An Automatic Pareto Classifier for the Multiobjective Optimization of an Electrostimulative Acetabular Revision System

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***Abstract*—In this paper, we present a Pareto classifier for a multiobjective evolutionary algorithm used to optimize the numerical model of an electrostimulative acetabular revision system. This classifier is based on the Hyper-Radial Visualization (HRV) method and enables us to automatically choose the most efficient stimulation electrode arrangement from a Pareto amount of optimal solutions to treat the pelvic bone after a hip revision surgery. It is based on two criteria: the average performance concerning all optimization goals and the general strength of trade-offs in each goal function to achieve this performance.**

***Index Terms*—Electrical stimulation, Numerical simulation, Optimization, Pareto analysis**

I. Introduction

In our prior works we introduced the numerical model of a total hip revision system which applies electric fields on the pelvic bone to enhance its growth [1]. This is based on the works of Bassett et al. [2] who characterized the accelerating effect of electromagnetic fields on osseous cells. In specific we use the method of Kraus [3] who applied a low-frequency electromagnetic field to successfully treat fractures. By this way it is also possible to use an inductively coupled system to transfer energy to an arrangement of stimulation electrodes on an implant for the pelvic bone as shown in Fig. 1. Since in practice each electrode has to be placed during the surgery, the number of stimulation electrodes is limited. For this reason our main focus is at the optimal positioning of the stimulation electrodes on the acetabular cup of the revision implant.

During the optimization different, partly contradictive optimization goals have to be reached. The solution of one optimization is represented by a Pareto amount of electrode arrangements from which one arrangement can be chosen. The more goals we have, the more difficult the choice. For this reason we implemented the Hyper-Radial Visualization (HRV) method to work as an automatic Pareto classifier.

II. Methods

A. Simulation and Optimization

Our approach consists of two parts: the simulation and the optimization. For the simulation we use the Finite-Integration-Technique program CST EM Studio® to compute the electric field within a CAD-model of the pelvic bone including the implant and one stimulation electrode. The simulation is done for each possible electrode position and the electric fields in the area of interest are saved to file.

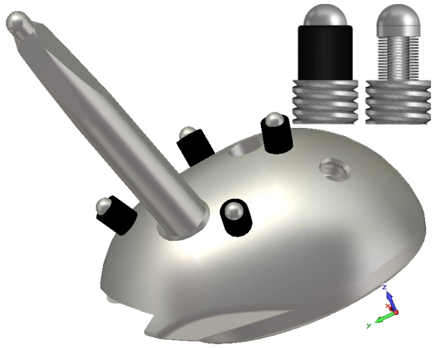

Figure 1: The simulation model of the acetabular cup including anchorage cone and four stimulation electrodes.

The optimization is done for three to six electrodes using a multidimensional evolutionary algorithm which is based on the superposition of these electric fields. A multitude of optimization goals can be defined as electric field strengths that have to be reached at different areas of the bone. Thus the stimulation system can be enabled to especially treat certain defects of the pelvic bone and to provide fixation stability of the revision implant. The results of the optimization form a Pareto amount that can be depicted within a solution space as long as there are only two or three optimization goals. With more goal functions a visualization of the available alternatives as well as an ideal manual selection of one electrode arrangement is quite difficult. According to experience, the number of these optimization goals varies between two and six.

In recent works, we introduced a multi-model optimization method, which enables us to optimize one arrangement for numerous pelvic bones by combining the optimization goals of all the models [4]. This has the practical background that a limited set of various acetabular cups shall cover all possible defects. Consequently, the number of optimization goals increases exponentially and a proper visualization of the solution space as well as selection of one solution cannot be done manually. For this reason we included an automatic Pareto classifier which returns one arrangement basing on the best average achievement of all optimization goals and the least trade-offs to reach these goals. It is based on the Hyper-Radial Visualization method as described by Chiu and Bloebaum [5].

B. The Hyper-Radial Visualization method

Since every goal functions (F) can have different values (i.e. 5 V/m, 70 V/m) at first a normalization is done so that they lie between 0 and 1 using (1). This also enables us to give objective functions with different units in future works. Equation (2) calculates the so-called hyper-radius (r) of each data point, where (n) is the dimension of our optimization respectively the total number of optimization goals. The smaller the hyper-radius, the closer the distance of the solution to the so-called "Utopia Point" at the origin of the multi-dimensional coordinate system.

$$\tilde{F}_i = \frac{F_i - F_{imin}}{F_{imax} - F_{imin}} \tag{1}$$

$$r = \sqrt{\frac{\sum_{i=1}^{n} \tilde{F}_i^{\,2}}{n}} \tag{2}$$

Especially in our case, the "Utopia Point" cannot be reached since there are certain trade-offs between different goal functions. If one goal function is completely fulfilled another can be in an undesirable area. One goal function for example is a minimal electric field of 5 V/m around the implant to provide stimulation to the adjacent bone. The maximal electric field should not excess 70 V/m to avoid tissue damages by overstimulation. This is a second goal function and quite a problem in close proximity to the electrodes. Because of this, the hyper-radius cannot be the only criterion to choose one solution.

If, for example, one arrangement nearly fulfills nine out of ten optimization goals (value 0) while the tenth goal (i.e. maximal electric field of 70 V/m) is not accomplished at all (value 1), the hyper-radius would be 0.3. An arrangement where all the solutions are on the border between desirable and tolerable (value 0.4) would have a hyper-radius of 0.4. In this case using the solution with the smallest hyper-radius would result in an electrode arrangement that provides overstimulation.

For this reason five preference ranges are defined for every goal function: highly desirable (HD), desirable (D), tolerable (T), undesirable (U) and highly undesirable (HU). The preference ranges can be distributed equally (i.e. HD: 0 .. 0.2, D: 0.2 .. 0.4, ...), statistically (i.e. HD: best 10 % of the arrangements, ...) or by experience. At this point of work the equal distribution is used.

By application of an elitist preference structure, all solutions are categorized in five groups as shown on the right of Fig. 2. On the left side the two dimensional visualization of the HRV method is shown. The blue arrow points at the solution with the smallest distance to the "Utopia Point", Point A, which is in a lesser group than point B. In this case the automatic Pareto classifier would select the arrangement of point B as final solution.

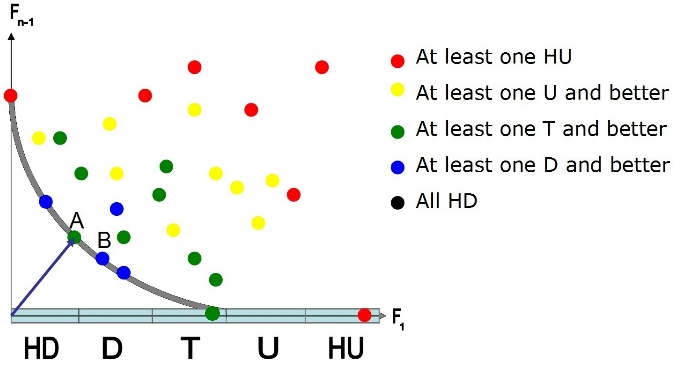

Figure 2: Visualization of a multidimensional solution space in two dimensions with color coding for the elitist preference structure. F_1 represents one goal function including the preference ranges, F_{n-1} represents the rest. The blue arrow points at the solution with the smallest distance to the "Utopia Point".

III. RESULTS

Our first tests of this method were done for two pelvic bones with central cavitary defect. The goal functions were set for both models to provide a minimal electric field of 5 V/m around the implant and at least 25 V/m in the area of the defect without exceeding the maximal electric field of 70 V/m. The optimization for these six goals (three goals per model) was done for four electrodes and resulted in an arrangement that provides sufficient stimulation on 69.7 % of the stimulation area of the first model and 70.5 % of the second model. Since the central cavitary defect requires a higher electric field than the rest of the implant, the four electrodes are arranged within or in close proximity to it. For this reason the areas above the outer rim of the implant and behind the anchorage cone are below the threshold of 5 V/m.

Because of this behavior at least one of the six preference ranges is only tolerable or better. Most of the solutions with small hyper-radius belong to this category and although the electrode positions change selecting another arrangement of these, only minor changes in the percentage of sufficiently stimulated bone are provided. Nevertheless this proves that the HRV method is most suitable to automatically select one solution of a Pareto amount.

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