Optimization of a Micro Fluidic Component Using a Parallel Evolutionary Algorithm and Simulation Based on Discrete Element Methods

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Abstract

In most cases, application of the powerful evolutionary optimizing method is limited to tasks which can manage with short simulation runtimes, e.g. less than one minute. More precise simulations like discrete element methods require much more time of up to 20 minutes and more. This can be solved by a parallelization of the optimization process. The parallel version of our optimization tool GADO (Genetic Algorithm for Design Optimization) based on structured populations scales linearly with the number of involved processors and, thus, enables us to handle optimization based on time-consuming simulation.

This paper introduces the parallelization in brief and describes the optimization task. The micro fluidic component is a micro structured polymeric film of 80 μm thickness, which works as an actuator plate and can be used e.g. for tactile arrays. By varying the structures of the film, the mechanical behavior can be affected. The main optimization goals are a great deflection at a given working pressure and a limited tension of the film in order to achieve a long life time of the device. This is a highly multimodal problem and it requires chromosomes of dynamic length, as the optimal number of structures is one of the optimization parameters and itself depends on the geometry of the structures on hand.

The obtained results are very promising and show that manual designs can be outdone in both performance and durability.

1 Introduction

Industrial application of micro systems requires short development times as well as reliable designs of high quality comparable to the state of the art in micro electronics. This means that two goals must be achieved: A (nearly) optimal design and the reduction of the time-consuming and material-consuming production of specimens. Advanced simulation and optimization techniques are therefore key methods for the successful introduction of new micro products to the market. As optimization usually requires more or less short simulation times, behavioral models which are fast, but often less exact have been used up to now in most cases. It was the goal of the work presented here to combine simulation based on the more precise discrete element methods (here in particular on FEM) and global optimization. As one FEM simulation run requires between five and ten minutes and global optimization needs some thousand evaluations, either very fast and expensive super computers are needed or the work load is parallelized and put on some common work-stations in order to obtain results within a reasonable period of time.

Another challenge of the optimization task, described in detail in section 3 is the variable number of the parameters to be optimized. Most optimization procedures like the Rosenbrock algorithm [1] or the COMPLEX [2] method are not applicable. Most implementations of Evolutionary Algorithms (EA) are also based on fixed parameter numbers, although this is not a restriction of the method itself. Our optimization tool GADO tailored to the needs of design optimization [3,4] is based on GLEAM (General Learning Evolutionary Algorithm and Method, formerly Genetic Learning Algorithm and Method) introduced by Blume [5], a procedure which was designed to handle problems of dynamic parameter space, as needed for some of the early applications [5, 6, 7]. As there is also an experimental parallel version available [8], it was decided to apply this parallel version of GADO to the design optimization task of the micro fluidic component described later.

2 Parallel Evolutionary Design Optimization

GLEAM can be considered as some sort of hybridization, as it combines data modeling from computer science with Genetic Algorithms (GA) [9] and the Evolution Strategy (ES) [10]. This concerns the gene representation as well as the genetic operators as outlined in the next section. Based on this, the parallelization method and its properties are described.

2.1 Gene Representation of GLEAM and Genetic Operators

A chromosome consists of genes which can be of different type and each gene type has its own set of real, integer or Boolean parameters. At present, there are three chromosome types available: Fixed-length chromosomes with relevant gene order, the same with irrelevant gene order, and chromosomes of dynamic length and relevant gene order, where each type can occur in any number, including zero. This provides the user with a very flexible mechanism of natural mapping of his problem to the chromosomes and genes, often resulting in genotypes, from which phenotypic properties can be derived easily. Thus, all problems known from traditional GAs, which arise with binary representations and the blind work of genetic operators, which sometimes yields in illegal solutions, are avoided.

As the type definition of genes includes the interval definitions of the parameters a set of generally applicable genetic operators taking into account explicit restrictions, was implemented. In addition to this problem-specific genetic operators can be added easily to the set of general ones, if desired. The relative mutation operator which is inspired by the ES causes small changes with a higher probability than larger ones, whereby the likeliness of an enlargement is equal to that of a reduction. But in contrast to ES, there are no strategy parameters for mutation included in the chromosome. Mutation is treated in a more general way as common to GAs or ES: Parameters or complete genes may be substituted by newly generated ones and in case of relevant gene order, genes may be moved. For dynamic chromosomes it is also possible to delete or replicate genes. Additionally, there are evolvable substructures within a gene, the so-called segments. They are subject to some sort of macro mutation like altering some parameters of all genes belonging to a segment, inversion of the gene order within a segment or displacement, deletion or duplication of a segment. The altering of segment boundaries or the merging of segments is also possible. Segments form the basis of crossover operators which are similar to those of traditional GAs: There are single and n-point crossover operators working on segment boundaries.

2.2 The Concept of Structured Populations

In biological populations mate selection is done with respect to some sort of neighborhood. This neighborhood can be viewed as the set of individuals a particular individual is in contact with. In contrast to this many EAs implement a panmictic population model, i.e. mate selection is based on the entire population. This allows fast spreading of the gene information and, thus, the best individual can dominate the complete population relatively easily leading to premature convergence. To avoid this and maintain diversity for a longer time, the concept of structured populations was introduced by Gorges-Schleuter [11]. The individuals are placed on a

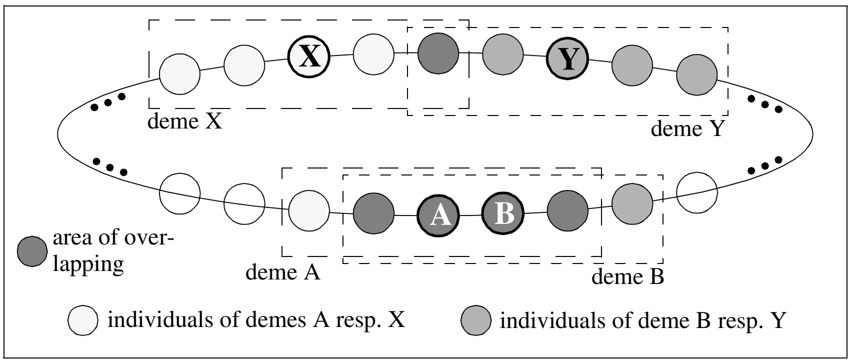

Figure 1: Two examples for overlapping demes: minimal overlapping at the top and maximal below

ring and each one has its neighbors on the right and on the left, called demes, as shown in Fig. 1. The demes of nearby individuals overlap, depending on the distance between the individuals defining the deme. Now, information can spread only via the areas of deme overlapping and, as a consequence, niches of comparable good content establish. This process is much more likely as with panmictic populations. After a certain amount of time, i.e. generations, the niches begin to merge and the competition between the best approaches to the solution begins. For multimodal problems, and most practical problems are of this type, this is the procedure of choice, because more different areas of the search space are investigated.

2.3 Parallel GLEAM

The deme concept has another effect: Information exchange and control are accomplished only within the borders of a deme, no global knowledge is needed to perform evolution as with panmictic populations. Thus, the evolution can be viewed as a parallel process of all individuals needing only information of the respective deme members. This implies a natural parallelization of the Evolutionary Algorithm: A master initializes and globally supervises the workers, who conduct the evolution of at least one individual. Synchronization between the workers is performed only when a generated offspring is accepted and the information of the updated individual is sent to the workers holding its deme members. This asynchronous behavior can cope with workers of different speed. It plays no role, whether these differences come from varying simulation runtimes due to different parameter settings or from varying computer hardware. As our parallel GLEAM is based on the PVM (parallel virtual machine) software package, we can use it in our LAN of different Sun workstations as long as each workstation is equipped with enough memory to perform the FEM calculations without too much swapping. If homogenous work processors are used and evaluation times are independent of the actual parameters, a linear speed-up of the overall performance with an increasing number of processors can be achieved [11,12]. This means that the communication overhead can be discarded for this type of parallelization.

3 Design of an Actuator Plate

Within the framework of the OMID joint project (1999 - 2002) funded by the BMBF (Federal Ministry for Education and Research), a fluidically driven actuator plate is being developed in cooperation with the project partners of Bartels Mikrotechnik GmbH and SIMEC GmbH. This actuator plate is to be applied as an integral component of a fluidic microsystem for the conversion of fluidic energy into mechanical energy.

The actuator plate is based on the use of a thin plastic foil (about 60 to 12 µm) which is microstructured using an excimer laser, see Fig 2. This method of laser structurization has been further developed by Bartels Mikrotechnik GmbH for use in various materials. Microstructurization is employed to specifically influence the mechanical deflec-tion behavior of the actuator plate. The design objective among others is to reach a maximum deflection of the actuator plate at a given operating pressure. At the same time, the actuator plate is to have a long service life, i.e. it must be resistant against frequent load cycles and external mechanical impacts. The latter is achieved not only by using a suitable material, but also by applying an appropriate geometry.

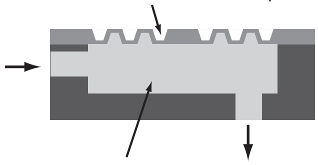

Figure 2: Schematic representation of the actuator plate

For the Ansys FEM tool, a parametrizable FEM model of the actuator plate has been generated for calculating the static structural behavior at a given uniform pressure load [13]. Due to its rotational symmetry, the FEM model is set up two-dimensionally. The FEM model is able to perform batch jobs, i.e. when giving a parameter vector the complete FEM simulation is performed in a fully automatic manner. This is a major prerequisite for the performance of comprehensive parameter studies or computer-aided optimizations [14,15]. Besides the basic parameters, e.g. radius and thickness of the actuator plate, the parameter vector contains an own parameter set for each notch, which describes the location, position, width, height, and wall angle of the notch. The number of notches is not specified in the FEM model. Consequently, the length of the parameter vector is determined by the number of notches. The results obtained by FEM simulation include among others the deflection of the actuator plate and the maximum Von-Mises stress that occurs locally in the structure under load. The maximum Von-Mises stress allows a statement to be made with regard to the mechanical load of the actuator plate.

A first manual design of a structured actuator plate was supplied by the Bartels Mikrotechnik company (see Fig. 3). This design contains four upper and three lower notches that are arranged such that the actuator plate has a meandering shape when presented in a sectional view. Similar to a bellows, this meandering shape is ex-pected to yield good properties in terms of the achievable deflection at a given oper-ating pressure. The pressure is applied from below to the entire surface of the actua-tor plate. Evaluation, i.e. non-linear static structural analysis, including automatic geometry modeling, meshing, and post-processing of the simulation results, takes about 3 to 10 minutes on a Sun workstation.

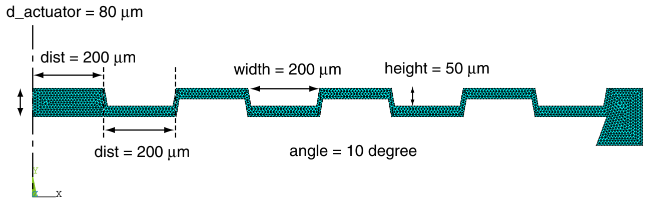

Figure 3: First manual design of the actuator plate as FEM model

Table 1 presents the deflections calculated for various actuator plates. The manually designed actuator plate shown in Fig. 3 reaches a deflection of 104.1 µm at an operating pressure of 100 hPa. Increase in the notch height to 60 µm yields a deflection improved by more than 150%. For comparison, the Table also gives the deflection of an unstructured actuator plate at the same actuator plate thickness of d_actuator = 80 µm. Obviously, the increase in the deflection of structured actuator plates is not only caused by the reduction of the wall thickness by the notches. This is shown by the comparison with the deflection of the unstructured actuator plate of d_actuator = 20 µm in thickness. This is the smallest wall thickness occurring in the modified design of the actuator plate.

Table 1. Simulated deflection of actuator plates (Young's modulus = 1 GPa, pressure = 100 hPa)

Actuator Plate	**Deflection (µm)**
Manual design	104.1
Mod. manual design (height = 60 µm)	160.3
Unstructured actuator plate (d_actuator = 80 µm)	23.1
Unstructured actuator plate (d_actuator = 80 µm)	95.5

As mentioned above, use of the FEM among others is aimed at finding an approprate structurization of the actuator plate, by means of which a maximum deflection is reached at a given operating pressure. In spite of manufacturing-inherent and matrial-related restrictions, the method used for manufacturing the actuator plate allows for a considerable variety of actuator plate designs in terms of structurization. When optimizing the actuator plate structure, the search space therefore is rather large. Therefore, specific search for an optimum structurization can hardly be accomplished without a good knowledge of structural mechanics and without the experience required. On the other hand, a systematic search, if performed at all, takes considerable time.

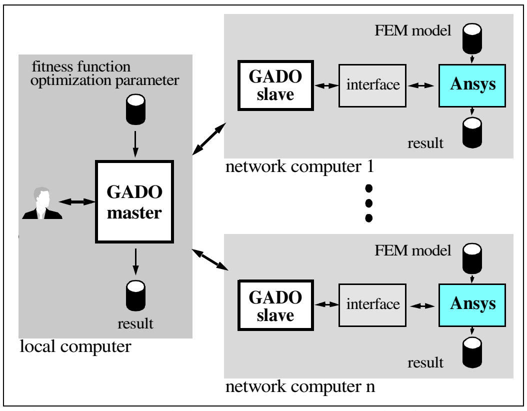

Figure 4:Parallel GLEAM coupled with Ansys

The problem of optimizing the actuator plate is characterized by a number of features. The optimization problem does not only include the optimization of a fixed number of geometry parameters, but also a topological optimization that takes place via the number and arrangement of notches. This means that the optimization problem leads to a parameter vector of dynamic length in combination with a high parameter number. In addition, the solution space is multimodal as a result of the discrete number of notches. Due to the variability of topology, use of FEM models is indispensable when solving the optimization problem. Here, a GADO version based on Parallel GLEAM is applied (see Fig. 4). It fulfils all necessary requirements. As the optimization is distributed over several network computers, average duration of a FEM simulation can be reduced considerably. GADO and Ansys are coupled via a special interface program, by means of which the FEM simulation flow is controlled and the data are processed. Another important task of the interface program consists in the plausibility check of the parameter vectors supplied by GADO. It is checked whether notches are covered, ranges are exceeded or whether given restrictions are violated. If a parameter vector is not found to be plausible, the simulator is not even started. Instead, a value depending on the plausibility error is returned to GADO. In GADO this value is taken into account when assessing an evaluation. Thus, GADO is rapidly moved from out of unpermissible parameter spaces even at the beginning of an optimization.

Based on the structural mechanics FEM model, first optimization runs were performed taking into account various manufacturing and material-relevant boundary conditions. The result of such an optimization run is represented below.

4 Optimization Results

The optimization run presented here was carried out over a weekend and took a total of two days and 17 hours. In addition to the local computer, a total of six network workstations were involved in optimization. Evolution ran over 189 generations with several thousand parameter vectors being generated. As evaluation criteria, the deflection of the actuator plate and the maximum Von-Mises stress as well as the plausibility error were used. Optimization was carried out under the boundary conditions of a maximum permissible aspect ratio of 4:1 of the structures as well as a minimum wall thickness of 20 µm. Among the other parameters given were the Young's modulus, the operating pressure, the actuator plate radius, the wall angle, and a maximum notch width. The optimization parameters included the actuator plate thickness, the width, position, and location of the notches, and the notch height for all notches. As a result of the optimization under the boundary conditions mentioned above, an actuator plate with two notches and a plate thickness of 100 µm was obtained, see Fig. 5.

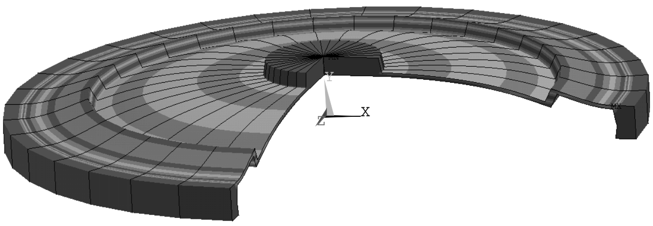

Figure 5: Actuator plate optimized by GADO

Compared to the manually designed actuator plate, the optimized actuator plate reaches a deflection which is more than twice as high, see Table 2. As compared to the modified design, the optimized actuator plate still represents an improvement by 40 %.

Table 2. Simulated deflection of the optimized actuator plate (Young's modulus = 1 GPa, pressure = 100 hPa)

Actuator Plate	**Deflection (µm)**
Manual design	104.1
Optimized design	160.3

Having a closer look at the optimized actuator plate, it becomes obvious that the given restriction margins have already been exhausted quite well by optimization. Among others, the notches are characterized by a very high packing density. Moreover, the range up to the upper limit of notch height has been utilized completely by both notches. Evaluation of several optimization runs indicates that a high packing density of the notches is a major prerequisite for an optimum actuator plate.

However, a higher packing density of notches also is associated with a significantly increased probability of leaving the permissible parameter space when parameters vary due to an associated notch coverage. As a consequence, the stagnation tendency increases in the course of an optimization run with an associated increase in notch packing density. Hence, the optimizer's risk of getting stuck in a sub-optimum grows.

5 A New Concept of Parallelization

Up to this optimization task, the experimental parallel GLEAM version was used to study effects of the parallelization itself, like different deme sizes or topologies other than a ring, e.g. a mesh. Simulation times were short and overall runtimes were about 2 or 3 hours at the maximum. The application on hand requires runtimes of more than half a day, better a few days. This makes the process much more sensitive to errors and hardware failures. If a worker process dies for whatever reason, its subpopulation dies with it, except for those individuals, of which copies exist on neighbored workers, as they belong to demes that are spread over more than one worker.

To overcome this situation, a new concept of parallelization was developed. The old concept based on demes is very well suited for applications where the runtime is more or less balanced between evolution and evaluation and both are considerably fast. But for design optimization this is not typical, as simulation runtimes are much more time-consuming than the related calculations for the evolution. This holds already for behavioral simulation models with simulation times of some seconds or more, which require about 100 times more runtime than the evolution, and it is even more true for FEM simulations. Thus, it was decided to put the evolution process on one computer and parallelize the simulation runs. A supervisor process controls the workers and feeds them with simulation jobs. This process only needs to know how many workers are involved and what their state is. As simulation is slow, the data exchange required for results and new jobs takes place at such a low rate that the communication overhead of this centralized approach can be neglected. The advantage is its robustness to failures: If a worker dies, the aborted simulation is simply repeated, but no data loss takes place. The implementation of this new approach is under way.

6 Conclusions

Our parallel GLEAM, together with its capacity to work with parameter vectors of dynamic length, allowed to successfully apply a global search strategy in combination with time-consuming FEM simulations.
Although an excellent result was obtained from the optimization run presented, existence of actuator plates with significantly better properties cannot be excluded. For this reason, additional runs with a further developed parallel version of GLEAM will be carried out.

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