Combined shape and topology optimization for minimization of maximal von Mises stress

This work shows that a combined shape and topology optimization method can produce optimal 2D designs with minimal stress subject to a volume constraint. The method represents the surface explicitly and discretizes the domain into a simplicial complex which adapts both structural shape and topology. By performing repeated topology and shape optimizations and adaptive mesh updates, we can minimize the maximum von Mises stress using the p-norm stress measure with p-values as high as 30, provided that the stress is calculated with sufficient accuracy.
3D interactive topology optimization on hand-held devices
This educational paper describes the implementation aspects, user interface design considerations and workflow potential of the recently published TopOpt 3D App. The app solves the standard minimum compliance problem in 3D and allows the user to change design settings interactively at any point in time during the optimization. Apart from its educational nature, the app may point towards future ways of performing industrial design. Instead of the usual geometrize, then model and optimize approach, the geometry now automatically adapts to the varying boundary and loading conditions. The app is freely available for iOS at Apple’s App Store and at http://www.topopt.dtu.dk/TopOpt3D for Windows and OSX.

General information
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Combined Shape and Topology Optimization

Shape and topology optimization seeks to compute the optimal shape and topology of a structure such that one or more properties, for example stiffness, balance or volume, are improved. The goal of the thesis is to develop a method for shape and topology optimization which uses the Deformable Simplicial Complex (DSC) method. Consequently, we present a novel method which combines current shape and topology optimization methods. This method represents the surface of the structure explicitly and discretizes the structure into non-overlapping elements, i.e. a simplicial complex. An explicit surface representation usually limits the optimization to minor shape changes. However, the DSC method uses a single explicit representation and still allows for large shape and topology changes. It does so by constantly applying a set of mesh operations during deformations of the structure. Using an explicit instead of an implicit representation gives rise to several advantages including straightforward modeling of the surface, improved scalability and ability to optimize multiple materials.

This dissertation describes the essential parts of the novel method for combined shape and topology optimization. This includes the structural analysis in Chapter 2, the optimization in Chapter 3 and the Deformable Simplicial Complex method in Chapter 4. Finally, four applications of the developed method are presented in the included papers and summarized in Chapter 5.

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Organisations: Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, Department of Mechanical Engineering, Solid Mechanics
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Combined shape and topology optimization of 3D structures
We present a method for automatic generation of 3D models based on shape and topology optimization. The optimization procedure, or model generation process, is initialized by a set of boundary conditions, an objective function, constraints and an initial structure. Using this input, the method will automatically deform and change the topology of the initial structure such that the objective function is optimized subject to the specified constraints and boundary conditions. For example, this tool can be used to improve the stiffness of a structure before printing, reduce the amount of material needed to construct a bridge, or to design functional chairs, tables, etc. which at the same time are visually pleasing.

The structure is represented explicitly by a simplicial complex and deformed by moving surface vertices and relabeling tetrahedra. To ensure a well-formed tetrahedral mesh during these deformations, the Deformable Simplicial Complex method is used. The deformations are based on optimizing the objective, which in this paper will be maximizing stiffness. Furthermore, the optimization procedure will be subject to constraints such as a limit on the amount of material and the difference from the original shape.

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Publication information
Automatic balancing of 3D models

3D printing technologies allow for more diverse shapes than are possible with molds and the cost of making just one single object is negligible compared to traditional production methods. However, not all shapes are suitable for 3D print. One of the remaining costs is therefore human time spent on analyzing and editing a shape in order to ensure that it is fit for production. In this paper, we seek to automate one of these analysis and editing tasks, namely improving the balance
of a model to ensure that it stands. The presented method is based on solving an optimization problem. This problem is solved by creating cavities of air and distributing dense materials inside the model. Consequently, the surface is not deformed. However, printing materials with significantly different densities is often not possible and adding cavities of air is often not enough to make the model balance. Consequently, in these cases, we will apply a rotation of the object which only deforms the shape a little near the base. No user input is required but it is possible to specify manufacturing constraints related to specific 3D print technologies. Several models have successfully been balanced and printed using both polyjet and fused deposition modeling printers.
Combined shape and topology optimization for minimization of von Mises Stress

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Multiphase Image Segmentation Using the Deformable Simplicial Complex Method
The deformable simplicial complex method is a generic method for tracking deformable interfaces. It provides explicit interface representation, topological adaptivity, and multiphase support. As such, the deformable simplicial complex method can readily be used for representing active contours in image segmentation based on deformable models. We show the benefits of using the deformable simplicial complex method for image segmentation by segmenting an image into a known number of segments characterized by distinct mean pixel intensities.

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Organisations: Department of Applied Mathematics and Computer Science, Statistics and Data Analysis, Image Analysis & Computer Graphics
Authors: Dahl, V. A. (Intern), Christiansen, A. N. (Intern), Bærentzen, J. A. (Intern)
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Topology optimization using an explicit interface representation

We introduce the Deformable Simplicial Complex method to topology optimization as a way to represent the interface explicitly yet being able to handle topology changes. Topology changes are handled by a series of mesh operations, which also ensures a well-formed mesh. The same mesh is therefore used for both finite element calculations and shape representation. In addition, the approach unifies shape and topology optimization in a complementary optimization strategy. The shape is optimized on the basis of the gradient-based optimization algorithm MMA whereas holes are introduced using topological derivatives. The presented method is tested on two standard minimum compliance problems which demonstrates that it is both simple to apply, robust and efficient.

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Improving Topology Optimization using Games

Topology optimization has had, and still has, a great impact on the design of structures and mechanical elements. Even though computers and topology optimization algorithms are able to find good solutions to most problems, it is also important for users of such programs to have a good intuition for whether a structure is optimal. We hypothesize that human intuition regarding topology optimization is often led astray. Our goal is to collect data in order to test this hypothesis and at the same time to actively train users (in particular students of mechanical engineering) in designing optimal structures. Consequently, we have created a game, the TopOptGame, which improves the player’s topology optimization intuition in a fun and engaging way while collecting data about the users performance.

Technically, the TopOptGame builds on the TopOptApp [1] - an interactive topology optimization application designed for hand-held devices. The TopOptApp solves the 2D minimum compliance problem with interactive control of loads, supports and volume fraction, and thus the TopOptApp allows the user to change the problem on the y and watch the design evolve to a new optimum in real time. TopOptApp is available free of charge on iOS and Android devices.

The TopOptGame is inspired by puzzle-games (a genre of computer games), which constantly challenges the players and gives rewards when progress is made. This engagement loop will take the player on a journey starting with simple problems with few supports and a single load and gradually increase the difficulty by adding more loads, restrictions on the design domain, distributed loads and multiple load cases. The goal is to distribute material in a discretized design domain, under some volume and time constrains, while searching for a good solution (minimum compliance). A visualization of the strain energy density will help the player finding a feasible solution.

Besides training the player in topology optimization, the game also tracks the progress of each player and sends this progress in anonymized form to a database. When enough data has been collected, this will allow us to analyze the data to measure human performance of topology optimization and more importantly, in which cases people's intuition succeed or fail.

The game is currently a working prototype and is scheduled for final release on both iOS and Android before WCSMO-10.

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Topology Optimization using an Explicit Interface Representation
Current methods for topology optimization primarily represent the interface between solid and void implicitly on fixed grids. In contrast, shape optimization methods represent the interface explicitly, but do not allow for any topological changes to
the structure. Using an explicit interface representation has a number of advantages as described below. Consequently, we propose to use the Deformable Simplicial Complex (DSC) method [1] which represents the interface explicitly as one or more closed piecewise linear curves in 2D.

As opposed to pure shape optimization methods, the DSC method is able to handle topology changes. It does so by discretizing the entire design domain into an irregular adaptive triangle mesh and thereby explicitly representing both the structure and the embedding space. In other words, the entire design domain is divided into triangles, where the interface is represented as piecewise linear curves between void and non-void triangles.

Another advantage of the DSC method is that we can exploit the triangle mesh for the FEM computations used in the optimization procedure. The non-void elements define the structure and their deformation is described by second order shape functions. To increase performance, degrees of freedom associated with void triangles are eliminated from the FE equation. Using the triangle mesh for computations is possible since the DSC method ensures a mesh with no degenerate elements. If the mesh contained degenerate or close to degenerate elements the FEM computations would break down and the results would no longer be valid. The DSC method solves this issue by a series of mesh operations which keeps the mesh ever well-formed. Put another way, the consequence of using a well-formed adaptive mesh is that the representation for the FEM calculations and the shape of the structure can be one and the same.

In addition to unifying calculations and representation of the structure, the approach also unifies shape and topology optimization into a single framework. Furthermore, it combines the two in a simultaneous optimization strategy. Here, the shape is optimized on the basis of the gradient based optimization algorithm Method of Moving Asymptotes whereas holes are introduced using topological derivatives. Since we combine these methods, and since FEM calculations are performed only on non-void triangles and gradients are calculated only for the interface nodes, the presented approach is efficient. An explicit representation is not just useful when considering simplicity and performance. In many cases, the explicitly represented interface is necessary to be able to model a problem. For example for ow or electromagnetic problems with localized boundary effects. Furthermore, control of boundary smoothness is simple to implement and can e.g. be used to control fillet radius at corners. The method also opens up for the opportunity to apply other local constraints, such as min/max length scale of the structure. Finally, the explicit interface is in all cases necessary when interpreting the final design. The status of the work is that the method has been developed and is showing promising results. For instance, the cantilever beam problem has been solved to a high precision using a fine discretization by evaluating the objective function approximately 500 times. This took around 100 seconds on an ordinary laptop utilizing a single thread. In addition, a coarse solution to the same problem has been obtained in approximately 10 seconds.

**Generic information**

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Organisations: Department of Applied Mathematics and Computer Science , Image Analysis & Computer Graphics, Department of Mechanical Engineering, Solid Mechanics

Authors: Christiansen, A. N. (Intern), Nobel-Jørgensen, M. (Intern), Bærentzen, J. A. (Intern), Aage, N. (Intern), Sigmund, O. (Intern)

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**Generic Graph Grammar: A Simple Grammar for Generic Procedural Modelling**

Methods for procedural modelling tend to be designed either for organic objects, which are described well by skeletal structures, or for man-made objects, which are described well by surface primitives. Procedural methods, which allow for modelling of both kinds of objects, are few and usually of greater complexity. Consequently, there is a need for a simple, general method which is capable of generating both types of objects. Generic Graph Grammar has been developed to address this need. The production rules consist of a small set of basic productions which are applied directly onto primitives in a directed cyclic graph. Furthermore, the basic productions are chosen such that Generic Graph Grammar seamlessly combines the capabilities of L-systems to imitate biological growth (to model trees, animals, etc.) and those of split grammars to design structured objects (chairs, houses, etc.). This results in a highly expressive grammar capable of generating a wide range of types of models. Models which consist of skeletal structures or surfaces or any combination of these. Besides generic modelling capabilities, the focus has also been on usability, especially userfriendliness and efficiency. Therefore several steps have been taken to simplify the workflow as well as to make the modelling scheme interactive. As proof of concept, a generic procedural modelling tool based on Generic Graph Grammar has been developed.

**Generic information**

State: Published
Monitoring the change in colour of meat: A comparison of traditional and kernel-based orthogonal transformations

Currently, no objective method exists for estimating the rate of change in the colour of meat. Consequently, the purpose of this work is to develop a procedure capable of monitoring the change in colour of meat over time, environment and ingredients. This provides a useful tool to determine which storage environments and ingredients a manufacturer should add to meat to reduce the rate of change in colour. The procedure consists of taking multi-spectral images of a piece of meat as a function of time, clustering the pixels of these images into categories, including several types of meat, and extracting colour information from each category. The focus has primarily been on achieving an accurate categorisation since this is crucial to develop a useful method. The categorisation is done by applying an orthogonal transformation followed by k-means clustering. The purpose of the orthogonal transformation is to reduce the noise and amount of data while enhancing the difference between the categories. The orthogonal transformations principal components analysis, minimum noise fraction analysis and kernel-based versions of these have been applied to test which produce the most accurate categorisation.
Kernel based pattern analysis methods using eigen-decompositions for reading Icelandic sagas

We want to test the applicability of kernel based eigen-decomposition methods, compared to the traditional eigen-decomposition methods. We have implemented and tested three kernel based methods methods, namely PCA, MAF and MNF, all using a Gaussian kernel. We tested the methods on a multispectral image of a page in the book ‘hauksbok’, which contains Icelandic sagas.

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Organisations: Image Analysis and Computer Graphics, Department of Informatics and Mathematical Modeling
Authors: Christiansen, A. N. (Intern), Carstensen, J. M. (Intern)
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Multi spectral imaging analysis for meat spoilage discrimination

In the present study, fresh beef fillets were purchased from a local butcher shop and stored aerobically and in modified atmosphere packaging (MAP, CO2 40%/O2 30%/N2 30%) at six different temperatures (0, 4, 8, 12, 16 and 20°C). Microbiological analysis in terms of total viable counts (TVC) was performed in parallel with videometer image snapshots and sensory analysis. Odour and colour characteristics of meat were determined by a test panel and attributed into three pre-characterized quality classes, namely Fresh, Semi Fresh and Spoiled during the days of its shelf life. So far, different microbiological and (bio)chemical methods are employed to assess meat spoilage, the majority of which are slow, time-consuming and expensive procedures and thus, it would be most preferable to be replaced by faster and directly applicable methods. Therefore developing a procedure by associating image data with corresponding sensory data would be of great interest. The purpose of this research was to produce a method capable of quantifying and/or predicting the spoilage status (e.g. express in TVC counts as well as on sensory evaluation) using a multi spectral image of a meat sample and thereby avoid any time-consuming microbiological tests. To accomplish this, first the images were converted into values that were comparable to the corresponding data, using the Minimum Noise Fraction (MNF) transformation and simple thresholding. Moreover, association of image data with sensory data was undergone using three different classification methods: Naive Bayes Classifier as a reference model, Canonical Discriminant Analysis (CDA) and Support Vector Classification (SVC). As the final step, generalization of the models was performed using k-fold validation (k=10). Results showed that image analysis provided good discrimination of meat samples regarding the spoilage process as evaluated from sensory as well as from microbiological data. The support vector classification (SVC) model outperformed other models. Specifically, the misclassification error rate (MER), derived from odour characteristics, was 18% for both aerobic and MAP meat samples. In the case where all data were taken together the misclassification error amounted to 16%. When spoilage status was based on visual sensory data, the model produced a MER of 22% for the combined dataset. These results suggest that it is feasible to employ a multi spectral image for the quantitative determination of meat spoilage status during storage in different conditions.

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Organisations: Image Analysis and Computer Graphics, Department of Informatics and Mathematical Modeling, Agricultural University of Athens, National Agricultural Research Foundation
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Kernel based eigenvalue-decomposition methods for analysing ham

Every consumer wants fresh ham and the way we decide whether the meat is fresh or not is by looking at the color. The producers of ham want a long shelf life, meaning they want the ham to look fresh for a long time. The Danish company Danisco is therefore trying to develop optimal storing conditions and finding useful additives to hinder the color to change rapidly. To be able to prove which methods of storing and additives work, Danisco wants to monitor the development of the color of meat in a slice of ham as a function of time, environment and ingredients. We have chosen to use multispectral images to monitor the change in color. We therefore have to be able to segment the ham into the different categories of which the ham consists. These categories include fat, gristle and two different types of meat. This segmentation is difficult when using the traditional orthogonal transformation methods, such as PCA, MAF or MNF. We therefore investigated the applicability of kernel based versions of these transformation. This meant implementing the kernel based methods and developing new theory, since kernel based MAF and MNF is not described in the literature yet.

The traditional methods only have two factors that are useful for segmentation and none of them can be used to segment the two types of meat. The kernel based methods have a lot of useful factors and they are able to capture the subtle differences in the images. This is illustrated in Figure 1. You can see a comparison of the most useful factor of PCA and kernel based PCA respectively in Figure 2. The factor of the kernel based PCA turned out to be able to segment the two types of meat and in general that factor is much more distinct, compared to the traditional factor. After the orthogonal transformation a simple thresholding is enough to segment the ham and to detect the color of a type of meat can be done by averaging the pixels that is categorised as that type of meat. Graphs of the change of color in ham as well as more images of the segmentation is included in the article found on www.student.dtu.dk/~s062211/.

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Projects:

Geometrical Design Representations for Topology Optimization
Technical University of Denmark
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Phd Student:
Christiansen, Asger Nyman (Intern)
Supervisor:
Krzysztof Misztal, Marek (Ekstern)
Sigmund, Ole (Intern)
Main Supervisor:
Bærentzen, Jakob Andreas (Intern)
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Dahl, Anders Bjorholm (Ekstern)
Maute, Kurt (Ekstern)
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