On the Coordination of Multidisciplinary Design Optimization Using Expert Systems

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1 Introduction

In the design of complex engineering systems involving multiple disciplines it is critical that the interactions between the subsystems of the problem are accounted for. Only by considering the fully coupled system can an optimal design emerge. Formal multidisciplinary design optimization (MDO) methods [1] fall into two broad categories; 1) monolithic formulations where a single optimizer addresses the whole problem and 2) multilevel methods where the problem is decomposed along disciplinary lines and optimization takes place at both a system and domain level. The single optimizer approach is simple to implement but can scale poorly for larger problems and increasing number of disciplines. It may also prove problematic in an industrial setting to bring all of the domain analysis tools under the control of a single optimizer. Multilevel architectures promote discipline autonomy. The system level is responsible for managing interactions between disciplines. Such an approach allows design teams to work in relative isolation based upon targets set at the system level. If MDO methods are to be accepted in an industrial context they must support this form of distributed design optimization for both organizational and computational reasons. In this work a related approach is proposed; that of replacing the formal system level optimizer with an expert system to reason over information from the domains and make decisions about changes to the common design variables vector or bounds. Such an approach sacrifices, possibly elusive, guarantees of convergence for potentially attractive returns in the enterprise.

2 Coordination of MDO Using an Expert System

An investigative framework has been developed exploiting an expert system as the coordinating process for multidisciplinary design optimization. This system level "master" process has access to a central repository of information which details both the present state of the design and the history of the MDO search. Data mining is employed to analyze the content of this database to present the expert system with facts about features in the domain and system level optimization data. The expert system employs a rule base to make decisions about

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how the domain level design optimizations should proceed. The results of the reasoning of the expert system are written into the central database and the domains, acting asynchronously, perform the next local optimization as resource becomes available. The expert system controls the design process by specifying the bounds and parameters provided as input to the domain optimizers working on their part of the decomposed problem. A rule base has been developed that solves the design problem by narrowing in on single values for the shared design variables through systematic reduction of their bounds, by managing the exchange and relaxation of the state coupling variables between the domains and by specifying the start points for the domain optimizers. In this work, the performance of the rule base is explored using two types of optimizer in the domains; a sequential quadratic program and a genetic algorithm.

To assess the performance of the rule based coordination a number of standard MDO algorithms from the literature have been implemented in Matlab using the SQP method `fmincon`. These include the methods: Multiple Discipline Feasible (MDF) [2], Individual Discipline Feasible (IDF) [2], All-At-Once (AAO), Collaborative Optimization [3], Bi-Level Integrated System Synthesis (BLISS) [4] and Multidisciplinary Design Optimization based on Independent Subspaces (MDOIS) [5]. A number of MDO problems have also been assembled from the literature ranging from simple numerical constructs, through relatively simple preliminary aircraft design problems to a cut-down and decomposed version of a commercial aircraft wing design tool. The problems have been implemented in both the rule base framework and the Matlab MDO framework to enable comparison of performance in both qualitative and quantitative terms. We present the results of the application of the MDO methods to two example MDO problems. The first numerical problem is taken from the third example study presented in Yi *et al.* [6] involving two disciplines. The second is a subsonic passenger aircraft design problem described by Lewis [7]. The problem is also composed of two domains; an aerodynamics model and a weights model.

3 Results

The results for the Yi3 problem are presented in Table 1. This minimization problem is solved by all methods and the rule base (RB) performs well in this instance. The global optimum value of the system objective function $f = 0.5$ is found exactly when using the SQP optimizer in the domains and is found less accurately when using the GA in the domains. However, it is noted that the problem does not have a unique global optimum and admits a number of solutions with the optimal system objective function value $f = 0.5$. The single optimizer methods all solve the problem using only two or three system level iterations. The bi-level methods need significantly more iterations for this problem. The MDO methods solve the problem to the tolerances set for the optimizers with the exception of CO which does not converge well. The rule base approach requires 8 and 18 system level iterations for the SQP and GA

Table 1. Performance of MDO methods for the Yi *et al.* example 3

Method	Objective Function	Maximum Constraint ($g \leq 0$)	Number system iterations	Domain-1 analysis calls	Domain-2 analysis calls
MDF	0.5000	0.0000	2(5)	281	281
IDF	0.5000	1.1102×10^{-16}	2	19	19
AAO	0.5000	-2.2204×10^{-16}	3	33	33
CO	0.4998	2.0609×10^{-4}	148	19530	18376
BLISS	0.5000	2.6671×10^{-7}	66(66)	4941	4950
MDOIS	0.5000	-4.2723×10^{-8}	21(21)	1168	1184
RB (SQP)	0.5000	0.0000	8	280	225
RB (GA)	0.5008	-7.4939×10^{-4}	18	25550	25550

domain level optimizers respectively and is competitive with the other bi-level methods. The performance of the algorithms is broadly comparable with the performance figures reported in Yi *et al.* [6] with the slightly greater number of function calls required in our framework likely attributable to the higher tolerances used.

Table 2 summarizes the results for the subsonic aircraft design problem. A consistent optimum is not found across the methods investigated but the rule base performs well compared to the other bi-level methods (CO, BLISS, MDOIS). The rule based approach (GA) and the MDF method find the best results. CO and BLISS exhibit poor performance for this problem and do not converge to an acceptable feasible solution. For BLISS it is possible that the trust region algorithm could be improved here but the performance of the algorithm on this problem, and others in our test suite, shows that it will often take the search to the bounds of the design variables. Conversely, the rule base in this case, finds a solution close to that of MDF. The broader search achieved using a GA in the domains provides an advantage over SQP for these problems. This also indicates that performance gains may be possible by improving the rules for managing the domain optimization start points.

Table 2. Performance of MDO methods for the subsonic aircraft design problem

Method	Objective Function	Maximum Constraint ($g \leq 0$)	Number system iterations	Domain-1 analysis calls	Domain-2 analysis calls
MDF	−2.0676	-5.7335×10^{-11}	13(27)	668	668
IDF	−2.0152	0.0	5	67	67
AAO	−1.9629	-1.4627×10^{-4}	5	127	127
CO	−2.0139	3.1050×10^{-2}	250*	156177	469726
BLISS	−1.6035	6.8202×10^{-2}	7(7)	148	148
MDOIS	−1.9706	-6.9561×10^{-7}	8(8)	297	308
RB (SQP)	−1.9735	0.0	46	2406	923
RB (GA)	−2.0549	-4.7834×10^{-5}	70	86870	94024

4 Discussion and Conclusions

The rule base approach is found to work well and has the advantage that it is relatively straight forward to integrate into existing organizational infrastructure. However, further work is required to assess whether the pragmatic rule base approach, that sacrifices formal guarantees of convergence, will be truly competitive across a large range of MDO problem. The relative ease with which a rule based system level control process can be implemented and managed is a significant advantage over methods like BLISS which can prove difficult to implement. Both BLISS and CO require domain experts to optimize constructs of the process rather than investigate the physics of the problem.

Initial studies have involved a number of MDO problems ranging from simple numerical schemes, through basic aircraft sizing studies to a cut-down commercial in-house design tool. The initial rule base works by managing the bounds of the shared design variable vector until the enclosed hyper-volume converges to a specified tolerance and all domains are feasible. The performance of the rule base is found to be competitive for a range of MDO problems (of which only two are presented herein). Future work will extend the use of data mining of domain optimizers for improved feature recognition and development of a more sophisticated rule base to improve performance across the range of problems assembled.

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