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Exact Constraint Design and its potential for Robust Embodiment

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Abstract

The design of exact, also referred to as minimal, constraints means applying just enough constraints between the various components of a mechanical assembly, in order to unambiguously define their positions in six degrees of freedom (3 translations, 3 rotations), their desired motions respectively. To ensure a predictable and reliable product performance, a systematic design of the corresponding elementary mechanical interfaces between components is of utmost importance. Overconstraints, i. e. part-to-part connections with redundant interfaces which constrain one single degree of freedom, are largely susceptible to variation and therefore result in design solutions which frequently experience production/ assembly issues, reduced performance, excessive and non-predictable wear-rates, etc.

Being a basic rule of embodiment design, literature provides various well-know and widely applied approaches for Exact Constraint Design. Examples are the calculation of a mechanisms' mobility using the *Grübler-Kutzbach criterion*, the analysis of statically determinate assemblies by means of the *screw theory* or so called *Schlussartenmatrizen*, as well as the analysis of engaging surfaces in terms of *location schemes* or *interface ambiguity*. However, despite the various existing approaches, workshops with practitioners and academics have shown that the systematic design of optimal constraints appears to be cumbersome for many engineers. Based on an overview of the most relevant approaches for Exact Constraint design, this contribution therefore reviews the challenges experienced by the workshop participants, discusses the necessity of kinematically correct constraints for robustness, and derives an initial prescriptive procedure for a coherent design of constraints throughout the embodiment design phase, which, despite a variety of available approaches, seems to be still missing.

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1. Introduction

Given the ever-increasing quality requirements towards more and more complex products, a systematic and purposeful quality management strategy is of vital importance for manufacturing companies. At the same time, many quality assurance activities focus almost exclusively on the control and the continuous improvement of manufacturing processes. The relevance of less visible upstream costs for quality assurance are in contrast largely neglected [1]. Despite indisputable achievements of quality initiatives, such as Total Quality Management, Lean Manufacturing, or Six Sigma, high safety factors, late and frequent design changes, or excessive inspection activities are consequently still prevalent in industrial practice [2], leading to the impression that:

"Quality issues are frequently mitigated by inefficient products and processes leading to quality at excessive costs."

In light of the above, there is a wide consensus that the widely implemented, production-focused quality management strategies have to be complemented by upstream quality

Nomenclature

EC	Exact Constraint
RD	Robust Design
RDM	Robust Design Methodology
R_x, R_y, R_z	rotational constraints
x, y, z	translational constraints

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efforts [3, 4]. Instead of controlling the compliance of partsand systems only in production, quality has to be systematically designed into products and processes and continuously monitored and optimised based on suitable verification and validation activities during development and ramp up.

Among other quality-oriented design methodologies, this insight has led to the emergence of various Robust Design (RD) principles, methods and tools over the last decades. Originating from the seminal work of Genichi Taguchi in the late 1950s [5], the term *robustness* describes the insensitivity of products or processes to the various sources of variation. Examples are production and assembly tolerances, load scenarios, ambient use conditions, or deterioration of components over time. A corresponding Robust Design Methodology (RDM) consequently aims at designing robust products and processes which perform consistently in spite of these noise factors, and thus an acknowledged way to avoid the inefficiencies of products and processes otherwise necessary to mitigate the resulting variation effects [5, 6].

Despite the potential benefits, the acceptance of RDM in industrial practice is limited though [7]. Traditionally focusing on an improvement of robustness via (computational) expensive virtual/physical experiments and the corresponding statistical analyses, the methodology has been often criticized for not offering enough guidance and support in early design stages [8, 9]. As a result, several contributions have sought to address concept generation aiming at attaining robustness, see for example the overview provided by *Jugulum and Frey* (2007) [9].

However, in the opinion of the authors, these predominant focal points of RD research, on either the earliest design phases or experiments with fully specified solutions/ prototypes at the end of the design process, largely disregard one of the essential facets of Robust Design. Robustness is essentially dependent on the early embodiment of a chosen principle solutions, i. e. on the determination of the general arrangement as well as preliminary shapes and materials of components. Overconstrained designs, ambiguous interfaces between components, unfavourable material combinations, etc. (1) *are largely susceptible to variation* and therefore frequently experience production/ assembly issues, reduced performance and excessive wear-rates. Due to over-complex structures, redundant interfaces between components, these variation effects are furthermore difficult to predict, resulting in a (2) *time and cost intensive, as well as inherently inaccurate variation analysis* during subsequent design verification and robustness optimisation activities.

Building on previous research [10], this contribution therefore aims at creating awareness for this fundamental phase of early embodiment. For this purpose, it discusses the potential of different approaches in the field of Exact Constraint (EC) design for a successful RDM, reviews available EC methods and reflects on their applicability based on a series of conducted RD Workshops.

2. Research Methodology and Outline

While this paper aims at fostering the use of EC design methods and tools for RD purposes, it has to be noted that the importance of optimally constrained mechanical assemblies is hardly new. On the contrary, the systematic design of unambiguously constrained mechanical connections is a basic rule of embodiment design [11], considered an essential task in precision engineering for well over a century [12], and has even been already classified as an essential RD activity by several authors [10, 13, 14]. For this reason, the research approach is twofold. Based on an overview of some of the most relevant contributions in the field of EC design * (*section 3*), the corresponding approaches are put into an initial method sequence based on the underlying model representations (*section 4*). For a first qualitative evaluation of this basic hypothesis, the method sequence is then used during a RD workshop build around the embodiment of a simple consumer product (*section 5*), i. e. a hand-held glue gun for thermoplastic adhesives. Concluding, the challenges faced by the industry delegates during the workshop, the results of this study as well as its implications for future research are summarised (*section 6*).

3. Theoretical Background

3.1. Engineering Design Methodology

Literature on Engineering Design Methodology provides a vast amount of design process models, prescribing a structured procedure for the systematic design of technical systems and products. Referring exemplarily to the explanations in [11], their purpose is to decompose the challenging and usually highly iterative development process into a series of subsequent design phases (e. g. *Task clarification*, *Conceptual Design*, *Embodiment Design*, *Detail Design*), subdivided into single working steps, as well as the corresponding intermediate results in order to reduce the complexity of the development tasks.

While being inherently generic, and hence requiring adaptation to the specific industry branch or development task [11], the corresponding design process models offer a fundamental understanding of the importance of engineering models during development. Basically, engineering models summarise the information about the developed product available in different design phases, and thus provide the basis for an evaluation its characteristics, its behavior, etc. In a coherent methodical design process, they consequently represent intermediate results on different levels of abstraction, which are gradually concretised and detailed towards a full design solution.

At the same time, it is the author's impression that, in spite of various well-described development processes and model

* The paper's main focus is the importance of EC design approaches for Robust Design, not a comprehensive literature survey. Although not claimed to be exhaustive, the chosen set of approaches is considered a good basis for deriving an initial Robust Embodiment Design procedure.