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Focused ultrasonic therapy planning: Metamodeling, optimization, visualization

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ABSTRACT

We present a generic approach for focused ultrasonic therapy planning on the basis of numerical simulation, multi-objective optimization, stochastic analysis and visualization in virtual environments. A realistic test case is used to demonstrate the approach. RBF metamodeling of simulation results is performed for continuous representation of two optimization objectives. The non-convex Pareto front of the objectives is determined by means of non-dominated set and local improvement algorithms. Uncertainties of metamodeling are estimated by means of a cross-validation procedure. The 3D visualization in virtual environment framework Avango allows detailed inspection of MRT images, the corresponding material model and spatial distribution of the resulting thermal dose.

1. Introduction

Focused ultrasonic therapy is a non-invasive therapy using magnetic resonance tomography for identification of tumor volume and focused ultrasound for the destruction of tumor cells. Numerical simulation becomes an important step for the therapy planning. Efficient methods for the focused ultrasonic simulation have been presented in paper [1]. It uses a combination of Rayleigh-Sommerfeld integral for near field and angular spectrum method for far field computations, which allows determining the pressure field in heterogeneous tissue. The bioheat transfer equation is used to determine the temperature increase in therapy region. Thermal dose is defined according to CEM model or Arrhenius model [2,3] as a functional of temperature–time dependence in every spatial point in therapy region. The simulation is considerably accelerated by GPU based parallelization.

The resulting cumulative thermal dose inside the target region ($\mathrm{TD_{in}}$) should be maximized, providing a maximal level of tumor destruction, while the thermal dose outside the target region ($\mathrm{TD_{out}}$) should be minimized, to decrease the influence to healthy organs. In such statement the therapy planning can be naturally formulated as a multi-objective optimization problem.

Multi-objective optimization considers a mapping from the space of design variables to the space of target criteria and tries to find an optimal manifold (the so-called Pareto front) in these multi-dimensional spaces. The Pareto front is a surface possessing tradeoff property: none of the criteria can be improved without a simultaneous deterioration of at least one other criterion. In this sense the points on the Pareto front are better than the points outside, but they are equally optimal among each other. Similar problems appear in engineering optimization, where the result typically depends on many control parameters, such as geometrical, material and process parameters. Mostly, these parameters determine the input for simulations of FEM models, from which one can find criteria that quantify the result. Quite often, the parameter-dependent criteria can only be evaluated by means of resource-expensive simulations or even by physical experiments. Response surfaces approximating the parameter-criteria dependencies can then be used as a basis for the optimization.

1.1. Previous work

Some examples of possible application areas of parameter optimization in product design can be found in Clees [4] and Clees et al. [5]. Our previous work on metamodeling, including an interactive graphical user interface for parameter exploration is described by Thole et al. [6]. The basics of surrogate-based optimization have been described in the overview of the topic by Jones [7]. Another

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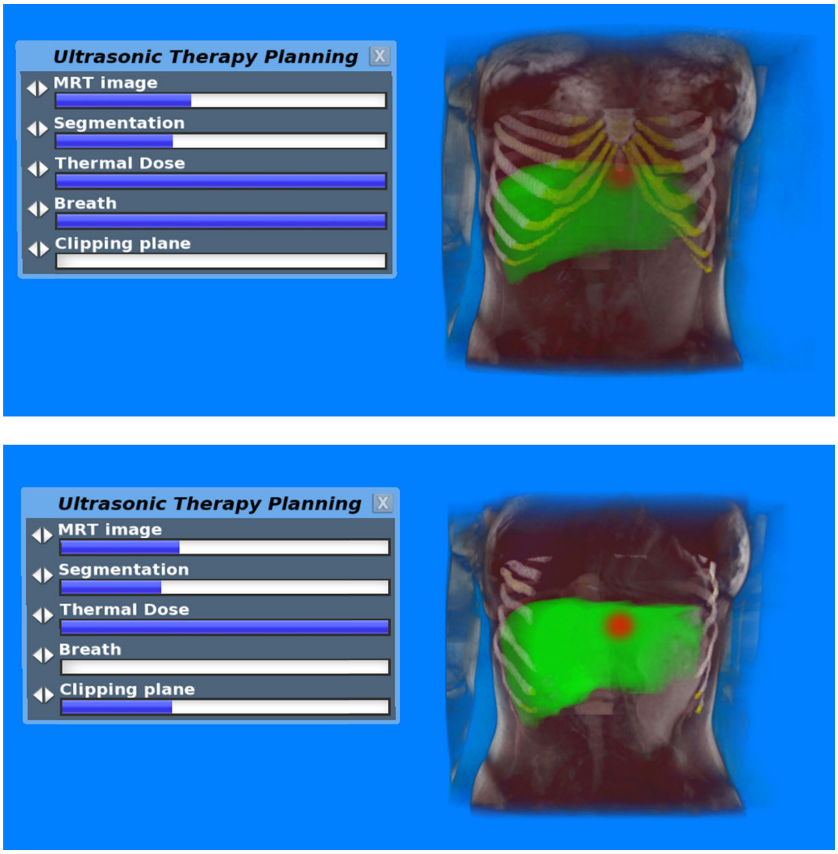

Fig. 1. Exemplary results of ultrasonic therapy simulation in Avango virtual environment framework. On the top: overlayed voxel models for MRT, material segmentation and thermal dose. On the bottom: cutting with a clipping plane, studying breathing effects.

survey is given by Queipo et al. [8]. Keane and Nair [9], chap. 5 discuss metamodelling in the application field of aerospace design and dedicate several chapters to optimization with approximate functions (see also [10]). Beyer and Sendhoff [11] discuss robustness in optimization. Some of our previous work on optimization of multi-objective functions with metamodels is summarized by Nikitin et al [12]. The problem of finding the optima of a set of vectors is reflected in the literature of a variety of application areas at least since the 1970s [13]. It can be implemented efficiently as an exhaustive search using recursion and divide and conquer strategies, see the description by Bentley [14] in comparison to Chen et al. [15] or by means of sequential linear programming [16].

1.2. Overview

In the present paper we select an efficient combination of these methods and apply them for solution of bi-objective optimization problem of focused ultrasonic therapy planning. In the following chapters we present the underlying methodology including multi-objective optimization, RBF metamodeling and sensitivity analysis. Further we describe the application of this methodology to focused ultrasonic therapy planning, discuss the obtained results and present the advantages of their 3D visualization in virtual environments (Fig. 1).

2. Methodology

Multi-objective optimization considers optimization problems of the type:

$$\text{maximize}\, y;\quad \text{where}\, y=f(x),\quad x\in R^n,\quad y\in R^m \tag{1}$$

i.e. a simultaneous optimization of multiple objectives y_i depending on multiple parameters x_j. The obtained optimum is typically not an isolated point but a hypersurface (Pareto front) composed of points satisfying a tradeoff property, i.e. none of the criteria can be improved without simultaneous degradation of at least one other criterion. Thus, for a bi-objective problem, the Pareto front is a curve on the plot (TD_{in}, TD_{out}) bounding the region of possible solutions, see Fig. 2. Efficient methods have been developed for determining the Pareto front.

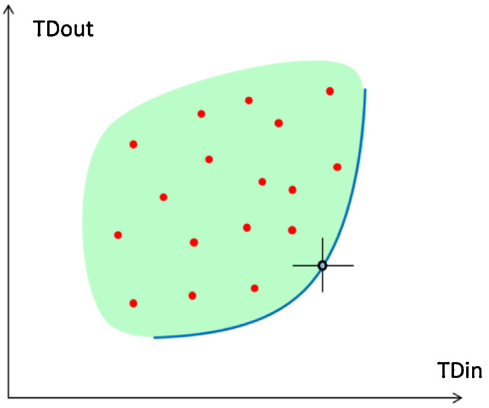

Fig. 2. Robust multi-objective optimization using metamodeling of simulation results. Red points denote simulation results, the continuous green region indicates a metamodel of simulation results, the blue curve the Pareto front, the black point with error bars an optimal representative with confidence limits. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)