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Internal Examiner Report – Doctoral Thesis

Report due date: Oct 5, 2020

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Degree/Unit: Doctor of Philosophy, Department of Mechanical Engineering

Thesis title: Optimization-driven set-based design for dynamic design requirements

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1. Makes an original contribution to knowledge	◉	○	○	○	○
2. Advances knowledge in the field	○	◉	○	○	○
3. Is situated in a broader context and appropriately acknowledges the larger field of research (e.g., citations/references)	◉	○	○	○	○
4. Details methodology and methods	◉	○	○	○	○
5. Reports results clearly	○	◉	○	○	○
6. Justifies analyses and conclusions	○	◉	○	○	○
7. Discusses implications	○	◉	○	○	○
8. Is presented appropriately for disciplinary norms (grammar, style, coherence, cohesion)	○	◉	○	○	○

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Recommendation	Select ONE
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(Prof. D. Lowther)

Comments on Ph.D. Thesis

"Optimization-driven set-based design for dynamic design requirements"

Khalil Al Handawi

Over the last few decades, computer simulation and modeling of engineering systems has developed to a point where it is possible to simulate a physical device and its performance reasonably accurately. At this point, it is faster to simulate a proposed system than to build the physical prototype and this capability allows the design space to be explored more effectively and faster than was hitherto possible. This has resulted in considerable research effort being addressed to the problem of optimization, since this is one of the main focuses of a design process. This in turn has led to the investigation of design systems capable of multi-physics and multi-objective design. The next step is to add into the systems, the impact of manufacturing technologies on the optimal design and, then, to examine how changes in specifications or requirements and uncertainties in these, which may happen dynamically, can be included. This latter is the subject of this thesis.

The challenge of creating a design in the face of uncertain requirements is significant and any work related to formalizing this process is likely to provide benefits in the overall costs and time taken in the process. The work makes several significant contributions. The first is a contribution to set-based design in terms of both surrogate modeling and optimization and the development of a scalability constraint in the parameter space. The second relates to the creation of a tool for margin quantification – necessary to understand how the device can respond to changing requirements throughout its lifecycle. Several of the concepts and algorithms developed as part of these two contributions are novel.

The work in the thesis is illustrated by the modification of an aeroengine component (the Turbine Rear Structure – TRS) through the use of additive manufacturing.

The thesis is well structured and develops both the main hypotheses and the methodology for proving them in a manner which is both consistent and where each section, or chapter, builds on the previous work. The thesis starts with an introduction to the area of engineering design with a particular emphasis on the product lifetime and the impact on both the initial design and redesign. The main problem being considered is to make design decisions at the early stages of the lifetime which will allow for modifications to the requirements and subsequent design through to the end of life. The literature review provided in Chapter 2 is in depth with over 100 references to elaborate the current state of the art in engineering design support. The literature survey is used to provide an audit of research that has been done and to highlight where there are gaps in the work. It is these gaps where the main thrust of the work in this thesis is directed. Before moving into the main work of the thesis, the third chapter provides the physics background to the example that will be used to test the approaches to design and remanufacture proposed in the following 3 chapters. The work involves multi-physics modeling, in particular thermal and stress, of part of an aeroengine (the TRS) and the process that is used in Direct Energy Deposition for additive manufacturing.

Chapter 4 describes one of the main contributions of the thesis. This is the development of Feasible Sets based on the intersections of constraints within the concepts of Set Based Design. To perform the experimental work, a surrogate modeling system is used to generate a response surface. It is fundamental to the work described in this chapter that the response surface is constructed from differentiable functions – which raises the question of whether this places any restrictions on the surrogates and the effort needed to construct them? The concept of optimal design based on scalability is then discussed and the process is described in Algorithm 1 (the first of 4 algorithms which are considered to be a main contribution of the research). The algorithm might have been a little better described and the variables defined at the start (and this is true of all the algorithms) – for instance, what is the value of "w"? Having obtained a set of optimal designs, the work proceeds to determine the scalability of the set. This is based on considering the volume of the component. This seems to be a limited view of scalability. Admittedly, for the example being considered it is appropriate, but can this be generalized to other properties of the component? Can the region of monotonicity be limited, i.e. for some range of values, monotonicity holds? Equation 4.11 defines designs which are scalable – is this in the sense of AM only? The concepts related to determining the scalable set (and in particular Algorithm 2) are tested, initially on Himmelbau's test function. Why is this a reasonable function to use? It has several minima but is this a good representation of the form of the space where the algorithm is to be applied? The concepts developed within the chapter are applied to the example described in Chapter 3 and the set of scalable designs is determined. The result is significant and demonstrates the effectiveness of the approach. The end result is to construct the convex hull of the scalable set in the design space – while numbers of samples, etc., are given, this seems to be an expensive exercise – what is the computational effort involved? The chapter ends with a statement that seems to place a qualification on the usefulness of the work by stating that robustness could be used to achieve the same effect. If so, then maybe there should have been a comment about when the algorithms developed in the chapter are more appropriate and what are the benefits of the proposed approach.

The work then moves onto approaching robustness through concepts of capability, buffer, excess and reliability in Chapter 5. This work is certainly novel and the descriptions are extremely dense. The concepts of buffer, i.e. capabilities that are not needed in the current set of requirements, and excess (the part of the capability set which is not in the requirements set) seem to be novel and contribute to the concept of robustness in the face of requirements changes. Again, some of the terminology used is a little lax, for example, In equation 5.9, is R' meant to mean "not R"? Also, some of the figures are not totally understandable – for example, Figure 5.2 is meant to show excess but it is not very clear, for instance the excess should be a red hashed area but it doesn't seem to show in the two diagrams – presumably, this is because several areas completely overlap and so obscure some of the results? The text mentions redesign choices and states that they are chosen from a list of available options, but where do these come from? The work relates to design and decision arcs that cover several epochs in the product life. Given the concept of design arcs and that these cover a series of epochs, the goal is to minimize the cumulative excess at the end of the design arc – but at any stage of the process, this means that the cumulative excess may not be minimized. Does this mean that there are times in the product life when the product is "over designed"? Presumably, to do this, the number of epochs needs to be known at the start of the design process – how is this determined? As in Chapter 4, some of the main contributions of this chapter are described in Algorithms 3 and 4 and they are coupled with flow charts that show the process. Again, the algorithms could be clearer – for example in step 4 of Algorithm 3, what does "reducing an optimal decision arc to an optimal decision arc" mean? Also, shouldn't the set S_E be initialized to zero at the start? Also, in Algorithm 4, the set N_R is initialized to zero but the set N_F is not – shouldn't they both be initialized? However, the methodologies developed are applied to the problem described in Chapter 3 with impressive results. The methods seem to be effective but a question that always comes up in computational modeling of processes is, what is the cost? The thesis does not really address the computational cost of the algorithms created but it would have been interesting to see this – is this a process which takes minutes or days to complete?

Finally, Chapter 6 brings in the concept of stochastic optimization as a method for handling uncertainty. This seems to be using more or less off the shelf optimization tools. While the use of stoMADS is illustrated and justified, could any stochastic optimizer have been used? The chapter is quite short and shows the impact of stochastic optimization. It claims that this approach can bypass large parts of Algorithms 1 and 3 – if so, does this lead to a significant speed up in the process. It seems that experiments could have been done in chapter 6 which matched those in chapter 5 to show how the algorithms are more effective and yield similar results.

Finally, the concepts developed are all illustrated on a single problem. It is not clear how well the system generalizes – what is the range of design problems that can be handled here? Can it deal with problems where the solutions might not be additive (or subtractive) manufacturing but where a component might need to be replaced?

Overall, this is a well written thesis. There are several grammatical errors but they could be found quickly with an appropriate grammar tool. In places the descriptions are very dense but the examples based on the model in Chapter 3 are useful.