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Design evolution and synthesis of multi-domain engineering systems using artificial immune system

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ABSTRACT

A multidisciplinary design method is developed in this paper to optimally evolve and synthesize multi-domain engineering systems. The design methodology utilizes two navigated optimization loops to handle the optimization of both topology and parameters. In the topology optimization, which is the outer loop, the proposed artificial immune system (AIS) tool, which contains a clonal selection algorithm (CLONALG) and negative selection techniques, is utilized to synthesize the number and the structure of the elements. A novel concept of "artificial vaccination" is developed, which is responsible for the incorporation of domain knowledge. In the inner loop, an optimization tool that incorporates simple AIS is utilized for parameter tuning in any generated topology. By acquiring knowledge and learning from prior trials, the evolution parameters are automatically and intelligently tuned to make the design model more reliable and to facilitate more effective navigation. Numerical study on the design of a hydraulic engine mount is presented. The results indicate that the proposed design flowchart enables the designers to successfully modify (specifically, extend or reduce) the initial colony in order to obtain the optimal solution.

1. Introduction

Today, with the advent of innovative technologies, many real engineering systems have become complex multidisciplinary systems. Due to dynamic interactions between the subsystems of a multi-domain mechatronic system, its modeling and design tools should take an integrated and concurrent approach, where different subsystems belonging to different domains are presented, analyzed and optimized via a unified domain independent tool [1]. The analogies between basic elements in different domains can help in achieving this requirement – a fact which is utilized in bond graph modeling of mechatronic systems. This is a more realistic and somewhat innovative viewpoint in comparison with conventional design approaches, which are sequential, where electrical, mechanical, thermal, and hydraulic subsystems are designed separately, ignoring their interrelations, and a controller is designed latter to compensate for possible design imperfections. Due to the interactions of the segments of individual domains in a complex engineering system, the final design will most likely not be optimal if its subsystems are optimized separately.

The present design procedure contains two levels: configuration synthesis [2] and parameter value tuning of its engineering elements [3]. The design flowchart presented in this paper is inspired by the biological immune systems. It synthesizes a model of the desired system by optimizing a preliminary system called the initial colony, which is provided by the designer. The optimization entails extending or even decreasing the size of the system in both topology and parameter-value levels.

In recent years, there has been considerable attention on the development of tools for autonomous generation of the topology of an engineering system. High multi-modality of the search space, discreteness, and lack of information to guide topology searching are some important challenges of topology synthesis. They are common in the design of any system with lumped parameters (e.g., electrical circuit, control system, and mechanical system structure) [4]. Due to these challenges, earlier work on design optimization employed evolutionary algorithms, where system optimization modifies an initially suggested solution in a somewhat random fashion. An evolutionary algorithm randomly generates huge numbers of solution trials, which can hardly be effective in the topology synthesis, due to the open-ended and unstructured nature of this problem. Therefore, incorporating available domain knowledge and also learning and memorizing valuable knowledge from prior design attempts (i.e., inspired by the concept of vaccination) in navigating the process of evolution seems a crucial asset in design, which has been overlooked in previous work.

In the field of designing lumped-parameter mechatronic systems, as a relevant approach for handling multi-domain

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engineering systems, the integration of bond graphs (BG) and genetic programming (GP) was developed by Seo [5] and extended by Behbahani and de Silva [6], leading to a tool called BGGP. They utilized GP as the optimization tool to evolve the BG representation of a mechatronic system. In that approach, the designer should provide a sub-program for calculating the fitness of any generated solution, while it may not be possible to represent all the design criteria for a complex mechatronic system in one single fitness function. Moreover, since the BGGP process was not controlled, an arbitrary evolution of a BG might result in a complex design, that was not feasible for practical implementation.

Later, Behbahani and de Silva extended their initial work by performing the topology and parameter optimization in two different levels, utilizing a hybrid of genetic algorithm (GA) and GP for design synthesis and optimization of a mechatronic system. Their method was also enhanced by incorporating a memory feature, in order to avoid the generation of repeated topologies [7]. They also introduced a niching genetic scheme, with the aim to find several elite configurations for different preferences, so that the human designer would be capable of evaluating elites and selecting the global optimum solution at the final stage [8].

In the present paper a novel design method guided by the domain knowledge of a human expert is proposed, and an associated tool is developed. Due to the particular characteristics of the problem, artificial immune system (AIS) is employed to handle both domain knowledge incorporation and concurrent mechatronic design.

An AIS tool has been developed, initially for the application in computer security, inspired by the biological immune system [9,10]. Later, other engineering fields such as control [11,12], controller design [13], scheduling [14] and pattern recognition have utilized AIS algorithms. In the optimization of engineering systems, AIS has been mainly used in robotic problems such as navigation [15] and multi-robot cooperation [16,17]. There is literature on the application of AIS in multi-objective optimization problems [18,19].

Despite the brilliant features of AIS, no specific research has been found in the application of AIS in the autonomous synthesis of the structure of a system, and particularly in multi-domain engineering design optimization.

In the field of numerical optimization, Freschi et al. have compared AIS and GA in solving some engineering problems. They have demonstrated that the AIS tool has detected more optimal points but in a more time consuming process [20].

The main contributions of the present paper are:

- Prior researchers have utilized GP as a topology optimization tool and GA for parameter value optimization, while in the present work AIS with dynamic mutation capability is utilized in both steps in order to acquire more accurate and feasible results. A supervisory algorithm is developed for intelligently guiding the design process through analyzing the weakness points of the prior trials. It is shown that AIS has great capabilities for dynamic and intelligent design evolution.
- In the present work, the negative selection algorithm in AIS is utilized for element elimination and design modification, while in prior work the preliminary suggested solution model could just be extended. Therefore, in the present paper even an existing system can be introduced as an initial solution. In other words, this methodology is capable of system modification beside design evolution from a preliminary model.
- One potentially attractive concept is to employ expert knowledge in generating a library of mechatronic system elements and sub-assemblies to be used for solving the problem. It is inspired by the formation of antibodies in biological immune systems. Engineering knowledge also helps in selecting effective elements from the library for solving a particular problem.

2. Artificial immune system (AIS)

AIS is a computational intelligence paradigm, which is inspired by the biological immune system. In order to introduce the technical terms of AIS, first the biological immune system is outlined. The biological immune system is a network of cells and organs that work together to defend the body against pathogenic organisms, toxins, and other foreign molecules called antigens. The fundamental constituents of the immune system, which are located throughout the body, are called lymphocytes. They are white blood cells that are the key players in the immune system. A B-cell is capable of producing one specific antibody that can recognize a particular type of antigen. Among different lymphocytes cellules, B lymphocytes produce antibodies to attack antigens while memorizing the effect of the previously produced antibodies on removing antigens. The biological immune system optimizes the production of antibodies with information stored in the memory. This is similar to human expert behavior in solving an engineering problem. The implementation of this capability in a systematic design flowchart is a novelty of the present paper. An expert configures different engineering elements to create an optimal system, and memorizes the effectiveness of the elements in producing successful systems, which eventually forms his experience and engineering knowledge for later design tasks.

Once an antigen attacks the human body, the B-cells are stimulated, and an antibody that matches the antigen will attach to the antigen to neutralize or eliminate it. However, as shown in Fig. 1, if a single antibody is unable to destroy the antigen, it will coordinate with other antibodies to cooperatively eliminate it.

As shown in Fig. 1, on the surface of a B-cell, there is a Y shaped receptor called antibody, which is responsible for recognizing antigens. The binding affinity term stands for the capability to form coordination bonds with a receptor. The greater the binding affinity between an antibody and an antigen chains, the higher the chance of the capability of that antibody to surround and eliminate the antigen.

The recognition of an effective antigen will stimulate the proliferation and differentiation of the immune cells that produce matching clones or antibodies. This process is called clonal expansion which generates a large population of antibody producing cells that are specific to the antigen. These clones get priority when exposed to similar antigens, which leads to rapid immune response. The process of amplifying only those lymphocytes that produce a useful antibody type is called *clonal selection algorithm (CLONALG)*.

The immune system is also able to attack its own antibody cells in the body, for example cancerous cells and tumors. This action is called *negative selection*, and it is a main feature that has inspired the present research.

3. Design evolution flowchart

In this paper, the main challenge is the development of a formal multidisciplinary design methodology which provides an innovative systematic design flowchart for concurrent synthesis of the topology and optimization of the parametric values of the system. Since the topology synthesis has an open-ended and unstructured search space, it is usually viewed as a problem that needs human intelligence and inference [6,7]. Therefore, a key objective in this field is to rather imitate some features of the human intelligence in synthesizing and evolving the topology of the systems. To achieve this objective, a model of the system that is capable of evolution and an evolutionary algorithm for optimizing the system are required.

Fig. 2 demonstrates the scheme of the proposed design flowchart. Any engineering system which can be modeled through