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A multilevel coordinate search algorithm for well placement, control and joint optimization

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ABSTRACT

Determining optimal well placements and controls are two important tasks in oil field development. These problems are computationally expensive, nonconvex, and contain multiple optima. The practical solution of these problems requires efficient and robust algorithms. In this paper, the multilevel coordinate search (MCS) algorithm is applied for well placement and control optimization problems. MCS is a derivative-free algorithm that combines global and local search. Both synthetic and real oil fields are considered. The performance of MCS is compared to generalized pattern search (GPS), particle swarm optimization (PSO), and covariance matrix adaptive evolution strategy (CMA-ES) algorithms. Results show that the MCS algorithm is strongly competitive, and outperforms for the joint optimization problem and with a limited computational budget. The effect of parameter settings for MCS is compared for the test examples. For the joint optimization problem we compare the performance of the simultaneous and sequential procedures and show the utility of the latter.

1. Introduction

Determining the optimal well locations and controls in an oil field is a challenging task. The decision is hard since the reservoir performance is affected by geological, engineering, economical and other parameters (Tavallali et al., 2013; Knudsen and Foss, 2013; Shakhsi-Niaei et al., 2014). Optimization algorithms provide a systematic way to solve this problem. By using optimization algorithms, a quality solution can be achieved automatically and hence reduce the risk in decision-making. Well placement and control optimization generally are computationally expensive and nonconvex, and not every optimization algorithm is appropriate for these problems. Therefore, finding and applying algorithms that are efficient and robust is one of most important tasks in solving well placement and control optimization problems.

In this work, we introduce and apply the multilevel coordinate search (MCS) algorithm for the problems of optimizing well placement, well control, and joint placement with control. MCS, introduced by Huyer and Neumaier (1999), is a global optimization algorithm and is designed to handle the complex topography and multimodality of the multidimensional nonlinear objective functions without requiring excessive computing resources. Rios and Sahinidis (2013) completed a systematic comparison using a test set of 502 problems and found that MCS outperforms the other 21 derivative-free algorithms tested (see Table 1). Though MCS has shown its superiority in benchmark and real world problems (Huyer and Neumaier, 1999; Rios and Sahinidis, 2013; Lambot et al., 2002), to the best of our knowledge, it has not been applied to the optimization of oil field development. We compare MCS, generalized pattern search (GPS), particle swarm optimization (PSO), and covariance matrix adaptive evolution strategy (CMA-ES) in four typical test cases from the field of optimal reservoir production development. Our results demonstrate that MCS is strongly competitive and outperforms the other algorithms in most cases.

Oil field development optimization has two main sub-problems: well placement optimization, and well control optimization. These two problems are often treated separately (Oliveira and Reynolds, 2014; Bouzarkouna et al., 2012; Wang et al., 2009; Brouwer and Jansen, 2004). Recently, there has been increasing focus on optimizing well placement and control jointly (Forouzanfar et al., 2015; Humphries et al., 2013; Isebor et al., 2014a). Well placement problems aim to optimize the locations of injection and production wells. The location of each vertical well is parametrized by its plane coordinates (x, y), which are usually integers in the reservoir simulator. Well control problems focus on optimizing production scheduling. The optimization variables are often the time-varying bottom hole pressures (BHPs) or the flow rates for each well. The joint problem optimizes well placement and control parameters

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Table 1
Derivative-free solvers considered by Rios and Sahinidis (2013).

Solver	Version	Language
ASA	26.30	C
BOBYQA	2009	Fortran
CMA-ES	3.26beta	Matlab
DAKOTA/DIRECT	4.2	C++
DAKOTA/EA	4.2	C++
DAKOTA/PATTERN	4.2	C++
DAKOTA/SOLIS-WETS	4.2	C++
DFO	2.0	Fortran
FMINSEARCH	1.1.6.2	Matlab
GLOBAL	1.0	Matlab
HOPSPACK	2.0	C++
IMFIL	1.01	Matlab
MCS	2.0	Matlab
NEWUOA	2004	Fortran
NOMAD	3.3	C++
PSWARM	1.3	Matlab
SID-PSM	1.1	Matlab
SNOBFIT	2.1	Matlab
TOMLAB/GLCCLUSTER	7.3	Matlab
TOMLAB/LGO	7.3	Matlab
TOMLAB/MULTIMIN	7.3	Matlab
TOMLAB/OQNLP	7.3	Matlab

simultaneously. Thus, the joint problems are more complex and challenging with an increase in the number and type of variables (Isebor et al., 2014a).

In the past, a number of algorithms have been devised and analysed for both separate and joint problem of well placement and control optimization. These algorithms fall into two categories: gradient-based methods and derivative-free methods. Applications of gradient-based methods to oil field problems have been presented in many papers (Volkov and Voskov, 2014; Wang et al., 2009; Brouwer and Jansen, 2004; Zandvliet et al., 2008; Sarma et al., 2006; Zhou et al., 2013). These methods take advantage of the gradient information to guide their search. The gradient of the objective function can be obtained by using adjoint-based techniques (Brouwer and Jansen, 2004; Sarma et al., 2006; Zandvliet et al., 2008; Volkov and Voskov, 2014), or may be approximated by using numerical methods such as finite differences (Wang et al., 2009; Zhou et al., 2013). The adjoint method, developed in the 1970s (Chen et al., 1974; Chavent, 1974), is widely used for assisted history matching (Wu et al., 1999; Li et al., 2003) and well production optimization (Asheim, 1988; Zakirov et al., 1996; Brouwer and Jansen, 2004). Gradient based methods have some drawbacks for the well placement and control problem; these problems are nonconvex and generally contain multiple optima. For some problems, particularly well placement, the optimization surface can be very rough, which results in discontinuous gradients (Ciaurri et al., 2011). However, the gradient-based methods are often the most efficient methods especially for the optimal well control problem (Zhao et al., 2013; Handels et al., 2007; Vlemmix et al., 2009; Wang et al., 2007; Forouzanfar and Reynolds, 2014).

For the joint well placement and control optimization problem, two procedures are proposed and studied. The first one is a simultaneous procedure, which optimizes over all well locations and control parameters simultaneously. The second one is a sequential procedure, that decouples the joint problem into the well placement optimization subproblem and the well control placement optimization subproblem. The simultaneous procedure ensures that the best solution exists somewhere in the search space. But it may be difficult to find the global optima because the search space may be very large and rough. The sequential procedure divides the optimization variables into two smaller groups and optimizes separately. For each subproblem, the search space is smaller than the simultaneous one, but it can not ensure the best solution exists in the search space because the optimal location depends on how the well is operated and vice-versa. There are several papers (Li et al., 2012; Bellout et al., 2012; Isebor et al., 2014b) which demonstrate that the simultaneous procedure is superior to the sequential approach. In Humphries et al. (2013) and Humphries and Haynes (2015), however, they found that a sequential procedure was competitive and even preferable to the simultaneous approach in some cases. To test this further, we do a further investigation of the effectiveness of these two procedures using a joint placement and control optimization example.

Many black-box, derivative-free methods have been used in oil field problems (Merlini Giuliani and Camponogara, 2015). Typical algorithms include genetic algorithms (GA) (AlQahtani et al., 2014; Bouzarkouna et al., 2012), particle swarm optimization (PSO) (Onwunalu and Durlofsky, 2009, 2011), generalized pattern search (GPS) (Asadollahi et al., 2014; Isebor, 2009), covariance matrix adaptation strategy (CMA-ES) (Bouzarkouna et al., 2012; Forouzanfar et al., 2015) and hybrid approaches (Isebor et al., 2014a; Humphries and Haynes, 2015). These algorithms can be classified as either deterministic or stochastic, and provide global or local search. The stochastic/global approaches have also been hybridized with deterministic/local search techniques. These algorithms only require the value of objective function and involve no explicit gradient calculations. For smooth objective functions, the derivative-free methods generally need more function evaluations to converge to a solution than the gradient-based ones. However, most of the derivative-free algorithms parallelize naturally and easily, which make their efficiency satisfactory (Ciaurri et al., 2011), and indeed these methods are less likely to become trapped in local optima.

We are particularly interested in using the multilevel coordinate search (MCS) algorithm for the following reasons: (1) it combines a global search with a local search, which leads to a quicker convergence than many methods that operate only at the global level. (2) It is an intermediate between heuristic methods that find the global optimum only with high probability and methods that guarantee to find a optimum with a required accuracy. (3) It does not need analytic or numerical derivatives. (4) It is guaranteed to converge if the objective is continuous in the neighbourhood of a global minimizer, no additional smoothness properties are required. (5) The algorithm parameters in MCS have a clear meaning and are easy to choose. (6) It has proved itself in benchmark tests and many real world problems (Huyer and Neumaier, 1999). Based on these features, we believe that MCS has great potential to solve oil field optimization problems, which are nonconvex, nonlinear, and contain many local optima and discontinuities.

In this paper, we apply MCS to optimization problems of varying complexity in terms of the number and type of optimization variables, the dimension and size of the reservoir models, and the number of wells. We investigate the effect of the algorithmic parameters (initialization list type, number of levels, and the effect of local search) on the optimization results. We propose a detailed comparison between MCS and three other popular derivative-free algorithms (GPS, PSO, and CMA-ES).

This paper is organized as follows: Section 2 describes the formulation of the optimization problems. Section 3 gives an overview of the optimization algorithms considered. In Section 4 we describe our numerical experiments and the corresponding results. Finally, in Section 5 we provide some concluding remarks.

2. Problem formulation

2.1. General problem statement

The objective functions for general oil field development optimization problems are often the net present value (NPV) or