DE/BBO: A Hybrid Differential Evolution with Biogeography-Based Optimization for Global Numerical Optimization

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***Abstract*— Differential Evolution (DE) is a fast and robust evolutionary algorithm for global optimization. It has been widely used in many areas. Biogeography-Based Optimization (BBO) is a new biogeography inspired algorithm. It mainly uses the biogeography-based migration operator to share the information among solutions. In this paper, we propose a hybrid DE with BBO, namely DE/BBO, for the global numerical optimization problem. DE/BBO combines the exploration of DE with the exploitation of BBO effectively, and hence it can generate the promising candidate solutions. To verify the performance of our proposed DE/BBO, 23 benchmark functions with a wide range of dimensions and diverse complexities are employed. Experimental results indicate that our approach is effective and efficient. Compared with other state-of-the-art DE approaches, DE/BBO performs better, or at least comparably, in terms of the quality of the final solutions and the convergence rate. In addition, the influence of the population size, dimensionality, different mutation schemes, and the self-adaptive control parameters of DE are also studied.**

***Index Terms*— Differential evolution, biogeography-based optimization, hybridization, global numerical optimization, exploration, exploitation**

I. Introduction

EVOLUTIONARY Algorithms (EAs, including genetic algorithms, evolution strategies, evolutionary programming, and genetic programming) have received much attention regarding their potential as global optimization techniques [1], both in single and in multi-objective optimization. Inspired by the natural evolution and survival of the fittest, EAs utilize a collective learning process of a population of individuals. Descendants of individuals are generated using randomized operations such as mutation and recombination. Mutation corresponds to an erroneous self-replication of individuals, while recombination exchanges information between two or more existing individuals. According to a fitness measure, the selection process favors better individuals to reproduce more often than those that are relatively worse.

Differential Evolution (DE) [2] is a simple yet powerful population-based, direct search algorithm with the generation-and-test feature for global optimization problems using real-valued parameters. DE uses the distance and direction information from the current population to guide the further search. It won the third place at the first International Contest on Evolutionary Computation on a real-valued function testsuite [3]. Among DE's advantages are its simple structure, ease of use, speed and robustness. Price and Storn [2] gave the working principle of DE with single scheme. Later on, they suggested ten different schemes of DE [3], [4]. However, DE has been shown to have certain weaknesses, especially if the global optimum should be located using a limited number of fitness function evaluations (NFFEs). In addition, DE is good at exploring the search space and locating the region of global minimum, but it is slow at exploitation of the solution [5].

Biogeography-Based Optimization (BBO), proposed by Simon [6], is a new global optimization algorithm based on the biogeography theory, which is the study of the geographical distribution of biological organisms. Similar to GAs, BBO is a population-based, stochastic global optimizer. In the original BBO algorithm, each solution of the population is a vector of integers. BBO adopts the migration operator to share information between solutions. This feature is similar to other biology-based algorithms, such as GAs and PSO. It makes BBO applicable to many of the same types of problems that GAs and PSO are used for. However, BBO also has several unique features compared with biology-based algorithms. For example, it maintains its set of solutions from one iteration to the next one [6]. Simon compared BBO with seven state-of-the-art EAs over 14 benchmark functions and a real-world sensor selection problem. The results demonstrated the good performance of BBO. With the migration operator, BBO has a good exploitation ability.

Hybridization of EAs is getting more and more popular due to their capabilities in handling several real world problems [7]. In order to balance the exploration and the exploitation of DE, in this paper, we propose a hybrid DE with BBO, referred to as DE/BBO, for the global numerical optimization problems. In DE/BBO, a hybrid migration operator is proposed, which combines the exploration of DE with the exploitation of BBO effectively. Experiments have been conducted on 23 benchmark functions chosen from the literature. In addition, five performance criteria are employed to fairly compare our approach with other algorithms. Furthermore, the influence of the population size, dimensionality, different mutation schemes, and the self-adaptive control parameters of DE are also investigated.

The rest of this paper is organized as follows. Section II

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briefly describes function optimization problem, the DE algorithm, and the BBO algorithm. In Section III, some related work of DE are presented. Our proposed approach is presented in detail in Section IV. In Section V, we verify our approach through 23 benchmark functions. Moreover, the experimental results are compared with several other approaches. The last section, Section VI, is devoted to conclusions and future work.

II. Preliminary

A. Problem definition

Global numerical optimization problems are frequently arisen in almost every field of engineering design, applied sciences, molecular biology and other scientific applications. Without loss of generality, the global minimization problem can be formalized as a pair (S, f) , where $S \subseteq R^D$ is a bounded set on R^D and $f : S \rightarrow R$ is a D-dimensional real-valued function. The problem is to find a point $X^* \in S$ such that $f(X^*)$ is the global minimum on S [8]. More specifically, it is required to find an $X^* \in S$ such that

$$\forall X \in S : f(X^*) \leq f(X) \tag{1}$$

where f does not need to be continuous but it must be bounded. In this work, we only consider the unconstrained function optimization.

In global numerical optimization problems, the major challenge is that an algorithm may be trapped in the local optima of the objective function. This issue is particularly challenging when the dimension is high. Recently, using the Evolutionary Computation (EC) [1] to solve the global optimization has been very active, producing different kinds of EC for optimization in the continuous domain, such as genetic algorithms [9], evolution strategy [10], evolutionary programming [8], particle swarm optimization [11], immune clonal algorithm [12], differential evolution [2], etc.

B. Differential evolution

The DE algorithm [2] is a simple EA that creates new candidate solutions by combining the parent individual and several other individuals of the same population. A candidate replaces the parent only if it has better fitness. This is a rather greedy selection scheme that often outperforms traditional EAs. Among DE's advantages are its simple structure, ease of use, speed and robustness. Due to these advantages, it has many real-world applications, such as data mining [13], [14], pattern recognition, digital filter design, neural network training, etc. [4], [15], [16]. Most recently, DE has also been used for the global permutation-based combinatorial optimization problems [17].

The pseudo-code of the original DE algorithm is shown in Algorithm 1. Where D is the number of decision variables. NP is the size of the parent population P. F is the mutation scaling factor. CR is the probability of crossover operator. $X_i(j)$ is the j-th variable of the solution X_i. U_i is the offspring. $\mathrm{rndint}(1, D)$ is a uniformly distributed random integer number between 1 and n. And $\mathrm{rndreal}_j[0, 1)$ is a uniformly distributed random real number in $[0, 1)$. Many schemes of creation of a candidate are possible. We use the DE/rand/1/bin scheme (see lines 6 - 13 of Algorithm 1) described in Algorithm 1 (more details on DE/rand/1/bin and other DE schemes can be found in [3] and [4]).

Algorithm 1 The DE algorithm with DE/rand/1/bin scheme

1: Generate the initial population P
2: Evaluate the fitness for each individual in P
3: **while** The halting criterion is not satisfied **do**
4: **for** $i = 1$ to NP **do**
5: Select uniform randomly $r_1 \neq r_2 \neq r_3 \neq i$
6: j_{rand} = rndint$(1, D)$
7: **for** $j = 1$ to D **do**
8: **if** $\mathrm{rndreal}_j[0, 1) > CR$ or $j == j_{rand}$ **then**
9: $U_i(j) = X_{r_1}(j) + F \times \Big(X_{r_2}(j) - X_{r_3}(j)\Big)$
10: **else**
11: $U_i(j) = X_i(j)$
12: **end if**
13: **end for**
14: **end for**
15: **for** $i = 1$ to NP **do**
16: Evaluate the offspring U_i
17: **if** U_i is better than P_i **then**
18: $P_i = U_i$
19: **end if**
20: **end for**
21: **end while**

From Algorithm 1, we can see that there are only three control parameters in this algorithm. These are NP, F and CR. As for the terminal conditions, one can either fix the maximum NFFEs *Max_NFFEs* or the precision of a desired solution *VTR* (value to reach).

Algorithm 2 Habitat migration

for $i = 1$ to NP **do**
 Select X_i with probability $\propto \lambda_i$
 if $\mathrm{rndreal}(0, 1) < \lambda_i$ **then**
  for $j = 1$ to NP **do**
   Select X_j with probability $\propto \mu_j$
   if $\mathrm{rndreal}(0, 1) < \mu_j$ **then**
    Randomly select a variable σ from X_j
    Replace the corresponding variable in X_i with σ
   end if
  end for
 end if
end for

C. Biogeography-based optimization

BBO [6] is a new population-based, biogeography inspired global optimization algorithm. In BBO, each individual is considered as a "habitat" with a habitat suitability index (HSI), which is similar to the fitness of EAs, to measure the individual. A good solution is analogous to an island with a high HSI, and a poor solution indicates an island with a low HSI. High HSI solutions tend to share their features with low HSI solutions. Low HSI solutions accept a lot of new features from high HSI solutions.

In BBO, each individual has its own immigration rate λ and emigration rate μ. A good solution has higher μ and lower λ, vice versa. The immigration rate and the emigration rate are

functions of the number of species in the habitat. They can be calculated as follows

$$\lambda_k = I\left(1 - \frac{k}{n}\right) \tag{2}$$

$$\mu_k = E\left(\frac{k}{n}\right) \tag{3}$$

where I is the maximum possible immigration rate; E is the maximum possible emigration rate; k is the number of species of the k-th individual; and n is the maximum number of species. Note that Eqns. 2 and 3 are just one method for calculating λ and μ. There are other different options to assign them based on different specie models [6].

Suppose that we have a global optimization problem and a population of candidate individuals. The individual is represented by a D-dimensional vector. The population consists of $NP = n$ parameter vectors. In BBO, there are two main operators, the migration and the mutation. One option for implementing the migration operator can be described in Algorithm 2[1]. Where $\mathrm{rndreal}(0, 1)$ is a uniformly distributed random real number in $(0, 1)$ and $X_i(j)$ is the j-th SIV of the solution X_i. With the migration operator, BBO can share the information among solutions. Especially, poor solutions tend to accept more useful information from good solutions. This makes BBO be good at exploiting the information of the current population. More details about the two operators can be found in [6] and in the Matlab code [18].

III. Related work to DE

Some previous researches pointed out that there are three main drawbacks of the original DE algorithm. First, the parameters of DE are problem dependent and the choice of them is often critical for the performance of DE [19], [20]. Second, choosing the best among different mutation schemes available for DE is also not easy for a specific problem [27], [28]. Third, DE is good at exploring the search space and locating the region of global minimum, but it is slow at exploitation of the solution [5]. Due to these drawbacks, many researchers are now working on the improvement of DE, and many variants are presented.

Adapting the DE's control parameters is one possible improvement. Liu and Lampinen [20] proposed a Fuzzy Adaptive DE (FADE), which employs fuzzy logic controllers to adapt the mutation and crossover control parameters. Brest *et al*. [21] proposed self-adapting control parameter settings. Their proposed approach encodes the F and CR parameters into the chromosome and uses a self-adaptive control mechanism to change them. Salman *et al*. [22] proposed a self-adaptive DE (SDE) algorithm that eliminates the need for manual tuning of control parameters. In SDE, the mutation weighting factor F is self-adapted by a mutation strategy similar to the mutation operator of DE. Nobakhti and Wang [23] proposed a Randomized Adaptive Differential Evolution (RADE) method, where a simple randomized self-adaptive scheme was proposed for the mutation weighting factor F. Das *et al.* [24] proposed two variants of DE, DERSF and DETVSF, that use varying scale factors. They concluded that those variants outperform the original DE. Teo [25] presented a dynamic self-adaptive populations DE, where the population size is self-adapting. Through five De Jong's test functions, they showed that DE with self-adaptive populations produced highly competitive results. Brest and Mauěc [26] proposed an improved DE method, where the population size is gradually reduced. They concluded that their approach improved efficiency and robustness of DE.

Qin and Suganthan [27] proposed a self-adaptive DE algorithm. The aim of their work was to allow DE to switch between two schemes: "DE/rand/1/bin" and "DE/best/2/bin" and also to adapt the F and CR values. The approach performed well on several benchmark problems. Recently, Qin *et al*. [28] extent their previous work [27]. In their SaDE, four schemes were adopted. And different CR values were also used for different mutation schemes. Their proposed algorithm outperformed the original DE and some other compared adaptive/self-adaptive DE variants [28].

Hybridization with other different algorithms is another direction for the improvement of DE. Fan and Lampinen [29] proposed a new version of DE that uses an additional mutation operation called trigonometric mutation operation. They showed that the modified DE algorithm can outperform the classic DE algorithm for some benchmarks and real-world problems. Sun *et al*. [30] proposed a new hybrid algorithm based on a combination of DE with Estimation of Distribution Algorithm (EDA). This technique uses a probability model to determine promising regions in order to focus the search process on those areas. Gong *et al*. [31] employed the two level orthogonal crossover to improve the performance of DE. They showed that the proposed approach performs better than the classical DE in terms of the quality, speed, and stability of the final solutions. Noman and Iba [32] proposed fittest individual refinement, a crossover-based local search (LS) method DE to solve the high dimensional problems. Based on their previous work [32], they incorporated LS into the classical DE in [5]. They presented a LS technique to solve this problem by adaptively adjusting the length of the search, using a hill-climbing heuristic. Through the experiments, they showed that the proposed new version of DE performs better, or at least comparably, to classic DE algorithm. Kaelo and Ali [33] adopted the attraction-repulsion concept of electromagnetism-like algorithm to boost the mutation operation of the original DE. Yang *et al*. [34] proposed a neighborhood search based DE algorithm. Experimental results showed that DE with neighborhood search has significant advantages over other existing algorithms on a broad range of different benchmark functions [34]. Wang *et al*. [35] proposed a dynamic clustering-based DE for global optimization, where a hierarchical clustering method is dynamically incorporated in DE. Experiments on 28 benchmark problems, including 13 high dimensional functions, showed that the new method is able to find near optimal solutions efficiently [35]. Rahnamayan *et al*. [36] proposed a novel initialization approach which employs opposition-based learning to generate initial population. Through a comprehensive set of benchmark functions

[1]Since the mutation operator of BBO is not used in our approach, we do not describe it here. Interested readers can refer to [6] and [18].

they showed that replacing the random initialization with the opposition-based population initialization in DE can accelerate convergence speed.

IV. Our approach: DE/BBO

As mentioned above, DE is good at exploring the search space and locating the region of global minimum. However, it is slow at exploitation of the solution [5]. On the other hand, BBO has a good exploitation for global optimization [6]. Based on these considerations, in order to balance the exploration and the exploitation of DE, in this work, we propose a hybrid DE approach, called DE/BBO, which combines the exploration of DE with the exploitation of BBO effectively. Our proposed DE/BBO approach is described as follows.

A. Hybrid migration operator

The main operator of DE/BBO is the hybrid migration operator, which hybridizes the DE operator with the migration operator of BBO, described in Algorithm 3. From Algorithm 3 we can see that the offspring U_i is possibly constituted by three components: the DE mutant, the migration of other solutions, and its corresponding parent X_i. The core idea of the proposed hybrid migration operator is based on two considerations. On the one hand, good solutions would be less destroyed, while poor solutions can accept a lot of new features from good solutions. In this sense, the current population can be exploited sufficiently. On the other hand, the mutation operator of DE is able to explore the new search space. From the analysis, it can be seen that the hybrid migration operator can balance the exploration and the exploitation effectively. It is worth pointing out that in Algorithm 3 the "DE/rand/1" mutation operator is illustrated, however, other mutation operators of DE can also be used in our proposed hybrid migration operator. And the influence of different mutation schemes will be discussed in Section V-F.

Algorithm 3 Hybrid migration operator of DE/BBO

for $i = 1$ to NP **do**
  Select uniform randomly $r_1 \neq r_2 \neq r_3 \neq i$
  j_{rand} = rndint$(1, D)$
  for $j = 1$ to D **do**
    if rndreal$(0, 1) < \lambda_i$ **then**
      if rndreal$_j[0, 1) > CR$ or $j == j_{rand}$ **then**
        $U_i(j) = X_{r_1}(j) + F \times \left(X_{r_2}(j) - X_{r_3}(j)\right)$ {The original mutation operator of DE.}
      else
        Select X_k with probability $\propto \mu_k$
        $U_i(j) = X_k(j)$
      end if
    else
      $U_i(j) = X_i(j)$
    end if
  end for
end for

B. Boundary constraints

In order to keep the solution of bound-constrained problems feasible, those trial parameters that violate boundary constraints should be reflected back from the bound by the amount of violation. In this work, the following repair rule is applied

$$X(i) = \begin{cases} l_i + \text{rndreal}_i[0,1] \times (u_i - l_i) & \text{if } X(i) < l_i \\ u_i - \text{rndreal}_i[0,1] \times (u_i - l_i) & \text{if } X(i) > u_i \end{cases} \quad (4)$$

where $\text{rndreal}_i[0, 1]$ is the uniform random variable from [0,1] in each dimension i.

C. Main procedure of DE/BBO

By incorporating the above-mentioned hybrid migration operator into DE, the DE/BBO approach is developed and shown in Algorithm 4. Compared with the original DE algorithm described in Algorithm 1, our approach needs only a small extra computational cost in sorting the population and calculating the migration rates. In addition, the structure of our proposed DE/BBO is also very simple. Moreover, DE/BBO is able to explore the new search space with the mutation operator of DE and to exploit the population information with the migration operator of BBO. This feature overcomes the lack of exploitation of the original DE algorithm.

Algorithm 4 The main procedure of DE/BBO

Generate the initial population P
Evaluate the fitness for each individual in P
while The halting criterion is not satisfied **do**
  For each individual, map the fitness to the number of species
  Calculate the immigration rate λ_i and the emigration rate μ_i for each individual X_i
  Modify the population with the hybrid migration operator shown in Algorithm 3
  for $i = 1$ to NP **do**
    Evaluate the offspring U_i
    if U_i is better than P_i **then**
      $P_i = U_i$
    end if
  end for
end while

V. Experimental results

In order to verity the performance of DE/BBO, twenty-three benchmark functions are chosen from [8]. Since we do not make any modification of these functions, they are only briefly described in Table I. A more detailed description of these functions can be found in [8], where the functions were divided into three categories: unimodal functions, multimodal functions with many local minima, and multimodal functions with a few local minima.

Functions f01 - f13 are high-dimensional and scalable problems. Functions f01 - f05 are unimodal. Function f06 is the step function, which has one minimum and is discontinuous. Function f07 is a noisy quartic function, where *random* [0,1) is a uniformly distributed random variable in [0,1). Functions f08 - f13 are multimodal functions where the number of local minima increases exponentially with the problem dimension. They appear to be the most difficult class of problems for many optimization algorithms. Functions f14 - f23 are low-dimensional functions that have only a few local minima.

TABLE I

BENCHMARK FUNCTIONS USED IN OUR EXPERIMENTAL STUDIES. MORE DETAILS OF ALL FUNCTIONS CAN BE FOUND IN [8].

Functions	Name	D	S	optimal
f01	Sphere Model	30	$[-100, 100]^D$	0
f02	Schwefel's Problem 2.22	30	$[-10, 10]^D$	0
f03	Schwefel's Problem 1.2	30	$[-100, 100]^D$	0
f04	Schwefel's Problem 2.21	30	$[-100, 100]^D$	0
f05	Generalized Rosenbrock's Functions	30	$[-30, 30]^D$	0
f06	Step Function	30	$[-100, 100]^D$	0
f07	Quartic Function	30	$[-1.28, 1.28]^D$	0
f08	Generalized Schwefel's Problem 2.26	30	$[-500, 500]^D$	-12569.5
f09	Generalized Rastrigin's Function	30	$[-5.12, 5.12]^D$	0
f10	Ackley's Function	30	$[-32, 32]^D$	0
f11	Generalized Griewank Function	30	$[-600, 600]^D$	0
f12	Generalized Penalized Function 1	30	$[-50, 50]^D$	0
f13	Generalized Penalized Function 2	30	$[-50, 50]^D$	0
f14	Shekel's Foxholes Function	2	$[-65.536, 65.536]^D$	1
f15	Kowalik's Function	4	$[-5, 5]^D$	0.003075
f16	Six-Hump Camel-Back Function	2	$[-5, 5]^D$	-1.0316285
f17	Branin Function	2	$[-5, 10] \times [0, 15]$	0.398
f18	Glodstein-Price Function	2	$[0, 1]^D$	3
f19	Hartman's Function 1	3	$[0, 1]^D$	-3.86
f20	Hartman's Function 2	6	$[0, 1]^D$	-3.32
f21	Shekel's Function 1	4	$[0, 10]^D$	-10.1532
f22	Shekel's Function 2	4	$[0, 10]^D$	-10.4029
f23	Shekel's Function 3	4	$[0, 10]^D$	-10.5364

A. Experimental setup

For DE/BBO, we have chosen a reasonable set of value and have not made any effort in finding the best parameter settings. For all experiments, we use the following parameters unless a change is mentioned.

- Population size: $NP = 100$ [5], [8], [21], [36];
- Habitat modification probability $= 1$ [6];
- Scaling factor: $F = \text{rndreal}(0.1, 1.0)$ [4], [16];
- Crossover probability: $CR = 0.9$ [2], [20], [25], [36];
- DE mutation scheme: DE/rand/1/bin [2], [5], [20], [25], [36];
- Value to reach: VTR = 10^{-8} [37], except for f07 of VTR = 10^{-2};
- Maximum Number of Fitness Function Evaluations (Max_NFFEs): For f01, f06, f10, f12, and f13, Max_NFFEs = 150000; for f03 - f05, Max_NFFEs = 500000; for f02 and f11, Max_NFFEs = 200000; For f07 - f09, Max_NFFEs = 300000; for f14, f16 - f19, f21, and f22, Max_NFFEs = 10000; for f15, Max_NFFEs = 40000; and for f20, Max_NFFEs = 20000.

Moreover, in our experiments, each function is optimized over 50 independent runs. We also use the same set of initial random populations to evaluate different algorithms in a similar way done in [5]. All the algorithms are implemented in standard C++. The source code can be obtained from the first author upon request.

B. Performance Criteria

Five performance criteria are selected from the literature [36], [37] to evaluate the performance of the algorithms. These criteria are described as follows.

- **Error** [37]: The error of a solution X is defined as $f(X) - f(X^*)$, where X^* is the global optimum of the function. The minimum error is recorded when the Max_NFFEs is reached in 50 runs. Also the average and standard deviation of the error values are calculated.
- **NFFEs** [37]: The number of fitness function evaluations (NFFEs) is also recorded when the VTR is reached. The average and standard deviation of the NFFEs values are calculated.
- **Number of successful runs (SR)** [37]: The number of successful runs is recorded when the VTR is reached before the max_NFFEs condition terminates the trial.
- **Convergence graphs** [37]: The convergence graphs show the mean error performance of the total runs, in the respective experiments.
- **Acceleration rate (AR)** [36]: This criterion is used to compare the convergence speeds between DE/BBO and other algorithms. It is defined as follows: $AR = \frac{\text{NFFEs}_{\text{other}}}{\text{NFFEs}_{\text{DE/BBO}}}$, where $AR > 1$ indicates DE/BBO is faster than its competitor.

C. General performance of DE/BBO

In order to show the superiority of our proposed DE/BBO approach, we compare it with the original DE algorithm and the BBO algorithm. The parameters used for DE/BBO and DE are the same as described in Section V-A. The parameters of BBO are set as in [6], and the mutation operator with $m_{\max} = 0.005$ is also used in our experiments. All functions are conducted for 50 independent runs. Table II shows the best error values of DE/BBO, DE, and BBO on all test functions. The average and standard deviation of NFFEs are shown in Table III. In addition, some representative convergence graphs of DE/BBO, DE, and BBO are shown in Figure 1.

When compared with DE: From Table II we can see that DE/BBO is significantly better than DE on 8 functions. However, DE/BBO is outperformed by DE on two functions (f03 and f05). For the rest 13 functions, there are no significant

TABLE II

BEST ERROR VALUES OF DE/BBO, DE, AND BBO ON ALL TEST FUNCTIONS, WHERE "MEAN" INDICATES THE MEAN BEST ERROR VALUES FOUND IN THE LAST GENERATION, "STD DEV" STANDS FOR THE STANDARD DEVIATION. "1 VS 2" MEANS "DE/BBO VS DE" AND "1 VS 3" MEANS "DE/BBO VS BBO". HEREAFTER, A RESULT WITH **BOLDFACE** MEANS BETTER VALUE FOUND.

F	DE/BBO			DE			BBO			1 vs 2	1 vs 3
	Mean	Std Dev	SR	Mean	Std Dev	SR	Mean	Std Dev	SR	*t-test*	*t-test*
f01	**8.66E-28**	5.21E-28	50	1.10E-19	1.34E-19	50	8.86E-01	3.26E-01	0	-5.81†	-19.21†
f02	**0.00E+00**	0.00E+00	50	1.66E-15	8.87E-16	50	2.42E-01	4.58E-02	0	-13.24†	-37.36†
f03	2.26E-03	1.58E-03	0	**8.19E-12**	1.65E-11	50	4.16E+02	2.02E+02	0	10.10†	-14.58†
f04	**1.89E-15**	8.85E-16	50	7.83E+00	3.78E+00	0	7.76E-01	1.72E-01	0	-14.65†	-31.96†
f05	1.90E+01	7.52E+00	0	**8.41E-01**	1.53E+00	6	9.14E+01	3.78E+01	0	16.73†	-13.28†
f06	**0.00E+00**	0.00E+00	50	**0.00E+00**	0.00E+00	50	2.80E-01	5.36E-01	38	0	-3.69†
f07	**3.44E-03**	8.27E-04	50	3.49E-03	9.60E-04	50	1.90E-02	7.29E-03	4	-0.29	-14.96†
f08	**0.00E+00**	0.00E+00	50	4.28E+02	4.69E+02	1	5.09E-01	1.65E-01	0	-6.45†	-21.78†
f09	**0.00E+00**	0.00E+00	50	1.14E+01	7.57E+00	0	8.50E-02	3.42E-02	0	-10.61†	-17.61†
f10	**1.07E-14**	1.90E-15	50	6.73E-11	2.86E-11	50	3.48E-01	7.06E-02	0	-16.66†	-34.81†
f11	**0.00E+00**	0.00E+00	50	1.23E-03	3.16E-03	43	4.82E-01	1.27E-01	0	-2.76†	-26.93†
f12	**7.16E-29**	6.30E-29	50	2.07E-03	1.47E-02	49	5.29E-03	5.21E-03	0	-1.00	-7.18†
f13	**9.81E-27**	7.10E-27	50	7.19E-02	5.09E-01	49	1.42E-01	5.14E-02	0	-1.00	-19.50†
f14	**0.00E+00**	0.00E+00	50	2.75E-13	1.55E-12	50	8.85E-06	2.74E-05	14	-1.26	-2.28†
f15	3.84E-12	2.70E-11	50	**4.94E-19**	5.20E-19	50	5.92E-04	2.68E-04	0	1.01	-15.65†
f16	1.15E-12	6.39E-12	50	**1.98E-13**	4.12E-13	50	6.75E-04	1.09E-03	0	1.05	-4.37†
f17	**2.92E-10**	1.38E-09	50	7.32E-10	2.21E-09	49	4.39E-04	4.26E-04	0	-1.19	-7.30†
f18	9.15E-13	6.51E-15	50	9.14E-13	5.01E-15	50	7.86E-03	9.57E-03	0	0.70	-5.81†
f19	**0.00E+00**	0.00E+00	50	1.36E-14	6.40E-15	50	2.51E-04	2.62E-04	0	-15.05†	-6.76†
f20	**0.00E+00**	0.00E+00	50	4.76E-03	2.35E-02	47	1.46E-02	3.90E-02	0	-1.43	-2.64†
f21	3.59E-03	1.44E-02	15	**6.83E-06**	1.26E-05	0	5.18E+00	3.34E+00	0	1.76	-10.95†
f22	**3.14E-07**	1.36E-06	29	7.26E-06	4.53E-05	1	3.67E+00	3.40E+00	0	-1.08	-7.63†
f23	**2.50E-08**	5.37E-08	27	3.70E-06	1.75E-05	0	2.73E+00	3.29E+00	0	-1.49	-5.87†

† The value of t with 49 degrees of freedom is significant at $\alpha = 0.05$ by two-tailed test.

TABLE III

NFFES REQUIRED TO OBTAIN ACCURACY LEVELS LESS THAN VTR. "NA" INDICATES THE ACCURACY LEVEL IS NOT OBTAINED AFTER MAX_NFFES. "1 VS 2" MEANS "DE/BBO VS DE" AND "1 VS 3" MEANS "DE/BBO VS BBO".

F	DE/BBO			DE			BBO			1 vs 2	1 vs 3
	Mean	Std Dev	SR	Mean	Std Dev	SR	Mean	Std Dev	SR	*AR*	*AR*
f01	**59926**	745.5	50	79688	1858.8	50	NA	NA	0	1.33	NA
f02	**82004**	983.9	50	119764	1871.2	50	NA	NA	0	1.46	NA
f03	NA	NA	0	**385990**	17193.4	50	NA	NA	0	NA	NA
f04	**296572**	4969.9	50	NA	NA	0	NA	NA	0	NA	NA
f05	NA	NA	0	**448583**	60428.8	6	NA	NA	0	NA	NA
f06	**21590**	573.3	50	28874	2014.5	50	119042	16882.8	38	1.34	5.51
f07	109574	21005.8	50	**103136**	29677.7	50	205000	23896.2	4	0.94	1.87
f08	**95952**	3126.7	50	251700	0	1	NA	NA	0	2.62	NA
f09	**170226**	8379.0	50	NA	NA	0	NA	NA	0	NA	NA
f10	**91308**	922.7	50	122340	2179.6	50	NA	NA	0	1.34	NA
f11	**62042**	1219.6	50	81986	1795.8	43	NA	NA	0	1.32	NA
f12	**54482**	873.3	50	71183	4700.9	49	NA	NA	0	1.31	NA
f13	**64772**	1133.4	50	93298	16916.8	49	NA	NA	0	1.44	NA
f14	**4532**	719.5	50	6768	766.0	50	5757	2351.3	14	1.49	1.27
f15	24028	3279.3	50	**12590**	977.8	50	NA	NA	0	0.52	NA
f16	**5676**	1012.7	50	5760	632.5	50	NA	NA	0	1.01	NA
f17	**7138**	1404.9	50	7271	1098.7	49	NA	NA	0	1.02	NA
f18	5050	374.3	50	**4610**	292.9	50	NA	NA	0	0.91	NA
f19	**4808**	352.2	50	5434	346.8	50	NA	NA	0	1.13	NA
f20	**9614**	705.1	50	14161	1553.3	47	NA	NA	0	1.47	NA
f21	**9560**	397.9	15	NA	NA	0	NA	NA	0	NA	NA
f22	**9527**	349.4	29	10000	0	1	NA	NA	0	1.05	NA
f23	**9533**	362.7	27	NA	NA	0	NA	NA	0	NA	NA

difference based on the t-test[2]. For the multimodal functions with many local minima (f08 - f13), DE/BBO can obtain the $VTR = 10^{-8}$ over all 50 runs within the Max_NFFEs. However, DE may trap into the local minima for five out of six functions. This indicates that our approach has the ability

[2]The paired t-test determines whether two paired sets differ from each other in a significant way under the assumptions that the paired differences are independent and identically normally distributed [38].

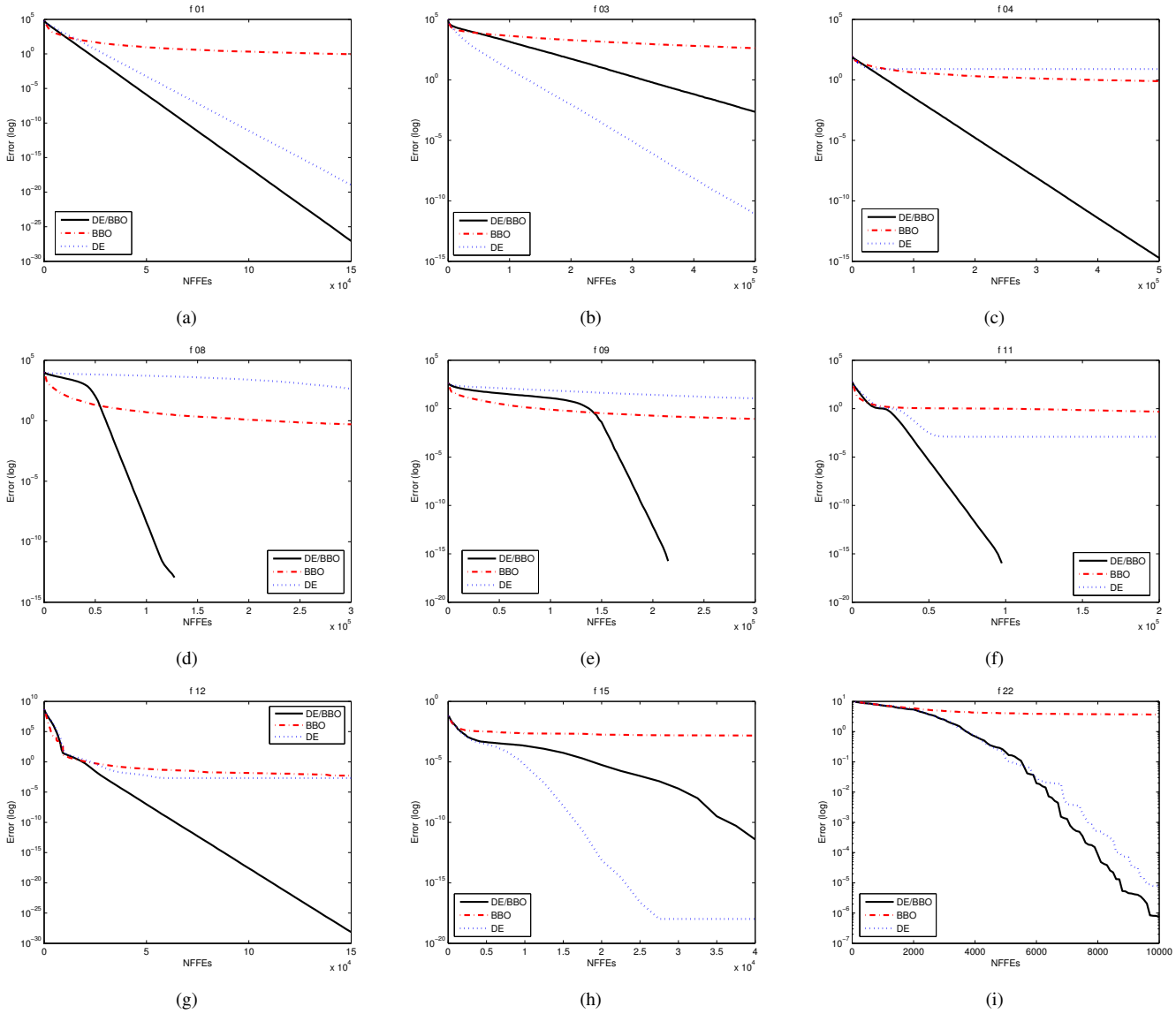

Fig. 1. Mean error curves of DE/BBO, DE, and BBO for selected functions. (a) f01. (b) f03. (c) f04. (d) f08. (e) f09. (f) f11. (g) f12. (h) f15. (i) f22.

to escape from poor local optima and locate a good near-global optimum. Apparently, from Table III it can be seen that DE/BBO requires less NFFEs to reach the VTR than DE on 18 functions. DE is faster than DE/BBO on the rest 5 functions. Additionally, for the majority of the test functions DE/BBO converges faster than DE as shown in Figure 1.

When compared with BBO: From Tables II , III and Figure 1, it is obvious that DE/BBO performs significantly better than BBO consistently with respect to all five criteria for all test functions. By carefully looking at Figure 1, we can see that in the beginning of the evolutionary process BBO converges faster than DE/BBO while DE/BBO is able to improve its solution steadily for a long run. The reason might be that BBO has a good exploitation but lacks the exploration. However, for DE/BBO with the hybrid migration operator, it can balance the exploration and the exploitation effectively.

In general, the performance of DE/BBO is highly competitive with DE, especially for the high-dimensional problems. Moreover, DE/BBO is significantly better than BBO for all problems. Since for the majority of the low-dimensional functions (f14 - f23), both DE/BBO and DE have no significant difference, we will not use these functions in the following experiments. In addition, we also don't compare the algorithms with BBO in the following experiments.

D. Influence of population size

The choice of the best population size of DE is always critical for different problems [19], [25], [26]. Increasing the population size will increase the diversity of possible movements, promoting the exploration of the search space. However, the probability to find the correct search direction decreases considerably [39]. The influence of population size is investigated in this section. For both DE/BBO and DE, all the parameter settings are the same as mentioned in Section V-A, only except for $NP = 50$, $NP = 150$, and $NP = 200$.

The results for different population size are shown in

Table IV. It can be seen that: i) for $NP = 50$ DE/BBO is significantly better than DE on 10 functions while it is outperformed by DE for function f03. For f05, DE/BBO is sightly better than DE. And for f13, DE/BBO can locate the near-global optimum over all 50 runs, however, DE traps into the local minima on 14 out of 50 runs. ii) When the population increases to $NP = 100$, DE can obtain higher overall successful runs than $NP = 50$. DE/BBO is significantly better than DE on 8 functions based on the t-test results. DE is significantly better than DE/BBO for functions f03 and f05. For the rest 3 functions, DE/BBO is better than DE. iii) For $NP = 150$ and $NP = 200$, DE/BBO is able to obtain significant better performance than DE on 8 and 9 functions, respectively. Similarly, for f03 and f05, DE/BBO is outperformed by DE significantly. In addition, from Figure 2 we can see that DE/BBO can obtain higher convergence speed to different population size for the majority of functions compared with DE.

In general, the overall performance of DE/BBO is better than DE to different population size. DE/BBO exhibits higher overall successful runs, higher convergence velocity, and more robustness than DE.

E. Effect of dimensionality

In order to investigate the influence of the problem dimension on the performance of DE/BBO, we carry out a scalability study comparing with the original DE algorithm for the scalable functions in the test suit. For functions f01 - f13, $D = 10, 50, 100, \text{and } 200$. The results are recorded in Table V after $D \times 10000$ NFFEs, and some representative convergence graphs are shown in Figure 3. From Table V we can see that the overall SR is decreasing for both DE/BBO and DE, since increasing the problem dimension leads to the algorithms sometimes unable to solve the problem before reaching the Max_NFFEs. However, similarly to $D = 30$, on the majority of functions, DE/BBO outperforms DE at every dimension. By carefully looking at the results, we can recognize that for f05 DE is better than DE/BBO at $D = 10$ and $D = 30$, however, DE is outperformed by DE/BBO at higher dimension ($D = 50, 100, \text{and } 200$). So, from the experimental results of this section, we can conclude that the hybrid migration operator has the ability to accelerate DE in general, especially the improvements are more significant at higher dimensionality.

F. Influence of different mutation schemes

There are ten mutation schemes proposed in the original DE [3], [4]. Actually, choosing the best among different mutation schemes available for DE is also not easy for a specific problem [27], [28]. In this section, we perform additional experiment to compare the performance of DE/BBO with that of DE to different schemes. Four schemes, namely, DE/best/1/bin, DE/rand/2/bin, DE/rand-to-best/1/bin, and DE/best/2/bin are chosen in these experiments. All remaining parameters are the same as mentioned in Section V-A. Table VI gives the results of DE/BBO and DE for the four schemes. Based on the t-test, the results can be summarized as "$w/t/l$", which means that DE/BBO wins in w functions, ties in t functions, and loses in l functions, compared with DE. From Table VI, for DE/best/1/bin, DE/rand/2/bin, DE/rand-to-best/1/bin, and DE/best/2/bin, they are $12/1/0$, $9/2/2$, $8/3/2$, and $10/2/1$, respectively. The results indicate that DE/BBO is able to obtain greater robustness than DE to different mutation schemes on the majority of functions.

G. Influence of self-adaptive parameter control

As mentioned above, the choice of the control parameters F and CR is sensitive for different problems [19]. Researchers have proposed the adaptive parameter control of DE, such as [20], [21], and so on. In order to show that DE/BBO can also improve the self-adaptive DE, in this section, we adopt the self-adaptive parameter control proposed in [21] to replace $F = \text{rndreal}(0.1, 1.0)$ and $CR = 0.9$ in the previous experiments. All other parameter settings are kept unchanged. The results for the self-adaptive DE (SADE) and self-adaptive DE/BBO (SADE/BBO) are given in Table VII.

According to Table VII, we can see that: first, for the Error values, both SADE/BBO and SADE can obtain the global optimum on five functions (f02, f06, f08, f09, and f11) over 50 runs. SADE/BBO is significantly better than SADE on five functions. SADE outperforms SADE/BBO on two functions (f03 and f05). Second, with respect to the NFFEs, it is obvious that SADE/BBO is significantly better than SADE on 11 functions. And the AR values are larger than 1 for these functions, it means that SADE/BBO is faster than SADE. For functions f03 and f05, SADE/BBO fails to solve the two functions over all 50 runs. Overall, integration of the hybrid migration operator can improve the performance of SADE.

H. Comparison with other DE hybrids

In this section, we make a comparison with other DE hybrids. Since there are many variants of DE, we only compare our approach with DEahcSPX proposed in [5], ODE proposed in [36], and DE/EDA proposed in [30].

1) Comparison with DEahcSPX and ODE: Firstly, we compare our approach with DEahcSPX and ODE. In DEahcSPX, a crossover-based adaptive local search operation to accelerate the original DE. The authors concluded that DEahcSPX outperforms the original DE in items of convergence rate in all experimental studies. In ODE, the opposition-based learning is used for the population initialization and generation jumping. In this section, we compare our proposed CDE with the original DE, DEahcSPX and ODE. All the parameter settings are the same as mentioned in Section V-A. For DEahcSPX, the number of parents in SPX sets to be $n_p = 3$ [5]. For ODE, the jump rate $J_r = 0.3$ [36]. The results are given in Table VIII. The selected representative convergence graphs are shown in Figure 4.

It can be seen that, from Table VIII, DE/BBO is significantly better than DEahcSPX on 8 functions while it is outperformed by DEahcSPX on two functions (f03 and f05). For the rest three functions, there are no significant difference between DE/BBO and DEachSPX. However, for f12 and f13, DE/BBO can obtain the near-global optimum over all 50 runs while

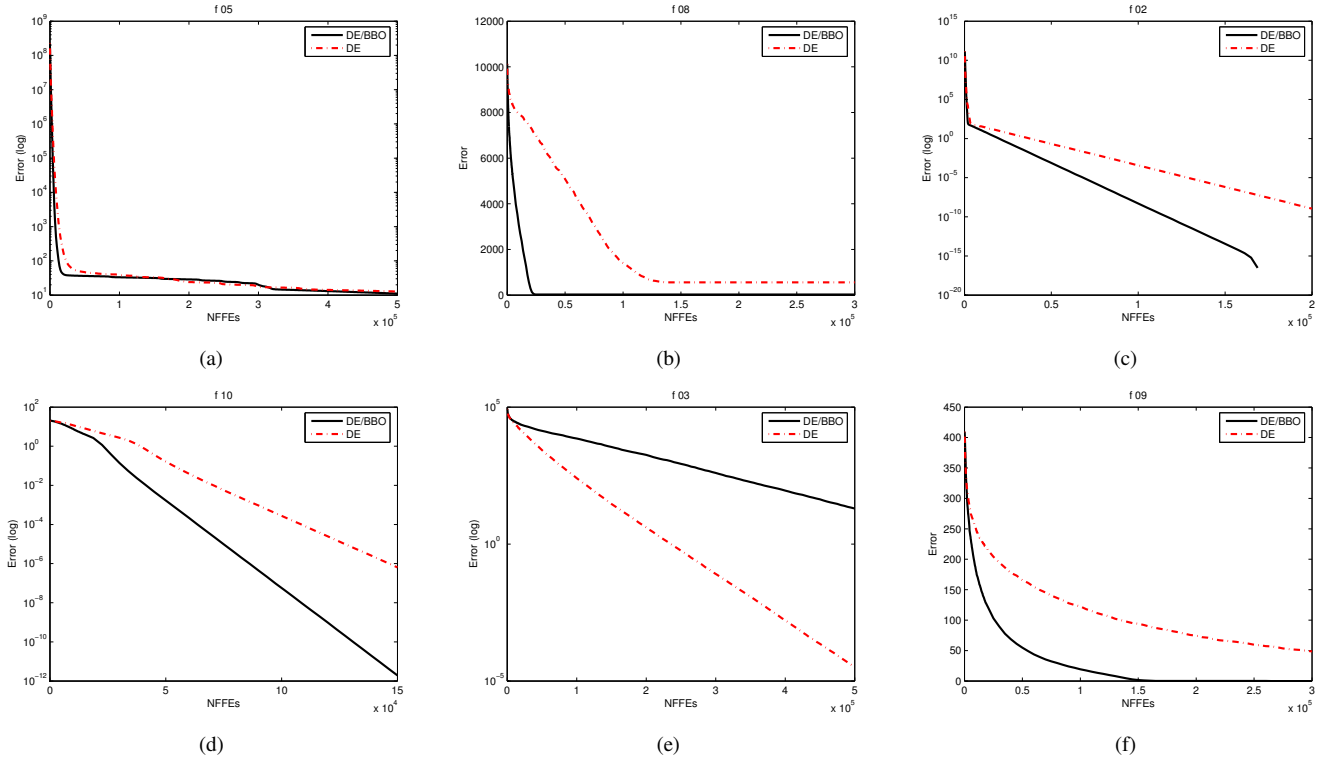

Fig. 2. Mean error curves of DE/BBO and DE to different population size for selected functions at $D = 30$. (a) f05 ($NP = 50$). (b) f08 ($NP = 50$). (c) f02 ($NP = 150$). (d) f10 ($NP = 150$). (e) f03 ($NP = 200$). (f) f09 ($NP = 200$).

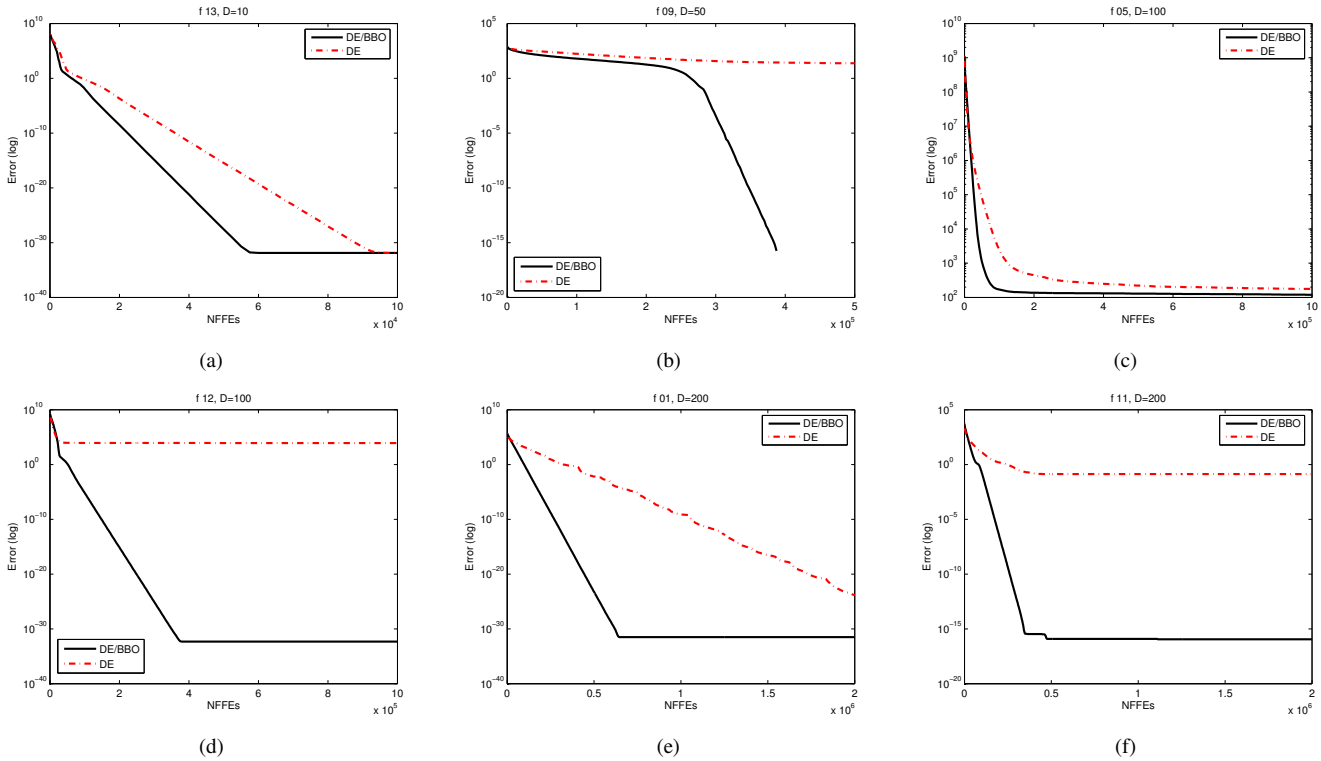

Fig. 3. Mean error curves to compare the scalability of DE/BBO and DE for selected functions. (a) f13 ($D = 10$). (b) f09 ($D = 50$). (c) f05 ($D = 100$). (d) f12 ($D = 100$). (e) f01 ($D = 200$). (f) f11 ($D = 200$).

TABLE IV

INFLUENCE OF THE PERFORMANCE TO DIFFERENT POPULATION SIZE FOR FUNCTIONS f01 − f13 ($D = 30$). HEREAFTER, (#) INDICATES THE NUMBER OF SUCCESSFUL RUNS AND $[a \pm b]$ DENOTES THE AVERAGED NFFES REQUIRED WHEN THE **GLOBAL MINIMUM** ACHIEVED BEFORE USING MAX_NFFES FOR ALL ALGORITHMS.

F	$NP = 50$		$NP = 100$	
	DE/BBO	DE	DE/BBO	DE
f01	**4.93E-34 ± 2.44E-33** (50)	6.73E-33 ± 9.09E-33 (50)†	**8.66E-28 ± 5.21E-28** (50)	1.10E-19 ± 1.34E-19 (50)†
f02	**0.00E+00 ± 0.00E+00** (50)	1.55E-17 ± 4.49E-17 (50)†	**0.00E+00 ± 0.00E+00** (50)	1.66E-15 ± 8.87E-16 (50)†
f03	7.69E-13 ± 8.68E-13 (50)	**3.03E-17 ± 2.10E-16** (50)‡	2.26E-03 ± 1.58E-03 (0)	**8.19E-12 ± 1.65E-11** (50)‡
f04	**1.37E-06 ± 6.00E-06** (40)	1.72E+01 ± 5.64E+00 (0)†	**1.89E-15 ± 8.85E-16** (50)	7.83E+00 ± 3.78E+00 (0)†
f05	**1.10E+01 ± 5.63E+00** (0)	1.27E+01 ± 7.26E+00 (0)	1.90E+01 ± 7.52E+00 (0)	**8.41E-01 ± 1.53E+00** (6)‡
f06	**[9.39E+03±3.09E+02]** (50)	[1.95E+04±6.20E+03] (50)†	**[2.16E+04±5.73E+02]** (50)	[2.89E+04 ± 2.01E+03] (50)†
f07	**1.64E-03 ± 3.67E-04** (50)	4.19E-03 ± 2.05E-03 (50)†	**3.44E-03 ± 8.27E-04** (50)	3.49E-03 ± 9.60E-04 (50)
f08	**2.37E+01 ± 5.35E+01** (41)	5.57E+02 ± 3.38E+02 (0)†	**0.00E+00 ± 0.00E+00** (50)	4.28E+02 ± 4.69E+02 (1)†
f09	**5.37E-01 ± 7.84E-01** (31)	1.23E+01 ± 4.17E+00 (0)†	**0.00E+00 ± 0.00E+00** (50)	1.14E+01 ± 7.57E+00 (0)†
f10	**4.14E-15 ± 0.00E+00** (50)	7.45E-02 ± 2.55E-01 (46)†	**1.07E-14 ± 1.90E-15** (50)	6.73E-11 ± 2.86E-11 (50)†
f11	**3.45E-04 ± 1.73E-03** (48)	4.83E-03 ± 7.90E-03 (32)†	**0.00E+00 ± 0.00E+00** (50)	1.23E-03 ± 3.16E-03 (43)†
f12	**1.57E-32 ± 0.00E+00** (50)	4.98E-02 ± 1.26E-01 (41)†	**7.16E-29 ± 6.30E-29** (50)	2.07E-03 ± 1.47E-02 (49)
f13	**1.36E-32 ± 7.15E-34** (50)	3.61E+00 ± 1.80E+01 (36)	**9.81E-27 ± 7.10E-27** (50)	7.19E-02 ± 5.09E-01 (49)
F	$NP = 150$		$NP = 200$	
	DE/BBO	DE	DE/BBO	DE
f01	**7.60E-23 ± 3.75E-23** (50)	6.36E-12 ± 4.24E-12 (50)†	**1.91E-16 ± 7.51E-17** (50)	7.24E-08 ± 2.98E-08 (0)†
f02	**0.00E+00 ± 0.00E+00** (50)	1.12E-09 ± 3.67E-10 (50)†	**1.88E-14 ± 4.27E-15** (50)	8.87E-07 ± 2.37E-07 (0)†
f03	8.10E-01 ± 4.63E-01 (0)	**1.16E-07 ± 2.24E-07** (2)‡	1.98E+01 ± 9.76E+00 (0)	**3.27E-05 ± 3.17E-05** (0)‡
f04	**2.33E-13 ± 1.02E-13** (50)	4.74E+00 ± 3.21E+00 (0)†	**6.53E-10 ± 2.04E-10** (50)	2.61E+00 ± 1.95E+00 (0)†
f05	1.99E+01 ± 5.26E-01 (0)	**1.84E+00 ± 1.58E+00** (0)‡	2.11E+01 ± 4.06E-01 (0)	**4.85E+00 ± 1.63E+00** (0)‡
f06	**[2.56E+04±6.27E+02]** (50)	[4.27E+04±1.53E+03] (50)†	**[3.36E+04±6.97E+02]** (50)	[5.78E+04 ± 1.74E+03] (50)†
f07	**3.93E-03 ± 7.69E-04** (50)	4.39E-03 ± 1.10E-03 (50)†	**5.03E-03 ± 1.09E-03** (50)	5.55E-03 ± 1.75E-03 (50)
f08	**0.00E+00 ± 0.00E+00** (50)	2.35E+03 ± 1.13E+03 (0)†	**0.00E+00 ± 0.00E+00** (50)	3.10E+03 ± 1.04E+03 (0)†
f09	**0.00E+00 ± 0.00E+00** (50)	3.27E+01 ± 1.43E+01 (0)†	**0.00E+00 ± 0.00E+00** (50)	4.86E+01 ± 1.21E+01 (0)†
f10	**1.91E-12 ± 5.21E-13** (50)	6.40E-07 ± 1.98E-07 (0)†	**3.11E-09 ± 5.76E-10** (50)	7.04E-05 ± 1.68E-05 (0)†
f11	**0.00E+00 ± 0.00E+00** (50)	2.22E-18 ± 1.57E-17 (50)	**0.00E+00 ± 0.00E+00** (50)	4.93E-04 ± 1.99E-03 (47)
f12	**5.13E-24 ± 3.15E-24** (50)	2.07E-03 ± 1.47E-02 (49)	**1.17E-17 ± 5.01E-18** (50)	1.58E-09 ± 1.01E-09 (50)†
f13	**6.84E-22 ± 5.10E-22** (50)	2.51E-03 ± 1.78E-02 (49)	**1.75E-15 ± 8.37E-16** (50)	9.58E-08 ± 7.78E-08 (0)†

†, ‡ The value of t with 49 degrees of freedom is significant at $\alpha = 0.05$ by two-tailed test.
‡ means that the corresponding algorithm is better than our proposed DE/BBO method.

DEahcSPX traps into the local minima on one run, respectively. In addition, Figure 4 shows that DE/BBO converges faster than DEahcSPX on the major functions.

With respect to ODE, the t-test is $9/2/2$ in Table VIII. It means that DE/BBO significantly outperforms ODE on 9 out of 13 functions. ODE is significantly better than DE/BBO on two functions (f03 and f07). For f01 and f10, there are no significant difference between DE/BBO and ODE, however, DE/BBO is slightly better than ODE. Moreover, on the majority of functions, DE/BBO exhibits higher convergence rate than ODE.

2) Comparison with DE/EDA: Secondly, the comparison between DE/BBO and DE/EDA is conducted in this section. The reason is that DE/BBO is similar to DE/EDA, i.e., both algorithms combine DE with another global optimization algorithm to improve the performance of DE. DE/EDA combines global information extracted by EDA with differential information obtained by DE to create promising solutions [30]. DE/BBO integrates the migration operator of BBO into DE to balance the exploration and the exploitation. In original DE/EDA algorithm[3], the DE mutation scheme is described as follows

$$U_i(j) = \Big[X_{r_1}(j) + X_i(j)\Big]/2 + F \times \Big[\Big(X_{r_1}(j) - X_i(j)\Big) + \Big(X_{r_2}(j) - X_{r_3}(j)\Big)\Big] \quad (5)$$

where X_i is the target vector of DE. In order to make a fair comparison, all compared algorithms (DE, DE/BBO, and DE/EDA) adopt the mutation scheme shown in Eqn. 5 to replace the DE/rand/1/bin scheme. All other parameters are the same as mentioned in Section V-A. The results are presented in Table IX. And the selected representative convergence graphs are shown in Figure 5.

When compared with DE: DE/BBO is significantly better than DE on 11 functions. For the rest two functions (f06 and f13), DE/BBO is also better than DE. Additionally, DE/BBO is able to obtain faster convergence velocity than DE for all functions.

When compared with DE/EDA: The overall SR of DE/BBO is better than DE/EDA. On 9 functions, DE/BBO is significantly better than DE/EDA. DE/EDA is significantly better than DE/BBO only on one functions (f03). For the rest three functions, there are no significant difference. By carefully looking at the results in Table IX, we can see that DE/BBO is substantial better than DE/EDA for all multimodal functions

[3]The source code of DE/EDA is available online at: http://cswww.essex.ac.uk/staff/qzhang/IntrotoResearch/HybridEDA.htm

TABLE V

SCALABILITY STUDY FOR FUNCTIONS f01 − f13 AT Max_NFFEs = $D \times 10000$.

F	$D = 10$		$D = 50$	
	DE/BBO	DE	DE/BBO	DE
f01	**[1.89E+04 ± 3.63E+02]** (50)	[3.08E+04 ± 8.41E+02] (50)†	**0.00E+00 ± 0.00E+00** (50)	1.87E-32 ± 1.64E-32 (50)†
f02	**[2.63E+04 ± 4.19E+02]** (50)	[4.71E+04 ± 7.61E+02] (50)†	**0.00E+00 ± 0.00E+00** (50)	1.44E-17 ± 3.97E-17 (50)†
f03	6.07E-14 ± 9.60E-14 (50)	**1.35E-21 ± 2.49E-21** (50)‡	5.20E+02 ± 2.48E+02 (0)	**1.12E-01 ± 8.06E-02** (0)‡
f04	**1.58E-16 ± 9.88E-17** (50)	1.39E-13 ± 1.22E-13 (50)†	**3.42E-03 ± 2.28E-02** (3)	1.95E+01 ± 4.14E+00 (0)†
f05	3.40E+00 ± 8.03E-01 (0)	**3.53E-11 ± 1.24E-10** (50)‡	**4.43E+01 ± 1.39E+01** (0)	5.33E+01 ± 2.89E+01 (0)
f06	**[6.62E+03 ± 3.28E+02]** (50)	[1.06E+04 ± 5.50E+02] (50)†	**[2.74E+04 ± 6.22E+02]** (50)	[5.57E+04 ± 1.64E+04] (50)†
f07	**1.11E-03 ± 3.96E-04** (50)	1.52E-03 ± 5.97E-04 (50)†	**4.05E-03 ± 9.20E-04** (50)	9.49E-03 ± 3.07E-03 (34)†
f08	**0.00E+00 ± 0.00E+00** (50)	1.51E-11 ± 1.05E-10 (50)	**2.37E+00 ± 1.67E+01** (49)	1.51E+03 ± 9.97E+02 (0)†
f09	**0.00E+00 ± 0.00E+00** (50)	3.75E+00 ± 2.72E+00 (5)†	**0.00E+00 ± 0.00E+00** (50)	2.33E+01 ± 8.27E+00 (0)†
f10	**5.89E-16 ± 0.00E+00** (50)	8.02E-16 ± 8.52E-16 (50)	**5.92E-15 ± 1.79E-15** (50)	3.52E-02 ± 1.74E-01 (48)
f11	**0.00E+00 ± 0.00E+00** (50)	8.54E-03 ± 1.56E-02 (31)†	**0.00E+00 ± 0.00E+00** (50)	5.08E-03 ± 1.62E-02 (9)†
f12	4.71E-32 ± 0.00E+00 (50)	4.71E-32 ± 0.00E+00 (50)	**9.42E-33 ± 0.00E+00** (50)	4.51E-02 ± 1.40E-01 (41)†
f13	1.35E-32 ± 0.00E+00 (50)	1.35E-32 ± 0.00E+00 (50)	**1.35E-32 ± 0.00E+00** (50)	1.34E-01 ± 5.74E-01 (40)

F	$D = 100$		$D = 200$	
	DE/BBO	DE	DE/BBO	DE
f01	**6.16E-34 ± 1.97E-33** (50)	2.30E-31 ± 1.37E-31 (50)†	**3.07E-32 ± 2.48E-32** (50)	1.41E-24 ± 3.14E-24 (50)†
f02	**0.00E+00 ± 0.00E+00** (50)	7.95E-16 ± 1.05E-15 (50)†	**5.83E-17 ± 8.11E-17** (50)	7.38E-09 ± 2.33E-08 (46)†
f03	3.10E+04 ± 1.12E+04 (0)	**1.31E+02 ± 5.76E+01** (0)‡	2.22E+05 ± 5.90E+04 (0)	**3.64E+03 ± 7.60E+02** (0)‡
f04	**2.71E+00 ± 2.58E+00** (0)	3.05E+01 ± 4.00E+00 (0)†	**1.59E+01 ± 3.43E+00** (0)	4.27E+01 ± 4.31E+00 (0)†
f05	**1.19E+02 ± 3.38E+01** (0)	1.76E+02 ± 4.22E+01 (0)†	**2.95E+02 ± 4.48E+01** (0)	4.39E+02 ± 1.11E+02 (0)†
f06	**[4.93E+04 ± 1.11E+03]** (50)	[3.30E+05 ± 1.34E+05] (50)†	**0.00E+00 ± 0.00E+00** (50)	3.00E+00 ± 7.75E+00 (20)
f07	**6.87E-03 ± 1.15E-03** (49)	4.84E-02 ± 2.19E-02 (0)†	**1.56E-02 ± 2.82E-03** (0)	2.19E-01 ± 7.38E-02 (0)†
f08	**7.11E+00 ± 2.84E+01** (47)	6.79E+03 ± 1.07E+03 (0)†	**2.01E+02 ± 1.68E+02** (23)	2.47E+04 ± 2.44E+03 (0)†
f09	**7.36E-01 ± 8.48E-01** (23)	7.28E+01 ± 1.07E+01 (0)†	**1.76E+01 ± 2.89E+00** (0)	2.12E+02 ± 2.12E+01 (0)†
f10	**7.84E-15 ± 7.03E-16** (50)	1.87E+00 ± 5.72E-01 (1)†	**1.09E-14 ± 1.12E-15** (50)	5.30E+00 ± 8.47E-01 (0)†
f11	**0.00E+00 ± 0.00E+00** (50)	8.43E-03 ± 1.71E-02 (36)†	**1.11E-16 ± 0.00E+00** (50)	1.33E-01 ± 2.50E-01 (0)
f12	**4.71E-33 ± 0.00E+00** (50)	8.07E+03 ± 2.82E+04 (26)†	**2.36E-33 ± 0.00E+00** (50)	5.71E+04 ± 7.31E+04 (8)†
f13	**1.76E-32 ± 2.68E-32** (50)	1.85E+03 ± 7.38E+03 (12)	**8.36E-32 ± 1.44E-31** (50)	1.65E+05 ± 2.91E+05 (0)

†, ‡ The value of t with 49 degrees of freedom is significant at $\alpha = 0.05$ by two-tailed test.
‡ means that the corresponding algorithm is better than our proposed DE/BBO method.

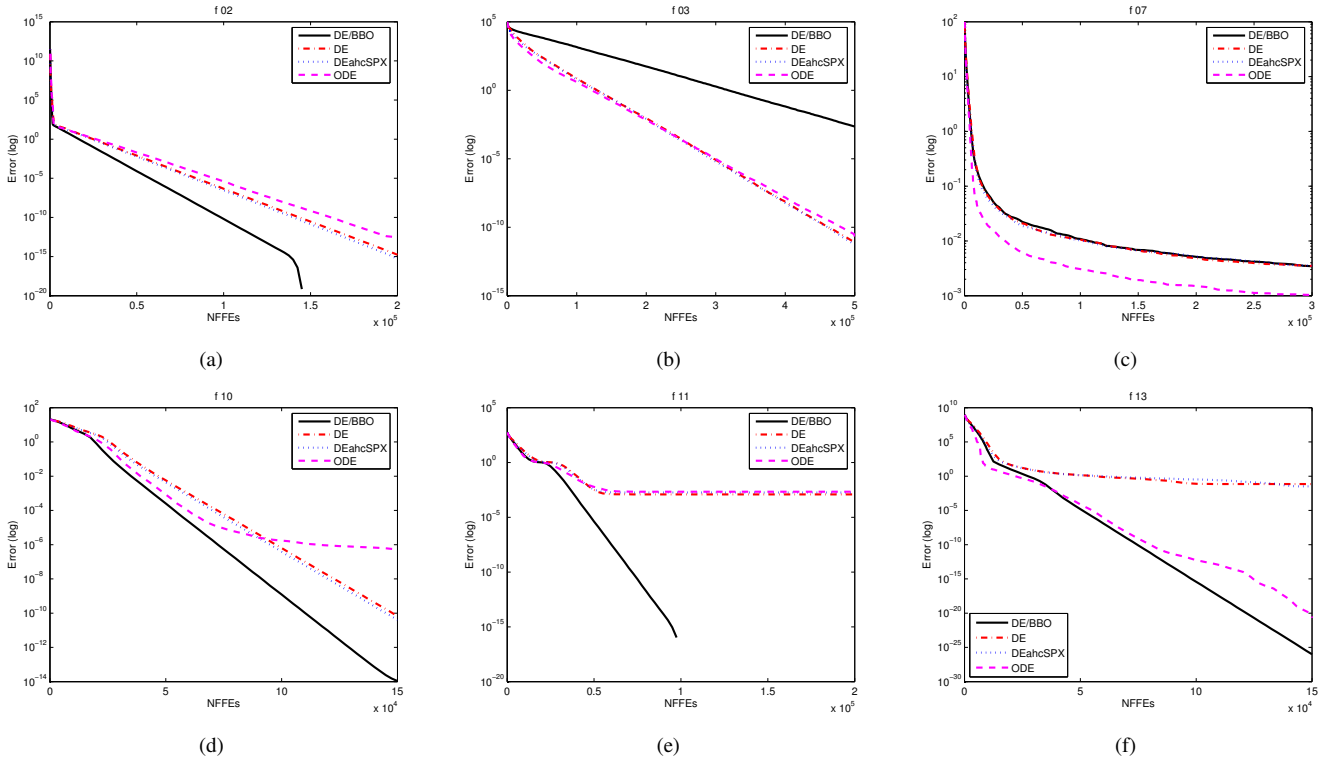

Fig. 4. Mean error curves of DE/BBO, DE, DEahcSPX, and ODE for selected functions. (a) f02. (b) f03. (c) f07. (d) f10. (e) f11. (f) f13.

TABLE VI

COMPARISON OF DE/BBO AND DE TO DIFFERENT MUTATION SCHEMES FOR FUNCTIONS f01 − f13 ($D = 30$).

F	DE/best/1/bin		DE/rand/2/bin	
	DE/BBO	DE	DE/BBO	DE
f01	**3.71E-32 ± 3.61E-32** (50)	1.25E+02 ± 1.55E+02 (0)†	**1.27E-17 ± 6.15E-18** (50)	1.53E-10 ± 8.92E-11 (50)†
f02	**5.46E-16 ± 1.81E-15** (50)	4.16E+00 ± 3.02E+00 (0)†	**4.70E-15 ± 1.54E-15** (50)	2.02E-08 ± 9.61E-09 (2)†
f03	**8.15E-30 ± 2.66E-29** (50)	2.62E+02 ± 3.04E+02 (0)†	1.31E+01 ± 7.15E+00 (0)	**7.28E-07 ± 8.90E-07** (0)‡
f04	**2.36E+01 ± 5.72E+00** (0)	2.97E+01 ± 6.06E+00 (0)†	**2.04E-09 ± 7.53E-10** (50)	5.18E+00 ± 3.41E+00 (0)†
f05	**8.72E+00 ± 1.43E+01** (8)	1.14E+04 ± 1.43E+04 (0)†	9.25E+00 ± 1.30E+00 (0)	**9.60E-02 ± 5.63E-01** (0)‡
f06	**1.56E+01 ± 2.98E+01** (0)	1.17E+03 ± 5.42E+02 (0)†	**[3.16E+04 ± 8.95E+02]** (50)	[4.74E+04 ± 1.88E+03] (50)†
f07	**4.07E-03 ± 1.39E-03** (50)	9.53E-03 ± 5.73E-03 (43)†	**5.21E-03 ± 1.26E-03** (50)	5.41E-03 ± 1.46E-03 (49)
f08	**6.58E+02 ± 2.94E+02** (0)	4.84E+03 ± 6.80E+02 (0)†	**0.00E+00 ± 0.00E+00** (50)	6.71E+03 ± 2.95E+02 (0)†
f09	**1.85E+01 ± 7.55E+00** (0)	7.26E+01 ± 1.51E+01 (0)†	**7.60E-05 ± 2.98E-04** (12)	1.16E+02 ± 2.28E+01 (0)†
f10	**2.48E+00 ± 1.16E+00** (2)	9.73E+00 ± 1.66E+00 (0)†	**8.65E-10 ± 2.00E-10** (50)	3.11E-06 ± 1.04E-06 (0)†
f11	**3.22E-02 ± 4.06E-02** (12)	2.13E+00 ± 1.33E+00 (0)†	**0.00E+00 ± 0.00E+00** (50)	6.41E-04 ± 2.22E-03 (46)†
f12	**6.70E-01 ± 1.15E+00** (20)	2.77E+01 ± 2.24E+01 (0)†	**1.31E-18 ± 1.09E-18** (50)	8.03E-12 ± 1.04E-11 (50)†
f13	**7.14E-01 ± 1.24E+00** (1)	2.67E+04 ± 1.28E+05 (0)	**3.28E-16 ± 3.02E-16** (50)	1.29E-04 ± 9.08E-04 (44)

F	DE/rand-to-best/1/bin		DE/best/2/bin	
	DE/BBO	DE	DE/BBO	DE
f01	**0.00E+00 ± 0.00E+00** (50)	1.23E-34 ± 6.10E-34 (50)	**1.65E-32 ± 1.37E-32** (50)	1.65E-31 ± 1.93E-31 (50)†
f02	**[3.42E+04 ± 3.97E+02]** (50)	[4.14E+04 ± 3.72E+03] (50)†	**3.11E-17 ± 6.65E-17** (50)	7.88E-15 ± 3.26E-14 (50)
f03	3.71E-25 ± 8.69E-25 (50)	**5.63E-32 ± 2.72E-32** (50)‡	3.28E-30 ± 5.47E-30 (50)	**1.07E-30 ± 8.69E-31** (50)‡
f04	**2.63E+00 ± 1.35E+00** (0)	2.95E+00 ± 1.31E+00 (0)	**2.31E-06 ± 6.77E-06** (3)	3.64E-02 ± 4.42E-02 (0)†
f05	1.28E+01 ± 3.24E+00 (0)	**1.04E+00 ± 1.77E+00** (37)‡	**1.10E+01 ± 5.63E+00** (0)	1.27E+01 ± 7.26E+00 (0)
f06	**2.00E-02 ± 1.41E-01** (49)	3.42E+00 ± 4.13E+00 (5)†	**2.20E-01 ± 4.65E-01** (40)	1.34E+01 ± 1.95E+01 (2)†
f07	**8.43E-04 ± 2.62E-04** (50)	2.17E-03 ± 7.98E-04 (50)†	**2.20E-03 ± 7.68E-04** (50)	5.33E-03 ± 2.81E-03 (46†
f08	**4.97E+01 ± 7.60E+01** (33)	3.15E+03 ± 5.79E+02 (0)†	**2.61E+01 ± 5.50E+01** (40)	4.60E+03 ± 5.21E+02 (0)†
f09	**3.98E-02 ± 1.97E-01** (48)	2.37E+01 ± 7.13E+00 (0)†	**1.11E+00 ± 1.25E+00** (19)	5.71E+01 ± 1.48E+01 (0)†
f10	**6.13E-15 ± 1.78E-15** (50)	1.69E+00 ± 7.01E-01 (0)†	**1.77E-01 ± 4.19E-01** (42)	3.99E+00 ± 1.14E+00 (0)†
f11	**1.23E-03 ± 3.24E-03** (43)	1.35E-02 ± 1.52E-02 (12)†	**6.74E-03 ± 8.82E-03** (23)	2.60E-02 ± 4.33E-02 (16)†
f12	**2.07E-03 ± 1.47E-02** (49)	7.06E-02 ± 1.71E-01 (34)†	**6.43E-02 ± 1.63E-01** (40)	1.54E+00 ± 2.35E+00 (8)†
f13	**2.20E-04 ± 1.55E-03** (49)	2.71E+00 ± 1.05E+01 (16)	**5.47E-03 ± 1.93E-02** (41)	1.99E+01 ± 2.41E+01 (0)†

†, ‡ The value of t with 49 degrees of freedom is significant at $\alpha = 0.05$ by two-tailed test.
‡ means that the corresponding algorithm is better than our proposed DE/BBO method.

TABLE VII

INFLUENCE OF SELF-ADAPTIVE PARAMETER CONTROL TO DE/BBO AND DE FOR FUNCTIONS f01 − f13 ($D = 30$).

F	Error		NFFEs		
	SADE/BBO	SADE	SADE/BBO	SADE	AR
f01	**0.00E+00 ± 0.00E+00** (50)	1.75E-27 ± 1.57E-27 (50)†	**3.91E+04 ± 8.15E+02**	6.11E+04 ± 1.12E+03†	1.56
f02	0.00E+00 ± 0.00E+00 (50)	0.00E+00 ± 0.00E+00 (50)	**5.12E+04 ± 8.17E+02**	8.45E+04 ± 1.40E+03†	1.65
f03	2.10E-01 ± 2.85E-01 (0)	**4.03E-13 ± 6.20E-13** (50)‡	NA	**3.57E+05 ± 1.84E+04**	NA
f04	**4.11E-16 ± 1.10E-15** (50)	3.44E-14 ± 1.83E-13 (50)	**2.25E+05 ± 3.57E+04**	3.09E+05 ± 4.54E+03†	1.38
f05	4.05E+01 ± 2.30E+01 (0)	**9.99E-02 ± 1.23E-01** (1)‡	NA	**4.81E+05 ± 0.00E+00**	NA
f06	0.00E+00 ± 0.00E+00 (50)	0.00E+00 ± 0.00E+00 (50)	**1.46E+04 ± 4.91E+02**	2.30E+04 ± 7.05E+02†	1.57
f07	**1.98E-03 ± 4.35E-04** (50)	3.46E-03 ± 9.00E-04 (50)†	**6.33E+04 ± 1.32E+04**	1.11E+05 ± 2.23E+04†	1.75
f08	0.00E+00 ± 0.00E+00 (50)	0.00E+00 ± 0.00E+00 (50)	**4.87E+04 ± 1.26E+03**	9.58E+04 ± 2.27E+03†	1.97
f09	0.00E+00 ± 0.00E+00 (50)	0.00E+00 ± 0.00E+00 (50)	**6.45E+04 ± 3.23E+03**	1.19E+05 ± 4.08E+03†	1.85
f10	**4.14E-15 ± 0.00E+00** (50)	1.54E-14 ± 5.48E-15 (50)†	**5.92E+04 ± 8.21E+02**	9.31E+04 ± 1.63E+03†	1.57
f11	0.00E+00 ± 0.00E+00 (50)	0.00E+00 ± 0.00E+00 (50)	**4.04E+04 ± 7.94E+02**	6.47E+04 ± 3.14E+03†	1.60
f12	**1.57E-32 ± 0.00E+00** (50)	1.15E-28 ± 1.15E-28 (50)†	**3.56E+04 ± 8.09E+02**	5.52E+04 ± 1.28E+03†	1.55
f13	**1.35E-32 ± 0.00E+00** (50)	3.92E-26 ± 5.22E-26 (50)†	**4.22E+04 ± 8.62E+02**	6.71E+04 ± 1.45E+03†	1.59

†, ‡ The value of t with 49 degrees of freedom is significant at $\alpha = 0.05$ by two-tailed test.
‡ means that the corresponding algorithm is better than our proposed DE/BBO method.

(f08 - f13). DE/BBO can locate the near-global optimum over all 50 runs for all these functions. However, DE/EDA traps into the local minima many times. Especially, for f08 and f09, DE/EDA fails to solve the two functions. In addition, Figure 5 shows that DE/BBO converges faster than DE/EDA on the major functions.

I. Discussions

The DE algorithm is a fast, robust, and simple global optimization algorithm. However, it may lack the exploitation. BBO is novel optimization algorithm for global optimization. BBO has a good exploitation with the migration operator. Therefore, in this work, we hybridize DE with BBO and propose a hybrid migration operator to generate the promis-

TABLE VIII
COMPARISON THE PERFORMANCE OF DE/BBO WITH DE, DEACHSPX, AND ODE FOR FUNCTIONS f01 − f13 ($D = 30$).

F	DE/BBO	DE	DEahcSPX	ODE
f01	**8.66E-28 ± 5.21E-28** (50)	1.10E-19 ± 1.34E-19 (50)†	2.90E-20 ± 2.28E-20 (50)†	4.33E-25 ± 1.86E-24 (50)
f02	**0.00E+00 ± 0.00E+00** (50)	1.66E-15 ± 8.87E-16 (50)†	4.47E-16 ± 3.66E-16 (50)†	2.81E-13 ± 1.74E-13 (50)†
f03	2.26E-03 ± 1.58E-03 (0)	8.19E-12 ± 1.65E-11 (50)‡	**5.11E-12 ± 9.27E-12** (50)‡	2.50E-11 ± 3.91E-11 (50)‡
f04	**1.89E-15 ± 8.85E-16** (50)	7.83E+00 ± 3.78E+00 (0)†	7.79E+00 ± 3.18E+00 (0)†	9.44E-02 ± 2.33E-01 (14)†
f05	1.90E+01 ± 7.52E+00 (0)	**8.41E-01 ± 1.53E+00** (6)‡	1.24E+00 ± 1.67E+00 (5)‡	2.80E+01 ± 9.24E+00 (0)†
f06	**[2.16E+04 ± 5.73E+02]** (50)	[2.89E+04 ± 2.01E+03] (50)†	[2.81E+04 ± 1.50E+03] (50)†	[2.29E+04 ± 1.81E+03] (50)†
f07	3.44E-03 ± 8.27E-04 (50)	3.49E-03 ± 9.60E-04 (50)	3.52E-03 ± 1.20E-03 (50)	**1.03E-03 ± 3.38E-04** (50)‡
f08	**0.00E+00 ± 0.00E+00** (50)	4.28E+02 ± 4.69E+02 (1)†	4.98E+02 ± 8.42E+02 (5)†	1.63E+03 ± 1.27E+03 (1)†
f09	**0.00E+00 ± 0.00E+00** (50)	1.14E+01 ± 7.57E+00 (0)†	1.30E+01 ± 8.11E+00 (0)†	1.65E+01 ± 1.17E+01 (0)†
f10	**1.07E-14 ± 0.00E+00** (50)	6.73E-11 ± 2.86E-11 (50)†	3.89E-11 ± 1.97E-11 (50)†	5.34E-07 ± 3.77E-06 (49)
f11	**0.00E+00 ± 0.00E+00** (50)	1.23E-03 ± 3.16E-03 (43)†	1.82E-03 ± 5.09E-03 (42)†	2.12E-03 ± 4.66E-03 (39)†
f12	**7.16E-29 ± 6.30E-29** (50)	2.07E-03 ± 1.47E-02 (49)	6.22E-03 ± 2.49E-02 (47)	3.44E-18 ± 1.95E-17 (50)†
f13	**9.81E-27 ± 7.10E-27** (50)	7.19E-02 ± 5.09E-01 (49)	3.22E-02 ± 2.26E-01 (46)	2.05E-22 ± 1.44E-21 (50)†

†, ‡ The value of t with 49 degrees of freedom is significant at $\alpha = 0.05$ by two-tailed test.
‡ means that the corresponding algorithm is better than our proposed DE/BBO method.

TABLE IX
COMPARISON THE PERFORMANCE OF DE/BBO WITH DE, AND DE/EDA FOR FUNCTIONS f01 − f13 ($D = 30$).

F	DE/BBO	DE	DE/EDA
f01	**0.00E+00 ± 0.00E+00** (50)	2.20E-08 ± 2.91E-08 (22)†	4.68E-25 ± 1.33E-24 (50)†
f02	**0.00E+00 ± 0.00E+00** (50)	8.46E-11 ± 8.62E-11 (50)†	8.33E-16 ± 2.85E-16 (50)†
f03	1.97E-06 ± 2.14E-06 (0)	3.93E-03 ± 5.06E-03 (0)†	**5.27E-16 ± 1.17E-15** (50)‡
f04	**1.46E+00 ± 1.01E+00** (0)	1.14E+01 ± 3.05E+00 (0)†	6.58E+00 ± 1.65E+00 (0)†
f05	2.08E+01 ± 7.69E+00 (0)	3.53E+01 ± 2.64E+01 (0)†	**1.97E+01 ± 1.72E+01** (0)
f06	**0.00E+00 ± 0.00E+00** (50)	2.00E-02 ± 1.41E-01 (49)	**0.00E+00 ± 0.00E+00** (50)
f07	**1.09E-03 ± 3.31E-04** (50)	1.04E-02 ± 3.70E-03 (23)†	3.10E-03 ± 1.31E-03 (50)†
f08	**0.00E+00 ± 0.00E+00** (50)	6.53E+03 ± 4.96E+02 (0)†	7.81E+03 ± 2.77E+02 (0)†
f09	**4.57E-12 ± 2.91E-11** (50)	2.48E+01 ± 2.32E+01 (0)†	7.72E+00 ± 2.52E+00 (0)†
f10	**4.07E-15 ± 5.02E-16** (50)	1.09E+00 ± 7.27E-01 (0)†	1.26E+00 ± 6.31E-01 (7)†
f11	**0.00E+00 ± 0.00E+00** (50)	1.28E-02 ± 1.70E-02 (24)†	1.67E-02 ± 1.91E-02 (16)†
f12	**1.57E-32 ± 0.00E+00** (50)	3.73E-02 ± 9.54E-02 (31)†	3.73E-02 ± 9.07E-02 (38)†
f13	**1.35E-32 ± 0.00E+00** (50)	1.18E+02 ± 7.77E+02 (0)	6.53E-01 ± 4.17E+00 (39)

†, ‡ The value of t with 49 degrees of freedom is significant at $\alpha = 0.05$ by two-tailed test.
‡ means that the corresponding algorithm is better than our proposed DE/BBO method.

ing candidate solution. And then, the DE/BBO algorithm is proposed based on the hybrid migration operator. From the experimental results we can summarize that

- Our proposed DE/BBO approach is effective and efficient. It can obtain the global, or near-global, optimum for the test functions.
- The overall performance of DE/BBO is superior to or highly competitive with BBO and other compared state-of-the-art DE algorithms.
- DE/BBO and DE were compared for different population sizes. On the majority of functions, DE/BBO is substantial better than DE.
- The scalability studies show that DE/BBO is able to accelerate DE in general, especially the improvements are more significant at higher dimensionality.
- Comparison of DE/BBO and DE to different mutation schemes, the overall performance of DE/BBO is more robust than that of DE.
- The self-adaptive parameter control can enhance the performance of DE/BBO and DE. Our proposed hybrid migration operator shows the potential to accelerate the self-adaptive variants of DE.
- For function f03, DE/BBO is worse than DE with DE/rand/1/bin scheme. However, from Tables VI and IX, we can see that DE/BBO is better than DE for DE/best/1/bin and scheme described in Eqn. 5. So, we can expect that the strategy adaptation as proposed in [28] may be used to make DE/BBO more robust.

VI. CONCLUSIONS AND FUTURE WORK

In order to balance the exploration and the exploitation of DE, in this paper, we propose a hybrid DE approach, called DE/BBO, which combines the exploration of DE with the exploitation of BBO. In DE/BBO, a new hybrid migration operator is proposed to generate the promising solutions. Since the hybrid migration operator has a good trade-off between the exploration and the exploitation, it makes our proposed DE/BBO approach be very effective and efficient. To verify the performance of DE/BBO, 23 benchmark functions chosen from literature are employed. Experimental results

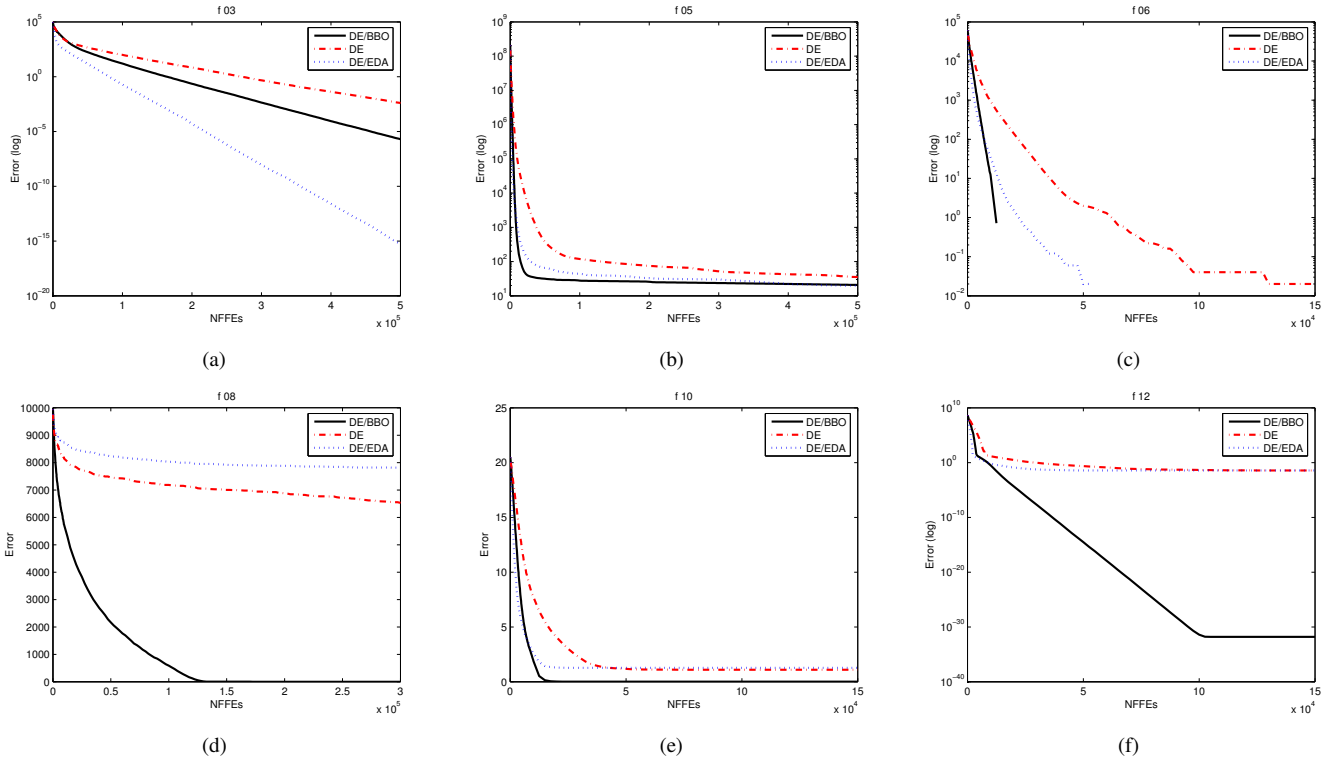

Fig. 5. Mean error curves of DE/BBO, DE, and DE/EDA for selected functions. (a) f03. (b) f05. (c) f06. (d) f08. (e) f10. (f) f12.

demonstrate the good performance of our approach. Compared with BBO, DE, DEahcSPX, ODE, and DE/EDA, the results show that DE/BBO is superior to or at least highly competitive with them. Moreover, the influence of the population size, dimensionality, different mutation schemes, and the self-adaptive control parameters of DE/BBO and DE are also investigated. And the results confirm that DE/BBO exhibits a higher convergence rate and greater robustness compared with DE.

In this work, we only consider the unconstrained function optimization. Our future work consists on adding the diversity rules into DE/BBO for constrained optimization problems.

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