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Design Optimization Methodology for Dry EEG Spikes Array Electrode

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Abstract – **Monitoring bio-electric events is a vital practice which provides medical data required in many clinical and research applications. Improving the performance of portable and ambulatory recording devices requires developing stable biomedical electrodes suitable for long term recording. This paper introduces an optimization design methodology to improve the electrical performance of dry electrodes used in electroencephalography through optimizing the geometrical design while abiding by design constraints which guarantee biocompatibility and mechanical stability.**

I. Introduction

Electrophysiological recording is based on detecting electric fields produced by the impressed current density associated with neuronal activation [1]. These fields can be measured on the surface of the head or directly on the brain tissue.

Recording is usually carried on using metallic disc electrodes and conductive gel which is applied to the scalp to increase the skin conductivity. This electrode technology is not suitable for long term recordings and portable devices [2] [3] [4] and dry electrodes in the form of an array of spikes are proposed for these applications.

Electrochemical impedance spectroscopy (EIS) was used to fully describe the electrode-skin interface circuit model. Experimental results showed that the skin-electrode interface for the proposed electrode layout can be modeled as Warburg impedance model circuit shown in figure 1. This impedance is affected by the surface area of contact between the electrodes and the electrolyte [5] [6]. And accordingly, in order to improve the electrical performance of the electrodes, it is required to optimize the electrode structure and geometry. This will enhance the signal strength and reduce the effect of noise and artifacts, and consequently boost the performance and accuracy of the succeeding system stages, i.e.; digital signal processing and analysis.

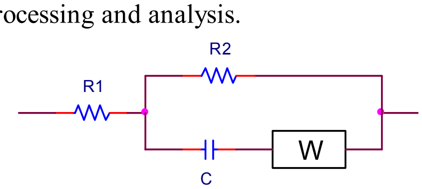

Figure 1 – Warburg impedance model

Accordingly, the objective of the design optimization is to increase the total surface area of contact between the spikes array and the electrolyte.

In this paper, a design optimization method is presented to maximize the electrode contact surface area.

II. Geometrical design optimization

A. Problem formulation

The objective of the optimization problem is to maximize the contact surface area between the electrode and the viable skin layers which make up the electrolyte. This will be accomplished through the maximizing the spikes height, maximizing the total perimeter of all spikes in the array, and maximizing the spikes packing.

B. Previous Research & Problem Definition

Boyce et al defined this problem as maximum and minimum area polygon (MAXP) given a set of vertices. Fekete and Pulleyblank (check on the reference formatting, because names and dates are not listed in the text usually) (1993) discussed the problem of optimizing the area of a simple polygon defined by a given set of vertices P and described it as "Minimum Area Polygon" (MAP) problem. Calculating the area of a polygon with rational vertices can be easily accomplished by adding the area of the triangles in a triangulation, which is not the case with determining the perimeter where it is more complicated [7]. It was also proven that the problem of finding a minimum weight polygon for a given vertex set is NP-complete which means that it is NP-hard to find a minimum area simple polygon with a given set of vertices [8]. Another method to tackle the problem is by using Grid Avoiding Polygon (GAP) and Pick's theorem Pick et al, 1899).

C. Design optimization

An analytical technique was used to model the problem by linear and nonlinear functions relating the parameters of the edges and vertices of the geometric shape to its dimensions combined with the given constraints.

The area of contact can be roughly evaluated as the lateral surface area of the electrode. Equation (1) expresses the

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total lateral surface area (AContact) as a function of the spike's geometry:

$$A_{Contact} \alpha (nN) x (h) x (P_{Needle}) \quad (1)$$

nN: number of spikes
h: individual spike height
PSpike : perimeter of spike
D. The maximal total lateral surface area

Maximizing the perimeter independently would lead to the expansion of the cross-sectional area of some geometric shapes. This uncontrolled increase in the spike's cross-section area is not desired because the available chip area will be consumed inefficiently, resulting in poor packing. Thus the perimeter optimization problem evolves to a "maximum perimeter minimum area" problem which introduced the polygon degree as a new degree of freedom to the problem.

E. Problem design procedure

The solution procedure begins with defining the objective function, and then the variable parameters influencing the design are identified. This will be followed by creating the ruling equations and finally, outlining the constraints. The asymptotic boundaries of the optimal solution were evaluated using analytical methods to confirm the optimization model. The consistency of the analytical approach results proved the validity of the model, while inconsistency will trigger remodeling the system. Finally, the valid model is used in the different design phases.

F. Constraints

Physiological issues imposed uncompromisable constraints that have to be satisfied including bio-compatibility and toxicity that limited the choice of materials. Skin anatomy [9-12] controlled the boundaries of spike dimensions which were also influenced by the micro-fabrication process technology constraints in terms of achievable aspect ratio and minimum feature size as well as the mechanical constraints which were set by the normal and shear stresses and buckling loads. Aesthetic considerations implied a minimal area and low profile design which requires maximum packing.

G. Optimization Tools and Techniques

The nature of the optimization model implied using Mixed Integer Non Linear Programming (MINLP) method to deal with the wide range of data and variable types including binary, integer and rational variables, besides to the various equations and relations.

A customized optimization tool was created using Matlab and the results were verified using an optimization model created in GAMS. The results produced by GAMS were successfully replicated and a sample result is shown in figures 2 and 3. Finally, the code was further developed to run in a Matlab graphical user interface.

H. Local and Global Optimization

The problem was broken down to a group of sub-problems, each is optimized individually. The results of local optimal solutions were useful in providing better understanding of the influence of each variable parameter and constraint on the performance of the system as well as for verifying the model consistency by comparing the fundamental blocks of the model with the analytically evaluated asymptotes and boundaries. The complexity of the model was increased gradually to accommodate more constraints. Finally, after tuning the model parameters and equations, the local optimization models were integrated into a single global optimization problem.

I. Iterations

The purpose of iterating the simulations during the process of model creation is to tune the model parameters to stabilize the system and the results converge towards the boundary values and asymptotes.

J. Sensitivity analysis and parametric programming

More iterations are required for the ranging and sensitivity analysis to determine the effect of different parameters on the optimal solution. Testing the influence of changing a group of parameters simultaneously was used in defining the boundaries and evaluating solutions at different operating points.

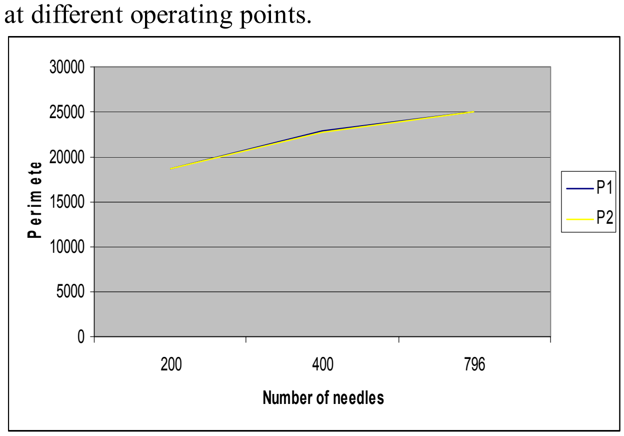

Figure 2 – Comparing GAMS and Matlab optimizer results, Perimeter vs. Number of needles

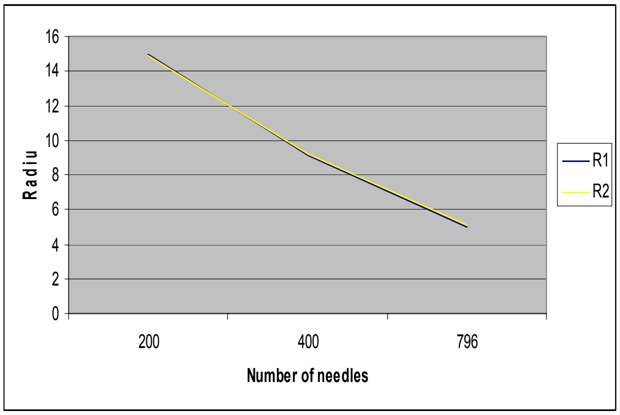

Figure 3 – Comparing GAMS and Matlab optimizer results, Inradius vs. Number of needles

III. Results

The simulation results showed that the total perimeter is a function of the product of the number of needles and the radius. Another factor that affects the total perimeter is the electrode base area. Regarding the geometry and cross-section; a certain perimeter can be achieved by different polygons, but triangular cross-section will consume the smallest area which is consistent with the analytical results. This will result in increasing the density of needles and consequently, expanding the total perimeter.

For a given set of constraints, where a maximum number of spikes per array was set to 1000, minimum feature size of 10µm and an electrode base area set to 1000µm x 1000µm, the optimal electrode architecture was found to be an array of 855 triangles with side length of 8.6µm to achieve a perimeter of 88854µm consuming 99.96% of the available area indicating a maximum packing. The results are shown graphically in figures 4, 5 and 6. The perimeter expansion factor when replacing cylindrical prisms with triangular ones is a function of the electrode base area as well as the number of needles. An array of 200 needles will provide a 23% gain in perimeter and this factor drops as the number of needles increases to reach a value of 14.27% in the case of 1000 needles where the perimeters are close in their values as shown in figure 7. Doubling the electrode area from 500µm x 500µm to 1000µm x 1000µm will expand the total perimeter by a factor of 3.6873 as plotted in figure 7.

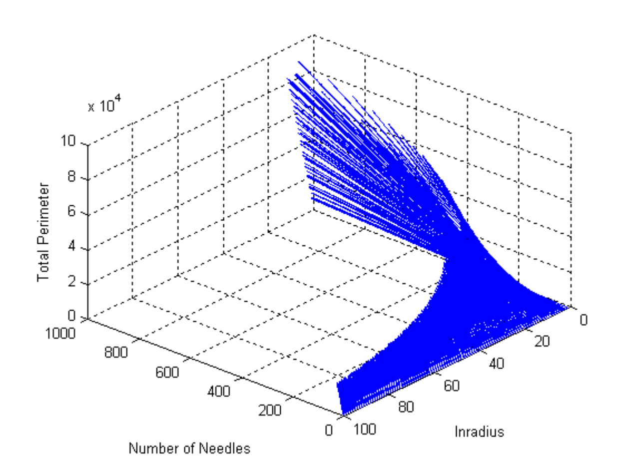

Figure 4 – Optimization results for polygons

VI. Conclusion

In this paper, a design optimization method for spike array electrodes is presented. The objective of this optimization technique is to maximize the contact surface area of the electrode-electrode interface to decrease the electrode impedance and specifically the electrode-electrolyte interface double layer impedance. This is achieved through choosing the electrode cross-section geometry that will maximize the total spikes perimeters and in the same time yield maximum spike packing.

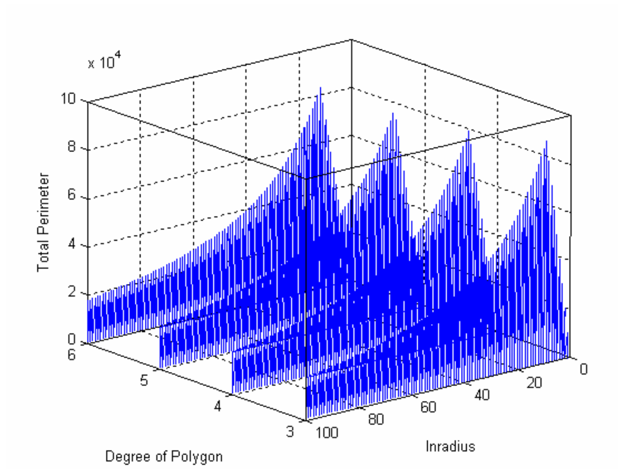

Figure 5 – Optimization results for polygons

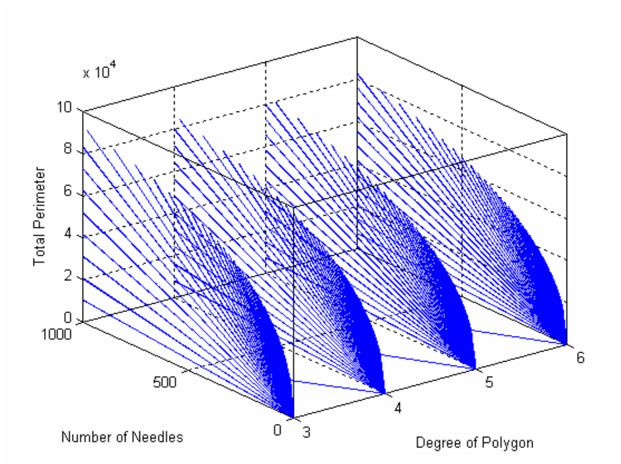

Figure 6 – Optimization results for polygons

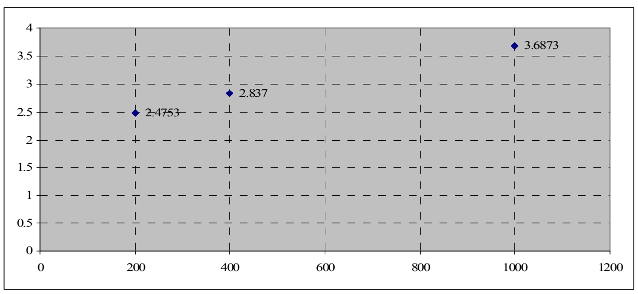

Figure 7 – Effect of electrode base on the total perimeter

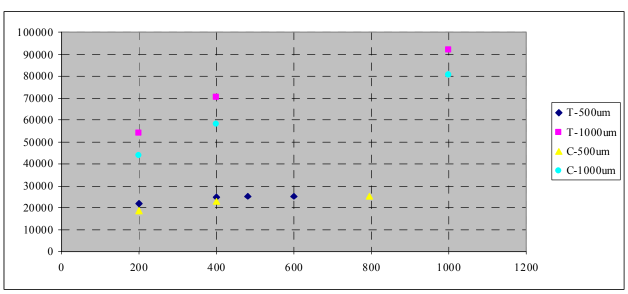

Figure 8 – Comparing triangular and circular cross-sections

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