Evolutionary Synthesis of Dynamical Systems – The Past, Current, and Future

Zhun Fan
Department of Electronic Engineering
Shantou University, Guangdong,
P.R. China
zfan@stu.edu.cn

Xinye Cai
College of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics,
Jiangsu, P.R. China
xinye@nuaa.edu.cn

Wenji Li
Department of Electronic Engineering
Shantou University, Guangdong,
P.R. China
wenji_li@126.com

Huibiao Lin
Department of Electronic Engineering
Shantou University, Guangdong,
P.R. China
13hblin@stu.edu.cn

Shuxiang Xie
Department of Electronic Engineering
Shantou University, Guangdong,
P.R. China
12sxxie1@stu.edu.cn

Sheng Wang
Department of Electronic Engineering
Shantou University, Guangdong,
P.R. China
12cwang2@stu.edu.cn

ABSTRACT

When Electronic Design Automation (EDA) has achieved great success both in academy and industry, design automation for mechanical systems seems to be lagged behind. One underlying reason for this is that the coupling of subsystems of mechanical systems is very strong, whereas this coupling for digital electronic system is usually much weaker. Or in other words, the modularity of electronic systems, especially digital electronic systems is much stronger. On the other hand, the mechatronic systems are becoming more and more modularized, which makes them more amenable to be designed automatically, just as digital electronic systems do. In this sense, Mechatronic Design Automation (MDA) is very likely to become the next wave after EDA both in academy and industry. In this paper, we give a survey of the topic of evolutionary synthesis of dynamical systems in general, and wish to shed some light on the future development of this subject.

Categories and Subject Descriptors

B.6.3 [Design Aids]: Automatic Synthesis.

General Terms

Design

Keywords

Automated synthesis, design automation, mechatronic systems

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1. INTRODUCTION

Mechatronic systems are intrinsically multi-domain physical systems, with possible addition of controllers (both continuous and logic ones). MDA research therefore entails automated concurrent design of both controllers and plant of multi-domain physics. Up to now, there is still no panacea in the research community to automate the optimal design of such a complicated system. The traditional single-discipline sequential-retrospective design model does not only incur long design cycles with frequent modifications, but also cannot guarantee the global optimum of the designed system. It is therefore every relevant and important to study a theory of design automation for general dynamical systems so that innovative designs can be generated automatically to help the designers to improve design efficiency. Moreover, adopting MDA can help the industry to design more innovative products, which will otherwise be difficult, if not impossible to be designed by human designers.

2. STATE-OF-ART OF THE RESEARCH

Design automation of mechatronic systems has not been reported widely in literature. However, design automation of electronic systems has received broad interests from the research community and extensive research results have been reported, especially in the area of design automation of digital electronic systems. Although design automation of electronic systems is focused on one single physical domain, many methods it utilizes can be borrowed in design automation of mechatronic systems. In the following sections, we will discuss related research in the following sequence: design automation of electronic systems -> design automation of MEMS -> design automation of mechatronic systems.

2.1 Design Automation of Electronic Systems (or Electronic Design Automation, EDA)

A lot of research has been conducted in design automation of electronic systems, especially in digital electronic systems.

Because digital electronic systems have very strong modularity, thus are very amenable for automated design. As a result, design automation of digital electronic systems has achieved great success in both academy and industry, and given birth to a huge industry called Electronic Design Automation (EDA) [1]. Compared with the design automaton of digital electronic systems, design automation of analog electronic systems is much more difficult. This is mainly due to two reasons: firstly, analog electronic systems have much stronger couplings between modules, or in other words, their modularity is much weaker than digital electronic systems. In addition, it is more complex to evaluate the performance of the analog electronic systems than that of the digital electronic systems, because more considerations of the design objectives and design constraints have to be taken into account.

Evolutionary algorithms are a class of methods used for automated design of analog electronic systems. Grimbleby [2] proposed using genetic algorithm to automatically design analog electric circuits. Lohn and Colombano [3] used parallel genetic algorithm and successfully designed analog filter and analog amplifier in an automatic manner. Koza et. al. [4] was the first to apply genetic programming in automated design of analog electric circuits. Using a systematic methodology, Koza et. al. have achieved successful results in designing eight different types of analog electrical circuits automatically, which demonstrates that genetic programming has strong capability of concurrent topology exploration and parameter optimization, and serves as a method that can be generalized well in design automaton of various analogy electrical systems. Alpaydin et. al. [5] applied a method that combines evolutionary strategy and simulated annealing to improve the efficiency of automated design, and utilized neuron-fuzzy model to address the issue of parameter uncertainty in manufacturing process. Compared with Koza's work in [4], this work is more emphasized on manufacturability of the circuits automatically designed. In addition, the design method was verified using the circuits manufactured in real world. However, the limitation of the method is that it can only optimize parameters of an electrical system with fixed topology, but lacks the ability to explore the open-ended design space automatically. Zhang et.al. [6] applied genetic algorithm to design power electronic systems automatically. Moreover, an adaptive search mechanism that can be used to coordinate the search in the controller space and the plant space is applied in his approach. The limitation of the approach is also that it can only optimize parameters of an electrical system with fixed topology. Mattiussi and Floreano [7] proposed a novel genetic encoding method inspired by gene regulatory network that enables evolutionary algorithm to achieve automatic design of dynamical systems such as analog electric circuits, neural networks etc. Compared with Koza's method [4], this method utilizes less computing resources, and the encoding does not need to cope with difficult tree structure. Overall, it is a promising approach that deserves further investigation.

Other representative works in this line include: Xie and Xiao [8] has conducted research of automated design of operational amplifier using genetic algorithm. Zhu and Li [9] proposed a concurrent recursive decomposition method that turns the evolutionary design process of the objective electrical systems into concurrent evolutionary design processes of multiple subsystems. It is reported that this method can improve the design efficiency and success rate of automated design of the objective electrical system. All these works in automated design of electrical systems provide significance and inspiration to the research of automated design of mechatronic systems, and dynamical systems in general.

2.2 Design Automation of Micro-Electro-Mechanical Systems (MEMS)

A special type of mechatronic systems – micromechatronic systems or micro-electro-mechanical systems (MEMS) has similar or the same substrate in their manufacture as microelectronic systems. Automated design of MEMS can be considered as an intermediate stage between automated design of electronic systems and automated design of mechanical systems. There have been significant progresses in the automated design of MEMS. For example, Fedder and Jing [10] proposed hierarchical design method. Based on this, Mukherjee and Fedder [11] applied hierarchical design method in automated design of MEMS. But their methods cannot simultaneously design and optimize the topology and parameters of MEMS. Kamalian [12] suggested an interactive evolutionary algorithm that can integrate human's design knowledge and subjective evaluation of the design candidates. The interactive evolutionary algorithm was used to automate the designing of both the topology and parameters of MEMS. Zhang [13] further develops the work of Kamalian in [12], and proposed a hybrid interactive evolutionary algorithm. The algorithm integrates a multi-objective evolutionary algorithm and a local optimization algorithm, which can more flexibly help designers to actively find superior design patterns and then optimize their parameters. In the previous work of the author, a hierarchical automated design framework for MEMS has also been proposed, which combines the capability of genetic programming for system level topology exploration and parameter optimization, and genetic algorithm for device level parameter optimization [14]. In [15], the author also proposed an automated robust design method for MEMS based on improved differential evolution.

2.3 Design Automation of Mechatronic Systems (or Mechatronic Design Automation, MDA)

The most distinguished difference of automated design of mechatronic systems and automated design of electronic systems is that mechatronic systems are intrinsically multi-physics systems with possible integration of controllers [16]. Charkrabarti [17-19] gives a framework of automated synthesis of mechanical systems. This framework can automatically provide a series of conceptual designs that satisfy the functional requirements of the system, without further investigation of the dynamical behaviors of the designed systems. Campbell [20] [21] studies and develops a framework of automated conceptual design of mechatronic systems based on Agent, which can adapt to dynamically changing design environment. The limitation of the framework is also that it lacks detailed analysis of the dynamical behaviors of the designed systems.

Bond graph is a modeling language that can be used to depict uniformly the multi-domain physics as well as the continuous controller, capable of detailed analysis of the dynamical behaviors of the designed systems [22][23]. Bond graph has been widely applied in modeling and analysis of a large variety of real world physical dynamical systems, such as hybrid electric car [24] and smart building [25] etc. Tay et.al. have automatically generated mechatronic designs that satisfy predefined specifications using bond graph as the unified modeling language of mechatronic systems, and genetic algorithm as the search tool in the design space [26]. Seo and the author [27] proposed a framework of automated design of mechatronic systems which combines bond graph as the modeling tool for the multi-domain physics and genetic programming as the search tool for exploration in the design space. The author has made successful designs for electrical circuits and mechatronic systems [28] [29]. Li et.al. also utilized this framework for automated design of a class of analog electrical circuit [30] [31]. Because the efficiency of the search algorithm can be a key for the success of the automated design method, improving the efficiency of the search algorithm is very critical. Hu et.al. proposed a hierarchical fair competition model [32] that can significantly improve the search efficiency of evolutionary algorithms. Oduguwa [33] put forward an intelligent design framework that integrates the exploration in the qualitative space and the search in the quantitative space. This framework can well incorporate human knowledge and judgment, and substantially improves the practicality of the design method.

In previous work, it is rarely reported on how to concurrently design both the controller and the plant of a mechatronic system. Lipson [34] once reported a famous result in Nature, in which he used evolutionary computation to generate the first computer-generated robot system with automatically synthesized neuron controller and plant morphology. The author used bond graph as the representation for both continuous controller and plant of mechatronic systems and automatically designed the plant and the controller of a vehicle suspension system using co-evolutionary algorithm [35] [36]. The author further developed the method so that it can incorporate discrete events and logic controller in the automated design framework. The results are reported in automated designing of a three-tank system [37] and a DC-DC converter [38].

3. FURTHER DEVELOPMENT OF THE RESEARCH

The general research field of the evolutionary synthesis of dynamical systems is going to undergo major progresses with the further developments in the following research directions:

3.1 Multi-objective (or even many-objective) Evolutionary Algorithms

In real world design applications, the designers usually consider not just one single design objective, but more often than not have to consider multiple conflicting design objectives at the same time. As a result, multi-objective evolutionary algorithms (MOEA) gradually become a must in the research of evolutionary synthesis of dynamical systems. When design objectives to be considered simultaneously are more than three, many-objective evolutionary computation is the choice of tool to tackle the automated design problem. Typical MOEAs include NSGA-II [39] and MOEA/D [40]. How to integrate mechanisms of these methods into genetic programming is worthwhile to be investigated in-depth in the future, since genetic programming is very useful to evolve both topology and parameters, and thus a very important tool in evolutionary synthesis of dynamical systems. How to endow genetic programming with multi-objective, and even many-objective search capability is of a critical significance to future development of the general area of evolutionary synthesis of dynamical systems.

3.2 Constrained Optimization Approaches

Real world design applications almost always have to face many design constraints. As a result, EAs, including MOEAs, have to search landscapes with both feasible and infeasible regions. How to handle infeasible solutions in the evolutionary search process becomes a critical issue because this can to a large extent influence the performance of the search algorithm. Deb's constraint handling approach is widely used [41], which is however not necessarily the best choice in all types of applications. Stochastic ranking method [42], for example is found to be more effective among other choices.

3.3 Integrating Data Mining Approaches into Evolutionary Algorithms

A large volume of data is generated in the evolutionary design process. However, most of the data is discarded during the evolutionary process in conventional EAs, without further processing and data mining. As a result, a lot of knowledge is discarded with the data without a chance to be discovered. Researchers have realized that integrating data mining approaches into evolutionary algorithms can not only improve the algorithm performance, but also help discover hidden knowledge in the designing process, thus leading to possible innovations in designs [43].

4. CONCLUSIONS

With the previous success of EDA, and the emerging significance of mechatronic products in the industry (plus upcoming popularity of service robots in our everyday life), there is good reason to believe that MDA, and in general, design automation of dynamical systems will face a bright future and receive increasing attention in the research community. This paper gives a preliminary survey of this research area, attempting to give it a relatively thorough review of the previous research and a momentum to future development.

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