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Coupled isogeometric Finite Element Method and Hierarchical Genetic Strategy with balanced accuracy for solving optimization inverse problem

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Abstract

The liquid fossil fuel reservoir exploitation problem (LFFEP) has not only economical signification but also strong natural environment impact. When the hydraulic fracturing technique is considered from the mathematical point of view it can be formulated as an optimization inverse problem, where we try to find optimal locations of pumps and sinks to maximize the amount of the oil extracted and to minimize the contamination of the groundwater. In the paper, we present combined solver consisting of the Hierarchical Genetic Strategy (HGS) with variable accuracy for solving optimization problem and isogeometric finite element method (IGA-FEM) with different mesh size for modeling a non-stationary flow of the non-linear fluid in heterogeneous media. The algorithm was tested and compared with the strategy using Simple Genetic Algorithm (SGA) as optimization algorithm and the same IGA-FEM solver for solving a direct problem. Additionally, a parallel algorithm for non-stationary simulations with isogeometric L2 projections is discussed and preliminarily assessed for reducing the computational cost of the solvers consisting of genetic algorithm and IGA-FEM algorithm. The theoretical asymptotic analysis which shows the correctness of algorithm and allows to estimate computational costs of the strategy is also presented.

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Keywords: hybrid global optimization, inverse problems, hierarchical genetic strategy, isogeometric finite element method

1 Introduction

The aim of solving the liquid fossil fuel reservoir exploitation problem (LFFEP), described and defined in [19], is to find optimal locations of pumps and sinks in the liquid fossil fuel reservoir exploited with hydraulic fracturing method to maximize the amount of the oil extracted but

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simultaneously to minimize the environmental impact, namely the contamination of groundwater. It is assumed that the three-dimensional map of both: the natural formation layers and the groundwater, was previously obtained with some imaging techniques. In [19] we propose combining evolutionary algorithm with IGA-FEM as a solver. The problem, however, is that every single fitness function evaluation requires expensive finite element method computations using explicit isogeometric dynamics simulator [21, 9] for modeling and simulating the non-stationary flow of the non-linear fluid in heterogeneous media. It lasts pretty long and consumes huge amounts of computational resources.

Combining evolutionary heuristics with the finite element methods seems to be a proper approach for solving the problem of LFFEP.

Also applying isogeometric finite element method (IGA-FEM) [3, 5, 10] seems to be a proper methodology for solving this kind of simulations—especially because the fast direct solvers can be used here [6, 7, 8].

Thus, to reduce the computational costs of the combined solver (GA+IGA-FEM) in this paper we investigate applying the coupled solver consisting of the Hierarchical Genetic Strategy (HGS) [14, 15, 16] with variable accuracy and the isogeometric finite element method (IGA-FEM) with different mesh sizes.

Additionally, we propose to utilize the parallel isogeometric finite element method for solving the time-dependent problem of non-linear flow in heterogeneous media for further computational time reduction.

2 IGA-HGS–the combination of HGS and IGA-FEM as an inverse problems solver

The hierarchical genetic strategy–HGS introduced by Kolodziej and Schaefer [14] enables effective solving of global optimization problems using a variable, dynamically adapting accuracy.

It produces a tree-structured, dynamically changing set of dependent demes with a restricted number of levels m. Each deme is governed by a separate instance of Simple Genetic Algorithm (SGA). All demes work asynchronously and are synchronized by the message-passing mechanism if necessary.

The demes of the lower order, closer to the root, perform a more chaotic search with lower accuracy. They detect promising regions of the optimization landscape, where a more accurate higher order demes are activated. In our case, the growing precision on consecutive levels of HGS tree is obtained by using the genotypes of a different length. The unique deme of the first order (root) utilizes the shortest genotypes, while the leaves utilize the longest ones. The maximum diameter of the mesh δ_j associated with demes of order j determines the search accuracy at this level of HGS tree. There is a coherency in the search between demes of different order thanks to the special kind of a hierarchical encoding that forms the sequence of a nested grids.

Each deme, except for the one of order m called leaves, sprouts the new child-deme after the constant number of genetic epochs K called metaepoch. The child-deme is activated surrounding the best-fitted individual, distinguished from the parental deme at the end of the metaepoch. HGS implements also two additional mechanisms to reduce the redundancy of the search process. They disable sprouting and reduce branches in regions already occupied or explored.

For solving the optimization inverse problem under consideration we propose a coupled strategy consisting of the isogeometric finite element method (IGA-FEM) for solving a direct problem and Hierarchical Genetic Strategy (HGS) for solving the optimization one. To obtain