-888206680.
** Corresponding author.
E-mail address: ysliu@cad.zju.edu.cn (Y. Liu).

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In this study, a pattern-based method is proposed for the effective integration of system optimization into mechatronic system design using a Meta-Object Facility (MOF) based on SysML [10]. A SysML-based scheme termed an optimization profile is proposed to formalize the definition of optimization problems and optimization methods. In addition, a semantics-based similarity evaluation method is proposed to find feasible optimization methods used in the existing patterns for solving specific optimization problems. In this scheme, a pattern serves the purpose of reserving the knowledge about the correlations between optimization problems and optimization methods. This research involves two primary hypotheses. Firstly, the modeled mechatronic system must have useful semantic information. Secondly, the modelled mechatronic system model must have a fine granularity to present the relevant attributes of its main components to provide a basis for the subsequent optimization process.

The rest of this paper is organized as follows. In next section, related work is reviewed. In Section 3, the structure of a pattern is defined and an overview of the proposed pattern-based approach is described in detail. The sub-profiles for describing an optimization problem based on SysML together with the engineering semantics are introduced in Section 4. The sub-profiles for describing an optimization method based on SysML is detailed in Section 5. The integration of system optimization into mechatronic system design is presented in Section 6. The implementation of the proposed approach in a case study is given in Section 7. Finally, the conclusions of this work are given in Section 8 along with a brief introduction to future work.

2. Related work

System design methodologies are of great importance for mechatronic systems. In particular, some computational design synthesis methods have been developed, such as the agent-based, graph-grammar-based and genetic-algorithm-based methods [11–14]. Additionally, some optimization methods have been applied to mechatronic systems optimization [15,16]. However, little research has been done on the automatic integration of system optimization into system design.

Recently, due to the good extendibility of SysML, a plug-in named ParaMagic was developed for the MBSE tool MagicDraw to make use of the powerful computational and analysis capabilities of Mathematica and Excel [17]. By defining profiles based on the parametric diagram of SysML, necessary information for both numerical calculation at the model layer and numerical instances at the model instance layer was extracted and then transferred to Mathematica to solve a model. However, this method has two main drawbacks: (1) the information obtained from the solution cannot be reused; and (2) designers using this method must be familiar with the Mathematica software.

Min et al. proposed a process of integrating design optimization for MBSE based on SysML and defined a profile for the integration of SysML and the ModelCenter software package [18,19]. In this way, model analysis and design exploration can be performed so as to achieve the integration of system design and optimization. However, ModelCenter has some limitations. For example, its integration process is quite complicated since complex parameter mapping and exported file format are adopted. Additionally, detailed rich semantics of complex product systems are not utilized during this process and the result information of optimization process cannot be reused and facilitated to the system design process.

The work on the integration of system design and simulation based on SysML can provide some inspiration. To evaluate the correctness of design model through system simulation, Vanderperren and Dehaene proposed two possible integration methods between UML/SysML and MATLAB/Simulink, i.e., co-simulation and integration based on a common underlying executable language [20]. Turki and Soriano developed a method in which activity diagram was used to represent the continuous dynamic behavior of mechatronic systems so as to support system analysis based on the Bond graph [21]. Similarly, Pop et al. [22] proposed the ModelicaML profile as an integration between Modelica [23] and UML [24] which enables users to specify the requirements and conduct Modelica-based simulations in a unified manner. Models created using this profile may be executed in the Modelica-based platforms such as MapleSim, SystemModeler, OpenModelica, and JModelica. In contrast to the previous methods, Johnson et al. [25] introduced an approach for modeling continuous system dynamics in SysML based on the language mapping between SysML and Modelica. Based on their work, a new standard, the SysML4Modelica profile, was proposed to represent the Modelica constructs. Recently, Qamar et al. extended SysML as a bridge between the detailed design models of different domains [26], for example, mechanical design models and control design models, to make the parameters more transferrable between different domains.

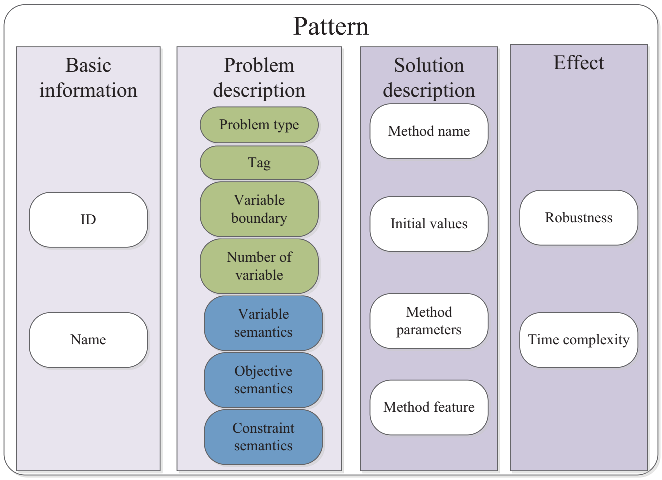

Fig. 1. The structure of a pattern.

3. An overview of the pattern-based integration method

3.1. Definition of the pattern scheme

Generally, differences exist in the various definitions of the term *pattern* in different contexts. In this study, a solution pattern scheme is defined to facilitate the integration of system optimization into mechatronic system design. As shown in Fig. 1, a pattern includes four main parts, namely basic pattern information, description of the design problem, description of the final design solution and performance of solution in terms of two main indictors (i.e. the effect part in Fig. 1).

(1) The 'basic information' part involves some basic information including pattern ID and pattern name, both of which are textual. With a unique value, the pattern ID attribute is used to differentiate different patterns. For a pattern name, it can in theory include arbitrary symbols such as numbers and letters. However, to indicate its meaning, it is usually composed of a combination of the abbreviations of the problem concerned and the solution developed.

(2) The 'problem description' part is used to describe an optimization problem. This part mainly includes two aspects. The first aspect is for the purpose of describing the structure of the optimization model, including the fields of problem type, tag, variable boundary and number of variables.

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