Multidisciplinary Design Optimization for Heavy Machinery Based on HLA

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Abstract

To achieve the global optimal of heavy machinery and other complex production, a computation environment of collaborative optimization for multidisciplinary design based on high level architecture (HLA) was constructed. According to the interface specification of HLA, the coupled state variables were mapped to corresponding published or subscribed attributes of an object class. So that the collaboration and interoperation between the disciplines were implemented. As a result, the global optimal of complex production was achieved based on the synergistic effect owing to the interoperation between the disciplines. Application of proposed optimization model in designing the schnabel car could not only take off the deadweight, but also improve its running stability.

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1. Introduction

In the past decade the multidisciplinary design optimization (MDO) approach has had an increasing development as promising approach for designing complex systems having considerably high level of coupling between the disciplines describing them[1]. MDO-oriented modeling and computation environment are the main research contents of MDO. These techniques require an integrated optimal design environment capable of dealing with extensive calculations. This environment must combine the analysis and optimization tools developed in various languages on various platforms in a convenient and efficient way[2].

MDO-oriented modeling and computation environment have experienced the development course from the special interface to the integrated environment. The special interface developed for inter-application integration dominated the early MDO technology. With increased number of discipline, the number of
interface increased sharply. Furthermore, it is difficult to maintain and upgrade the system because of the tight coupling among systems. In view of the shortage of the special interface, a model of collaborative optimization for multidisciplinary design optimization based on high level architecture was brought in this paper. HLA is an architecture standard for distributed simulations[3]. HLA supports the development of federations of network-connected simulations, called federates, that exchange data at run-time.

The predominant research of the MDO was centered on aerospace[4-6], with few contributions from the civilian industry. As a kind of complex product of civilian industry, the schnabel car is very heavy, and its design optimization is a complex engineering system, which is multidisciplinary, multivariable, and multi-object. In this paper, the research of MDO-oriented modeling and computation environment based on HLA was centered on the heavy machinery of civilian industry, and a case of design optimization of the schnabel car was given finally.

2. Model of single discipline optimization

The general formulation of an model of single discipline optimization is shown as below[7]:

\[
\begin{align*}
\min f(x, \mathbf{p}) \\
x = [x_1, \ldots, x_n]^T, \mathbf{p} = [p_1, \ldots, p_m]^T \\
x_{i, LB} \leq x_i \leq x_{i, UB}, i = 1, 2, \ldots, n \\
s.t. g(x, \mathbf{p}) < 0, h(x, \mathbf{p}) = 0
\end{align*}
\]

where \( f(x, \mathbf{p}) \) is the function to be minimized, \( x \) is a \( n \)-dimensional vector of design variables with lower and upper bounds, \( \mathbf{p} \) is a vector of fixed parameters that influence the behavior of the system but cannot be freely chosen (material properties, operating conditions,...), and \( g(x, \mathbf{p}) \) and \( h(x, \mathbf{p}) \) are inequality and equality constraints, respectively. Corresponding single discipline optimization loop operating on a very limited design variables to optimize a system level objective is shown as Fig. 1.

![Fig.1 single discipline optimization loop](image)

3. Model of MDO based on HLA

MDO-oriented computation environment must allow the integration of disciplinary analysis codes as well as tools for facilitating cross-disciplinary tradeoffs.

3.1 Model of MDO

MDO is not simply a collection of individually optimized subsystems, but is that the contributions of all mutually influential disciplines and inter-disciplinary couplings are concurrently taken into account. Therefore, the general model of MDO can be shown as below:
where \( f() \) is the function to be minimized, \( X \) is a \( n \)-dimensional vector of system-level design variables, \( X_i \) is a \( n \)-dimensional vector of subsystem-level design variables, \( P_i \) is a \( m \)-dimensional vector of fixed parameters that influence the behavior of the subsystem, and \( g_i() \) and \( h_i() \) are inequality and equality constraints, respectively. \( Y_{ji} \) is coupled state variable from discipline \( j \) to \( i \). Correspondingly, a model of MDO with 3 subsystems (disciplines) was given as Fig. 2.

3.2 Implementing interaction among disciplines based on HLA

HLA is an architecture standard for constructing distributed simulations. It facilitates interoperability among
different simulation systems and types and promotes reuse of simulation software modules. In order to combines different disciplinary models and simulation tools together, HLA enabled template is designed to facilitate transform actions of commercial simulation models, meanwhile, the runtime infrastructure (RTI) is given to a software implementation of the interface specification.

Based on HLA, an individual simulation is referred to as a federate. A group of federates that intend to interoperate with one another form a federation. At a high level, MDO can distinguish between system level optimization and subsystem level optimization. The former is regarded as federation, and the latter is encapsulated as federate based on HLA. When running a MDO task, HLA enabled template must have been embedded in every model that participate in simulation and optimization, and these collaborative models make up of a federation. The coupled state variables are defined as object attributes which are sent (published) or received (subscribed) so that the interactions among disciplines are implemented. Its principle shows in Fig. 3.

Where \( y_i \) is coupled state variable which is output of discipline \( i \), meanwhile, it is defined as object attribute published by the federate \( i \) according to the specification of HLA. \( y_{ji} \) is coupled state variable from discipline \( j \) to \( i \), it is defined as object attribute which is published by federate \( i \), and subscribed by the federate \( j \) according to the specification of HLA.

4. A case of MDO based on HLA

The schnabel car type D45, which is heavy special machinery, developed by china has loading capacity 450t, its deadweight was 250t as initial design. Not only taking off the deadweight, but also improving its running stability are the optimization objective of schnabel car. So the system design variable is 2-dimensional vector and the formulation of MDO is shown as below:

\[
\mathbf{x} = \begin{bmatrix} x_1 & \ldots & x_n \end{bmatrix}^T = \begin{bmatrix} G & W \end{bmatrix}^T
\]

where \( G \) is the deadweight of the schnabel car, \( W \) is its running stability index. After simplification, the system model of MDO for Schnabel car can be decomposed to 3 subsystem models: multi-body dynamic model (model 1) built by Adams, hydraulics model (model 2) built by Hopsan, and the control model (model 3) built by MATLAB/Simulink. The 5 input interfaces of the model 3, which are defined as subscribed attributes, are mapped to the output interfaces of model 1, which are defined as published attributes. In the same way, the 4 control signals, as the output of the model 3, are mapped to the input interface of model 2. The control forces, as the output of the model 2, are mapped to the input interface of model 1. The model of MDO for schnabel car is shown as Fig. 4.
The local design variable ($x_1$) of multi-body dynamic model includes running velocity ($V$), acceleration ($A$), height of gravity center ($H$), and centrifugal force ($F$).

$$x_1 = [V, A, H, F]^T$$

Where the local design variable ($x_2$) of hydraulics model includes the diameter of hydraulic cylinder ($D$), Pressure ($P$), and flow ($Q$).

$$x_2 = [D, P, Q]^T$$

The local design variable ($x_3$) of control model includes of 4 control signals, it is also the coupled state variable $y_{32}$ and $y_{12}$.

$$x_3 = y_{32} = y_{12} = y_3 = [C]^T = [c_1, c_2, c_3, c_4]^T$$

The acceleration ($A$), height of gravity center ($H$), and running velocity ($V$) are defined as the coupled state variable of model 1 built by Adams.

$$y_1 = [A, H, V]^T = [a_f, a_r, h_i, h_1, h_2, h_3, h_4, v_1, v_2, v_3, v_4]^T$$

where $a_f$, $a_r$, $h_i$, and $v_i$ is front lateral acceleration, rear lateral acceleration, the height of the test point of number i, and the velocity of the test point of number i, respectively.

The control forces are the coupled state variable from model 2 to model 1.

$$y_{ji} = y_{2i} = y_2 = [F_c]^T$$

In the same way, the coupled state variable from model 1 to model 3 is defined as below:
\[ \mathbf{y}_{13} = [a_1, h_1, h_2, h_3, h_4] \]

According to the analysis mentioned above, the optimization objectives of Schnabel car, which is not only to take off the deadweight, but also to improve its running stability, are achieved. Finally, the weight of the Schnabel car type D45 is 208t.

5. Conclusion

Because all disciplines in the engineering design process are tightly interrelated and affected by each other, the process requires MDO methodologies that account for multiple fields simultaneously. The environment must be convenient and intuitive for the user, yet it must still integrate distributed resources. In response to these requirements, the computation environment of multidisciplinary design optima based on HLA has been constructed in this paper. The collaboration and interoperation among the 3 disciplines: multi-body dynamic, hydraulics, and control in the case of MDO for the Schnabel car were implemented. Results show that it is feasible to construct the computation environment of MDO based on HLA.

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References


