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Constraint-based conceptual design and automated sensitivity analysis for airship concept studies

Automatische Constraint-Basierte Entwurfs- und Sensitivitätsanalyse im Luftschiffentwurf

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Abstract

A core aspect of systems engineering is the system design based on coupling and sensitivity analyses of submodules which are combined together. If the submodule properties are presented as equations, i.e. as constraints between the module design parameters in symbolic form, knowledge processing techniques by means of graph theoretic methods provide a powerful means for the automatic derivation of the solution path of the conceptual system design equations. The automatic derivation of the solution path simplifies the study of the couplings between system design parameters and helps to automate the desired sensitivity analysis. The integration of constraint-based processing techniques into the conceptual design phase represents therefore a major step towards a useful support tool for systems engineering. An airship concept case study will be used to demonstrate the strategic advantages and the inherent flexibility for conceptual systems design and analysis which can be achieved with such generic constraint processing techniques. Based on the so-called relevance list of the design variables, the approach is even applicable in design cases, where an explicit mathematical model of the constraints is not yet available or analytically known. Furthermore, some theoretical and practical problems associated with the derivation of an automated sensitivity analysis of a conceptual airship are also discussed.

Zusammenfassung

Ein wesentlicher Aspekt des Systems Engineering ist die Kopplungs- und Sensitivitätsanalyse von Systemen, die aus einer Vielzahl von Teilsystemen und Einzelkomponenten aufgebaut sind. Ist das Verhalten der Teilsysteme und/oder der Einzelkomponenten in Form von symbolischen Gleichungen, d.h. in Form von Beschränkungen der Entwurfsvariablen der Komponenten, bekannt, so können mächtige graphentheoretische Methoden der Beschränkungsanalyse in Form von sogenannten Lösungspfadgeneratoren sehr vorteilhaft zum automatischen Zusammenbau und zur automatischen Analyse der Entwurfsgleichungen eingesetzt werden. Die automatische Bestimmung von Lösungspfaden der Entwurfsgleichungen vereinfacht die Analyse der Kopplungen der Entwurfsgrößen und unterstützt die weitgehende Automatisierung der erwünschten Sensitivitätsanalysen. Die Verwendung der Beschränkungsanalyse in der Vorentwurfsphase stellt daher einen wesentlichen Entwicklungsschritt im Hinblick auf ein zukünftiges Softwarewerkzeug für das Systems Engineering dar. Zur Darstellung der Eigenschaften sowie der strategischen Vorteile und der immanenten Flexibilität der Beschränkungsanalyse in der Systemauslegung und -analyse wird das Fallbeispiel des Vorentwurfs eines Luftschiffes verwendet. Aufbauend auf einer Relevanzliste der Einflußgrößen ist die Technik der Beschränkungsanalyse sogar in Entwurfssituationen anwendbar, in der noch keine expliziten analytischen Gleichungen der Einzelkomponenten bekannt oder vorhanden sind und deshalb mit einer Liste von verbalen Bezeichnern gearbeitet werden muß. Die mit der Beschränkungsanalyse einhergehenden theoretischen und praktischen Gegebenheiten werden dazu am Beispiel des Vorentwurfs eines Luftschiffes dargestellt und diskutiert.

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1. Introduction

Systems engineering in aerospace engineering is usually concerned with all aspects of design and is therefore of interdisciplinary nature. Systems engineering is therefore not only confronted with a specific design problem in a particular physical domain such as fluid mechanics, heat transfer, structural mechanics or electronics, but suffers besides these individual design problems from the need to integrate these specialized views into the overall system analysis as well. Furthermore, the different models used throughout the design phase vary significantly in terms of detail and precision. This modeling problem is inherent to system engineering, design analysis and integration and is shown in Fig. 1.

System design as reasoned about by a human design engineer is usually done using an abstract, simplified view of the design object using relatively few design parameters. These parameters involve the geometry (parameters such as width, depth, height, ...) as well as the description of the main physical aspects of the design object (parameters such as power, weight, drag, ...) which make up for the simplified analytical model parameters as shown in the top of the modeling triangle in Fig. 1.

A more detailed study of the design properties usually involves the creation of a more detailed object geometry and of more detailed analytical and numerical models based on multibody system approaches, finite element/boundary element methods or other specialized numerical simulation techniques (e.g. CFD) as shown in Fig. 1.

Fig. 1 emphasizes that despite the fact that (with additional information) the more detailed models can be generated out of the simpler models, the inverse mapping of the detailed design analysis onto the main design parameters is usually not known and may theoretically even not exist because of the different dimensionality in the DOF in the different design models [10,11].

A great deal of the design effort still goes into the task of maintaining the consistency of the various differently detailed and domain-dependent simulation models. Since any geometry change may cause changes in fluid flow, heat transfer and so on, and that changes in physical properties of the design object may require geometry changes respectively, it is clear that an automation of these required model updates may save time and may help to eliminate numerous error sources.

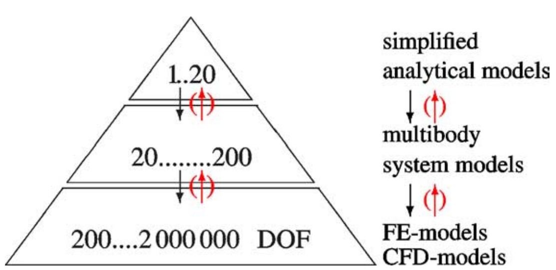

Fig. 1. The coordinates/degrees of freedom (DOF) of different, usually non-invertible models [10,11].

Fig. 2 shows the interference of the different design modules in respect to the system design. Each module may affect a certain design variable or property, and the analysis of the resulting system couplings are central to the understanding of the resulting system behaviour. Successful system design techniques need therefore efficient methods for an automatic model update. Since constraint processing techniques offer such capabilities they are investigated in this context in the following.

Because of its attractiveness for system design multiple efforts have been undertaken in the past to support and automate constraint processing techniques in system design. In 1963 Sutherland [14] pioneered with *Sketchpad* the use of interactive computer graphics and constraint-based design techniques. Gosling [5] conceived a system for simple line drawings with added symbolic mathematical capabilities. The *Edinburgh Designer System* [9] can be viewed as a constraint satisfaction system that integrates several solution techniques. Gross [6] describes a constraint-based system for architectural design. These systems treat design mostly as inequalities and try to deduce the remaining design freedom through techniques of constraint propagation.

This paper presents a constraint processing system for conceptual design which has been developed in the framework of the German Lighter-Than-Air research group FOGL (DFG-Forschergruppe *"Luftschifftechnologie"*) at the University of Stuttgart. As an extension to previous works of the authors [10,15,16], it concentrates on the analysis of the solution paths under the aspect of the constraint origin. To demonstrate the ease of application and the insight gained,

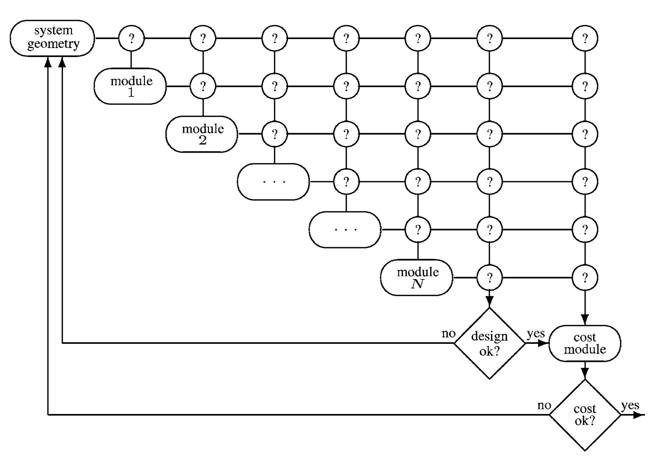

Fig. 2. Coupling problem in system design [10].