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A genetic algorithm-based method of neutron emissivity tomographic inversion for tokamak plasma

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ABSTRACT

A new method of neutron emissivity tomographic reconstruction for fusion plasma was developed. The method is based on genetic algorithms. The developed method was tested using a synthetic data set. The results obtained with the synthetic data and a generic neutron tomographic system layout show that the method provides reliable reconstructions after ∼10000 iterations. The method capabilities were also tested against the noise present in the line-integrated projections.

1. Introduction

Reconstruction of the neutron emissivity distribution in a poloidal cross-section of a fusion device such as tokamak is of great importance for retrieving information on spatially resolved fusion rates. The reconstruction is performed from line-integrated quantities measured by a set of cameras equipped with neutron detectors. Due to technical constrains, the total number of neutron cameras as well as the number of lines of sight (LoS) in all existing tokamaks is very limited (e.g. two cameras with 19 LoS, at Joint European Torus [1]). Thus, the problem of such a tomographic reconstruction is very challenging due to sparse coverage of the plasma region. In mathematical terms, the inversion is a non-trivial, ill-posed problem of the limited angle tomography [2]. Several approaches to the reconstruction of neutron emissivity in magnetic-confinement fusion (MCF) devices have been developed and applied. Perhaps, the most commonly used methods are based on Tikhonov regularization (TR) [3,4], minimization of Fisher Information (MFI) [5] or maximization of entropy (ME) or likelihood (ML) [6]. Also, other approaches such as a hybrid pixel/analytic algorithm based on a poloidal Fourier transform and radial Abel inversion [7], a parametric model for fusion neutron emissivity tomography [8] or a neural networks-based method [9] were successfully applied.

In this paper, a new method of neutron emission reconstruction based on genetic algorithms (GA) is presented. Genetic algorithms have been already applied in the field of electrical impedance [10,11], optical [12] and X-ray [13] tomography. However, so far there are no reports on application of GA for tomographic inversion in MCF devices. GA are adaptive heuristic search methods inspired by evolutionary ideas of natural selection and genetics. They use probabilistic selection rules, rather than deterministic ones. It is well known that parallelization of the standard reconstruction method e.g. based on the sparse Generalized Singular Value Decomposition (GSVD) is not a trivial task. Contrary, GA are inherently parallel and can be easily distributed among many CPUs or GPUs. Moreover, GA search parallel from a population of points. Therefore, they have the ability to avoid being trapped in a local optimal solution like traditional methods, which search from a single point. GA are also well suited for optimization in noisy environments. All these points suggest that GA are worth testing for being a candidate as a tomographic inversion method in fusion devices. There are a large number of textbooks and papers that tackle the problem of GA. The field of GA is very dynamic and continuously developing. Thus, the comprehensive overview of GA is definitely outside the scope of this paper.

The aim of this work was to test the feasibility of application of GA to the neutron emissivity tomographic inversion and investigate its robustness. The article is structured as follows. Section 2 provides the general definition of the tomographic inversion problem. In Section 3 the newly proposed method based on GA is described. Section 4 provides results of tests of the method using a synthetic data set. Finally, the summary, conclusions and future plans are presented in Section 5.

2. General definition of tomographic problem

The tomographic inversion problem consists in determining the neutron emissivity distribution in a poloidal cross-section of plasma confined in a fusion device. This inversion is carried out from a set of experimentally measured line-integrated quantities – projections. In this paper, to develop and test the new method we use a generic experimental setup presented in Fig. 1. The system consists of two cameras, each camera features 16 neutron detectors. It is worth noting that

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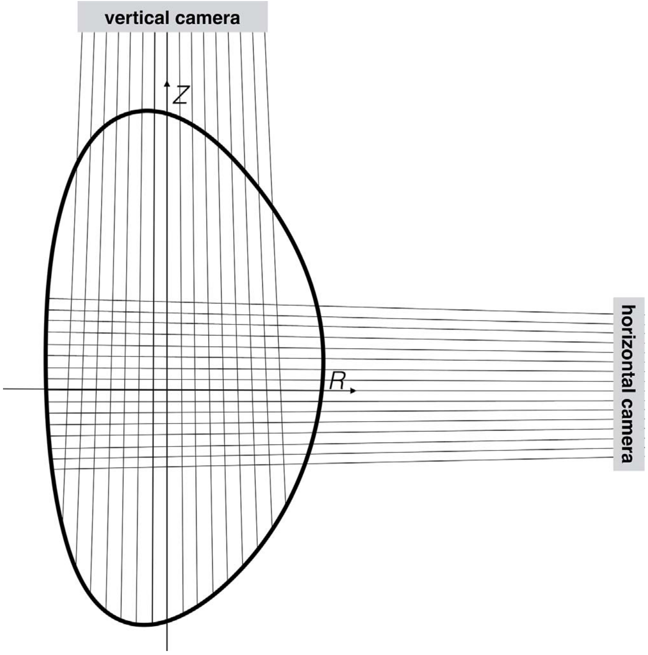

Fig. 1. Geometrical layout of the LoS of the generic neutron tomographic system. The neutron imaging system consists of two cameras with 32 LoS in total.

the method can be easily adapted and applied to any tokamak's neutron diagnostic geometry. In the presented approach, the ill-posed inversion problem is solved using a discrete Cartesian coordinate system (mesh). Thus, the emissivity is discretized on a grid as a matrix E of $N \times N$ square elements. Each element is associated with a value of the emissivity that is assumed to be constant within the pixel. The grid size is a parameter that can be tuned and it should be chosen as a trade-of between the number of degrees of freedom of the ill-conditioned problem, the resolution of the reconstructed neutron emissivity, and the computing time. In the presented work, $N = 19$ was found as a good compromise between the resolution and computing time. The discrete inverse problem of tomographic reconstruction is defined by the following set of linear equations:

$$p_k = \sum_{i=1}^{N_p} w_{ki} f_i, \; k = 1 \ldots N_d \tag{1}$$

In Eq. (1) f_i is the i-th element of the plasma neutron emissivity represented by $N^2 \times 1$ column vector $\boldsymbol{f}$, i.e. $\boldsymbol{f}$ is a row-major ordered vector form of emissivity matrix E, N^2 is the total number of elements for the discrete representation of the neutron emissivity, N_d is the number of LoS (detectors) and p_k is the k-th element of $N_d \times 1$ column vector $\boldsymbol{p}$ that represents the available data along the LoS. The element w_{ki} of the geometrical matrix W represents the contribution of i-th element of emissivity to the k-th projection. The matrix W (of size $N_d \times N^2$) is constructed based on the geometrical layout of the LoS. Since solving Eq. (1) is a highly ill-posed problem, the direct matrix inversion fails and usually some kind of regularization method is applied [2]. In the next chapter an alternative approach based on GA is presented.

3. Tomographic inversion method

The proposed method is based on an iterative approach. The workflow of the reconstruction method is presented in Fig. 2. The reconstruction starts with the initialization phase. In this step, M random solutions $\boldsymbol{f}^j$ $(j = 1.M)$ (chromosomes in GA terminology) are created. To speed-up the convergence process, an alternative version of initialization step can be also used. In this case, the initial population of the solutions is taken as M solutions of Kaczmarz method (known also as the Algebraic Reconstruction Technique (ART)) [14,15] with the iteration number selected randomly, instead of the completely random initial solutions. It is a known fact that the ART itself does not provide, in general, physically meaningful results for undetermined, ill-posed problem of tomographic reconstruction of fusion plasmas [16]. Fig. 3 presents results of the reconstruction of three test phantoms defined in Section 4 after 100 iterations when the convergence of the solution was reached (i.e. further iterations do not improve the quality of the reconstruction). In the next step, the solutions are evaluated based on the objective function:

$$f_{obj}^{j} = \left\| W\boldsymbol{f}^j - p \right\|^2 + \lambda \left\| L\boldsymbol{f}^j \right\|^2, \tag{2}$$

where L is a matrix representation of the derivative operator that imposes a smoothness constraint on the reconstructed solutions and λ is a constant that controls the weight given to the minimization of this side constraint relative to the minimization of the residual norm. Selection of λ parameter can be optimized during the reconstruction using an iterative approach, however it would additionally increase the computational cost of the method. Thus, during the development phase λ was set to 1. This choice was based on the experience from several

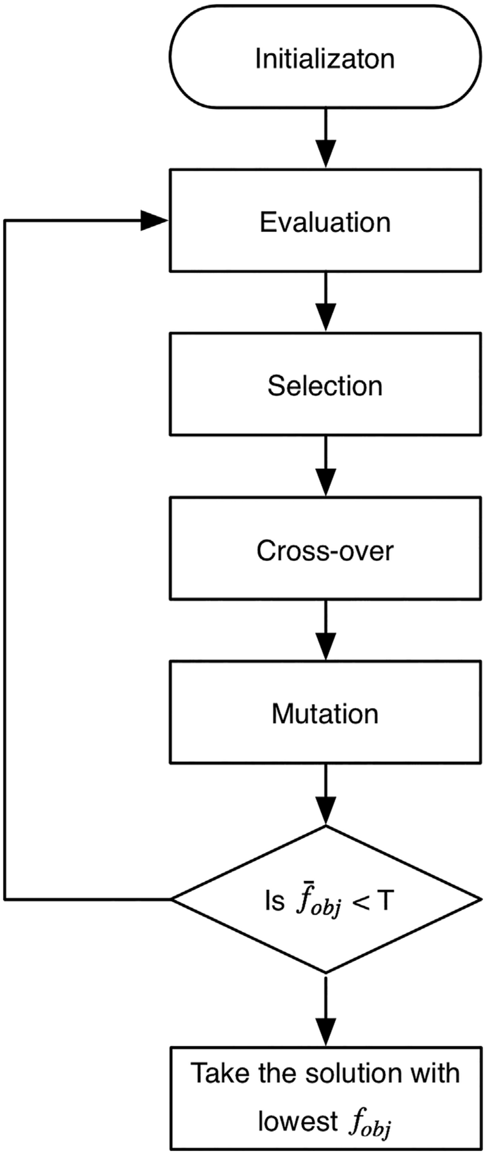

Fig. 2. Workflow diagram of the reconstruction method.