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Genetic Algorithm as a New Design Tool for MEMS Devices with Freeform Geometries

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Abstract

The vast majority of micro-electro-mechanical systems (MEMS) devices rely in their mechanical design on very simple geometrical layouts comprising only a few primitives such as beams, rectangular masses and – more rarely – rings or disk-shaped structures. The beams and rectangular structures are typically combined in a Manhattan grid structure to form a suspension system, resonating structures, the proof mass of inertial sensors, comb drives, pick-off capacitive electrodes, etc. However, practically all MEMS devices having movable structures (physical sensors such as inertial sensors, force sensors, pressure sensors, actuators, as well as biochemical sensors based on resonators or beams exhibiting stress induced static deflections) are compliant devices. In other words, they don't rely on linear or rotational joints as commonly used in macroscopic mechanical designs. However, for compliant devices, orthogonal designs based only on the combination of rectangles may not be the best design approach. Depending on the parameter of interest for a particular device, much more complex geometrical shapes may result in superior performance. Parameters to be maximized could be the deflection of a proof mass in response to an input (e.g. inertial) force, the linear travel range of an electrostatic actuator for a given input voltage, the force in response to an electrostatic drive (e.g. for a micro-gripper), the pull-in voltage, the linearity of a mechanical suspension system, etc. Such a design approach requires substantially higher degrees of freedom for the shapes of the mechanical geometry, rather than restricting it to very few simple primitives. Using simple geometrical shapes is a reminiscence of early MEMS design: the designer had to intuitively understand the design and being able to model it analytically using linear approximations. With modern design tools such as MEMS+, this requirement is no longer a limiting constraint, as these tools can predict the behavior (including nonlinear effects) of virtually arbitrarily complex shapes and designs by multi-physics FEM (finite element modelling) simulations. This offers the exciting possibility for geometrical shape optimization for certain goal parameters for a wide range of MEMS devices.

The presented work aims to introduce a novel and powerful design methodology for a wide range of MEMS devices relying on compliant mechanism. The proposed optimization relies on a GA that has already been successfully employed for optimizing the electronic parameters of closed-loop, electro-mechanical sigma-delta modulator control systems for inertial sensors. The primary objective of this thesis is to apply, for

the first time, a GA to MEMS devices for freeform geometries. The GA based algorithm running within MEMS+ is capable of quickly and efficiently designing high performance, near optimal freeform compliant mechanisms for many MEMS devices. The semi-automated design procedure is expected to result in rather unusual geometrical shapes that have not been seen in MEMS designs to date and is therefore likely to establish an entirely new research area for MEMS. It is expected that important performance indicators for many MEMS devices will be substantially improved.

In the thesis, firstly, a the novel, semi-automated design methodology based on a genetic algorithm (GA) using freeform geometries for MEMS devices is introduced. A detailed description of the optimization process is presented including, mechanical model building, figure of merit, robustness analysis.

As a first demonstrostator, a MEMS a MEMS accelerometer comprising a mechanical motion amplifier, is presented to validate the effectiveness of the design approach. Experimental results show an improvement of the product of sensitivity and bandwidth by 100% and a sensitivity improvement by 141% compared to a device designed in a conventional way. Furthermore, excellent immunities to fabrication tolerance and parameter mismatch were achieved.

As a second demonstrator an actuator, specifically a MEMS microgripper, is designed with this novel methodology. The use of freeform geometries significantly improved the performance of the microgripper. Experimental data shows that the designed microgripper has a large displacement (91.5 μm) with a low actuation voltage (47.5 V), which agrees well with theoretical and simulation results. The microgripper has a large actuation displacement and can handle micro-objects with a size from 10 μm to 100 μm. A grasping experiment on human hair with a diameter of 77 μm was performed to prove the functionality of the gripper. The result confirmed the superior performance of the new design methodology enabling freeform geometries.

Dissertation organization

This thesis is split into six chapters discussing the novel, semi-automated design methodology for a wide range of MEMS devices comprising freeform geometries. The chapters discuss the general design and optimization methodology for compliant structures. Two MEMS devices are designed by this method to demonstrate the effectiveness of the design approach. Experimental data of the fabricated devices are presented with the analysis of the optimization results. A brief overview of the different chapters is provided below.

In Chapter 1, the background of MEMS devices, motivation as well as thesis organization are introduced.

In Chapter 2, the detailed introduction of the optimization in different design level is presented including, system-level, device-level, mask synthesis, robustness as well as optimization efficiency. Different optimization algorithms for designing MEMS devices are also discussed, including gradient-based optimization algorithm, topology optimization (TO) algorithm, genetic algorithm (GA). In contrast to the gradient-based method, a GA can perform a global search. Compared to a TO, a GA has many advantages. For example, a GA is a MMO method, satisfying the multiple objects of MEMS designs. Furthermore, design feasibility does not have to be checked by frequent manual intervention as in TO, since implementing constraints of the fabrication is much more straight-forward in a GA. Thus, it will generate only design solutions that are feasible. Thus, among these optimization approaches, a GA is capable of solving multi-objective problems and gains better performance for searching global optimum solutions. GA is selected to develop a novel, semi-automated design methodology in Chapter 3.

In Chapter 3, a novel, semi-automated design methodology based on a GA using freeform geometries for MEMS devices is described. The general design and optimization principle of the novel design methodology is explained. Detailed introduction of the optimization process is presented including, mechanical model building, figure of merit (FOM), robustness analysis. The GA based algorithm running within MEMS+ is capable of quickly and efficiently designing high performance, near optimal compliant mechanisms for many MEMS devices. The semi-automated design procedure is expected to result in rather unusual geometrical shapes that have not been seen in MEMS designs to date and is therefore likely to establish an entirely new research area for MEMS.

In Chapter 4, the effectiveness of this design approach is verified by the optimization of a MEMS sensor, i.e. a MEMS accelerometer comprising a mechanical motion pre-amplifier. The proposed design methodology greatly expedites the design process and gives much confidence that the results are both optimal and robust against fabrication tolerances. Detailed explanation is given in terms of mechanical model, FOM, optimization process as well as robustness analysis. This chapter also delves into the analysis of the optimization results and convergence. Finally, the fabrication process and experimental result are presented which includes sensitivity, linearity, frequency response as well as noise floor. The experimental performance of different designs are compared to prove the effectiveness of the design approach. Experimental results show an improvement of the product of sensitivity and bandwidth by 100% and a sensitivity improvement by 141% compared to a device designed in a conventional way. Furthermore, excellent immunities to fabrication tolerance and parameter mismatch are achieved. The result confirms the superior performance of the new design methodology enabling freeform geometries.

In Chapter 5, the effectiveness of this design approach is further verified by the optimization of a MEMS actuator, i.e. a microgripper with freeform geometries. Two types of microgrippers with freeform geometries and one microgripper with orthogonal geometries are optimized by this method. FEA simulations are used to analyze the static and dynamic performance as well as the stress distribution of the designed microgrippers. Detailed theoretical analysis and experimental validation are conducted. A manipulation experiment using the designed microgripper for grasping a human hair is shown. Moreover, the pull-in effect in the electrostatically actuated microgrippers is also discussed. The experiment shows that the microgripper with freeform geometries has a large displacement (91.5 μm) for a low actuation voltage (47.5 V), which agrees well with the theory. This makes it possible to manipulate a wide range of objects (size ranging from 10 μm to 100 μm). The concept is successfully demonstrated by grasping a human hair with a diameter of 77 μm. Under the same actuation voltage, microgrippers with freeform geometries improves displacement by 150-200% compared with orthogonal geometries in the same die area. Thus, freeform geometries have two advantages i) higher energy efficiency (lower actuation power to reach the same displacement), ii) less harm to fragile subjects during gripping and releasing. Compared with two of the best electrostatic microgrippers in the literature (in terms of actuation ability or range), the microgrippers with freeform geometries developed in this work have a larger gripping range. The result further confirms the superior performance of the new design methodology enabling freeform geometries.

In Chapter 6, it presents conclusions and a summary of future work that can be carried out to improve many other MEMS devices with this method. It suggests future work should include the further investigation of the convergence and parallel computation of this design method. Besides, the current design method only includes parameters in the mechanical domain. The inclusion of parameters from other physical domains (such as thermal and electronic domains) will further demonstrate the strength and universality of this design method. Moreover, currently, the mechanical and electronic parts of MEMS devices are designed separately. Little attention is being paid to optimizing the interaction between these two domains. The development of a suitable tool that implements and demonstrates such a unified optimization approach will facilitate the MEMS design process flow at the system level.