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A new methodology for multi-objective multidisciplinary design optimization problems based on game theory

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ABSTRACT

The design of engineering systems often involves multiple disciplines and competing objectives, which requires coordination, information exchange and share amongst the disciplines. However, in practical design environments, designers have to make decisions in isolation due to organization barriers, time schedules and geographical constraints. This paper will propose a new approach for the multi-objective multidisciplinary design optimization (MDO) problems in non-cooperative environments based on gene expression programming (GEP) and Nash equilibrium in the game theory. In this approach, the GEP method is used as a surrogate to construct the approximate rational reaction sets (RRSs) in the Nash model. The effectiveness of the proposed method is demonstrated by the design of a thin-walled pressure vessel and the hull form parameter design of a small waterplane area twin hull (SWATH) ship. The results show that this approach can fully explore and provide the explicit functional relationship between the strategy of an isolated player and the control variables of the other players, thus able to obtain a better Nash equilibrium solution.

1. Introduction

The design of engineering structural and mechanical systems, such as aircrafts, automobiles and ships, usually involves multiple mutually coupled disciplines. The couplings between different disciplines will normally cause complicated and time-consuming interactive analysis during the design process. To improve the design efficiency, there have been more and more attentions for seeking a better way to process the design of engineering systems. Multidisciplinary design optimization (MDO) (Sobieszczanski-Sobieski & Haftka, 1997) has emerged as a popular and systematic design methodology for complex structural and mechanical systems in the field of engineering design optimization, which has been applied to a number of engineering design problems. MDO allows designers to make trade-off decisions that incorporate the interactions among all individual disciplines in one integrated design system. The final design of MDO will be superior to the design obtained by sequentially optimizing the individual disciplines. In recent years, MDO has experienced rapid growth by means of coherently exploiting the synergism of mutually interacting phenomenon, and is becoming increasingly important in providing a feasible solution in the design of various engineering problems (Agte et al., 2010; Li, Luo, Sun, & Zhang, 2013; Weck et al., 2007), because it is practically impossible to obtain a unique solution that is optimal for a complex MDO system. However, the complexity of MDO problems has imposed computational and organizational difficulties beyond those encountered in the design optimization of single discipline problems.

To mitigate the computational and organizational burdens in the MDO systems, a number of design and optimization strategies have emerged in the field of MDO. Typically, decomposition strategies, which divide a large coupled MDO problem into a series of smaller and more tractable sub-problems, have attracted many attentions from the academia and industry (Li, Lu, & Michalek, 2008; Zadeh, Toropov, & Wood, 2009). Up to now, some decomposition strategies have been successfully developed. Generally, the decomposition strategies can be classified into two categories, namely the single-level and multi-level methods (McAllister, Simpson, Hacker, Lewis, & Messac, 2005).

For single-level methods, only a single optimizer exists and its structure is nonhierarchical, such as the methods of the simultaneous analysis and design (SAND) (Haftka, 1985), the multidisciplinary feasible (MDF) (Grossman, Gurdal, Strauch, Haftka, & Eppard, 1988) and the individual discipline feasible (IDF) (Haftka, Sobieszczanski-Sobieski, & Padula, 1992). After the concurrent subspace optimization (CSSO) method proposed by

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Sobieszczanski-Sobieski (1988), the multi-level decomposition strategies become more and more popular. They employ a hierarchical framework, and the optimizers exist in each level. Some other popular multi-level decomposition strategies include the collaborative optimization (CO) (Braun & Kroo, 1995), the bi-level integrated system synthesis (BLISS) (Sobieszczanski-Sobieski, Agte, & Sandusky, 1998), and the analytical target cascading (ATC) (Kim, Michelena, Papalambros, & Jiang, 2003) methods. However, the above methods are mainly developed for single-objective MDO problems (Huang, Galuski, & Bloebaum, 2007).

In practice, however, most of the engineering problems involve multiple design requirements, which make the MDO problems usually involve a set of objective functions. The single objectives are often competitive and conflicting in relation to the same design requirement. Hence, methods need to be developed to deal with the multi-objective MDO problems effectively. Due to the inherent couplings of different disciplines and the competing and conflicting objective functions in the multi-objective MDO problems, coordination, information exchange and share between the coupled disciplines are required. However, in some practical design environments, designers have to make decisions in isolation because of organization barriers, time schedules and geographical constraints. Therefore, they have to be faced with solving the multi-objective MDO problems in non-cooperative environments.

This paper proposes a new approach based on gene expression programming (GEP) and Nash equilibrium for the multi-objective MDO problems in non-cooperative environments. In this approach, the GEP method is employed to construct the approximation models for the rational reaction sets (RRSs) of the players in the Nash model, due to the favorable performances of the GEP algorithm to be a metamodel, such as high approximation accuracy and good transparency. The clear and explicit functional relationship between the strategy of an isolated player and the control variables of the other players can be provided. Solutions of the multi-objective MDO problems in non-cooperative environments are solved by evaluating the intersections of the explicit RRSs.

The remainder of this paper is structured as follows. Section 2 gives an overview of relevant literature on the multi-objective MDO problems. In Section 3, the intrinsic similarity between game theory and MDO is analyzed; three common game theoretic models are introduced. The multi-objective MDO approach based on GEP and Nash equilibrium is elaborated in Section 4. In Section 5, the design of a thin-walled pressure vessel and the hull form parameter design of a small waterplane area twin hull (SWATH) ship are taken as two case studies to test the proposed approach. Conclusions and future work are given in Section 6.

2. Literature review

With respect to the multi-objective MDO problems, one approach is to combine the multi-objective optimization methods with the existing MDO decomposition strategies. For instance, Tappeta and Renaud (1997) proposed a multi-objective CO method, which integrates the weighted sum method within the CO framework. McAllister et al. (2005) proposed the integration method of linear physical programming within the CO framework, in which the physical programming method allows designers to express their preferences for conflicting objectives using physically meaningful parameters. Similarly, other multi-objective MDO integration methods were also developed based on the CSSO framework, such as the multi-objective Pareto CSSO (Huang, 2003; Huang et al., 2007), and the multi-objective range/target CSSO (Huang & Bloebaum, 2004) methods. It is noted that each of these methods provides only one Pareto solution after its implementation. In order to generate a Pareto frontier, all of them require multiple system convergence cycles by using different initial starting points. To overcome this shortcoming, Parashar and Bloebaum (2006) developed the multi-objective genetic algorithm CSSO method, in which many Pareto solutions can be generated simultaneously after a single run of this method. Furthermore, to obtain a number of uniformly and widely distributed points to represent the Pareto frontier, Zhang, Han, Li, and Song (2008) proposed the integration of the adaptive weighted sum method within the CSSO framework. Li et al. (2013) proposed a multi-objective MDO method using the MDF method and interval uncertain model. Mastroddi and Gemma (2013) conducted the analysis of Pareto frontiers for MDO of aircraft, in which the local weighed global criterion method was used for Pareto frontier building. Maheri and Isikveren (2013) developed a goal programming approach using a weight-free aggregate function to produce enhanced design alternatives for the multi-objective MDO problems. Wang, Wen, Li, and Xi (2014) combined the NSGA-II method with radial basis function meta-model to find the compromise between the conflicting demands in MDO of the blades in a mixed flow fan. Wang, Zhu, Wilamowska-Korsak, Bi, and Li (2014) proposed a systematic methodology to determine the variable weights of multiple objectives based on a modular neural network. A multi-objective MDO problem was converted into the problem with an equivalent single objective.

Besides the aforementioned methods, some game theoretic methods were also employed to solve the multi-objective MDO problems. Lewis and Mistree (1997a, 1997b) developed a game theoretic approach to model interactions in the multidisciplinary designs. Three different game models, namely the Pareto or cooperative, Nash or non-cooperative, and Stackelberg or leader/follower models, were developed to represent three different multidisciplinary design scenarios. According to the principle of the game theory, Xiao, Zeng, Allen, Rosen, and Mistree (2005) modeled the relationships between engineering design teams to facilitate collaborative decision making. Shiau and Michalek (2007) utilized a game theoretic approach to find market equilibriums for automotive designs under various environmental regulation scenarios. Takai (2010) proposed a two-person prisoner's dilemma game theoretic model to analyze collaboration of engineers in a design project, which has both team and individual components.

To solve the multi-objective MDO problems in non-cooperative design scenario, the game theoretic method based on the non-cooperative model was used by Lewis and Mistree (1997a, 1997b). However, the accuracy of solutions using the non-cooperative game theoretic approaches depends largely on the precision of constructed RRSs (Lewis & Mistree, 1997a, 1997b). Hence, to obtain more accurate solutions for the multi-objective MDO problems in non-cooperative environments, this paper proposes a new approach based on GEP and Nash equilibrium.

3. Game theory and multidisciplinary design optimization

In this section, an analysis of the intrinsic similarity between two areas (i.e., game theory and MDO) is presented. The three common game theoretic models are also introduced briefly.

3.1. Game theory and MDO

Game theory is the study of mathematical models for conflict and cooperation between intelligent rational decision-makers (Myerson, 1991). A complete game theoretic model is composed of three basic elements, namely, players, strategies and utilities. It is well known that conflict and cooperation widely exist between the players. MDO is a design methodology for complex engineering systems and subsystems that coherently exploit the synergism of mutually interacting phenomena (Sobieszczanski-Sobieski &