Benchmark Functions for the CEC'2013 Special Session and Competition on Large-Scale Global Optimization

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Abstract

This report proposes 15 large-scale benchmark problems as an extension to the existing CEC'2010 large-scale global optimization benchmark suite. The aim is to better represent a wider range of real-world large-scale optimization problems and provide convenience and flexibility for comparing various evolutionary algorithms specifically designed for large-scale global optimization. Introducing imbalance between the contribution of various subcomponents, subcomponents with nonuniform sizes, and conforming and conflicting overlapping functions are among the major new features proposed in this report.

1 Introduction

Numerous metaheuristic algorithms have been successfully applied to many optimization problems [1, 2, 5, 9, 10, 15, 16, 17, 21, 35, 39]. However, their performance deteriorates rapidly as the dimensionality of the problem increases [3, 19]. There are many real-world problems that exhibit such large-scale property [8, 20] and the number of such large-scale global optimization (LSGO) problems will continue to grow as we advance in science and technology.

Several factors make large-scale problems exceedingly difficult [45]. Firstly, the search space of a problem grows exponentially as the number of decision variables increases. Secondly, the properties of the search space may change as the number of dimensions increases. For example, the Rosenbrock function is a unimodal function in two dimensions, but it turns into a multimodal function when the number of dimensions increases [37]. Thirdly, the evaluation of large-scale problems are usually expensive. This is often the case in many real-world problems such as gas turbine stator blades [14], multidisciplinary design optimization [38], and target shape design optimization [25].

Another factor that contributes to the difficulty of large-scale problems is the interaction between variables. Two variables interact if they cannot be optimized independently to find the global optimum of an objective function. Variable interaction is commonly referred to as *non-separability* in continuous optimization literature. In genetic algorithm literature this phenomenon is commonly known as *epistasis* or *gene interaction* [7, 33].

In an extreme case where there is no interaction between any pair of the decision variables, a large-scale problem can be solved by optimizing each of the decision variables independently. The other extreme is when all of the decision variables interact with each other and all of them should be optimized together. However, most of the real-world problems fall in between these two extreme cases [43]. In such problems usually a subset of the decision variables interact with each other forming several clusters of interacting variables.

The modular nature of many real-world problems makes a *divide-and-conquer* approach appealing for solving large-scale optimization problems. In the context of optimization, this divide-and-conquer approach is commonly known as decomposition methods [6, 11, 12]. Some algorithms such as estimation of distribution algorithms (EDAs) [24, 29, 30, 31, 32] perform an implicit decomposition by approximating a set of joint probability distributions to represent each interaction group. Some other methods such as cooperative co-evolution (CC) [34] explicitly subdivide a large-scale problem into a set of smaller subproblems [44]. In recent years cooperative co-evolutionary algorithms have gained popularity in the context of large-scale global optimization [4, 18, 19, 26, 27, 47, 46]. Memetic algorithms [23] in which a local search operator is used in an evolutionary framework are also gaining popularity in large-scale optimization [22].

The IEEE CEC'2010 benchmark suite [42] was designed with the aim of providing a suitable evaluation platform for testing and comparing large-scale global optimization algorithms. To that end, the CEC'2010 benchmark suite is successful in representing the modular nature of many-real world problems and building a scalable set of benchmark functions in order to promote the research in the field of large-scale global optimization. However, the advances in the field of LSGO in recent years signals the need to revise and extend the existing benchmark suite. The aim of this report is to embark on the ideas proposed in the CEC'2010 benchmark suite and extend the benchmark functions in order to better represent the features of a wider range of real-world problems as well as posing some new challenges to the decomposition based algorithms. The benchmarks problems described here are implemented in MATLAB/Octave, Java and C++ which accompany this report [1].

2 Changes to the CEC'2010 Benchmark Suite

This report introduces the following features into the CEC'2010 benchmark suite.

- Nonuniform subcomponent sizes;
- Imbalance in the contribution of subcomponents [28];
- Functions with overlapping subcomponents;
- New transformations to the base functions [13]:
  - Ill-conditioning;
  - Symmetry breaking;
  - Irregularities.

The need for each of the above features is discussed and motivated in the following sections.

2.1 Nonuniform subcomponent sizes

In the CEC'2010 benchmark suite the sizes of all non-separable subcomponents are equal. This only allows for functions with uniform subcomponent sizes which are not representative of many real-world problems. It is arguable that the subcomponents of a real-world optimization problem are very likely to be of unequal sizes. In order to better represent this feature, the functions in this test suite contain subcomponents with a range of different sizes.

[1] `http://goanna.cs.rmit.edu.au/~xiaodong/cec13-lsgo/competition/lsgo_2013_benchmarks.zip`

2.2 Imbalance in the contribution of subcomponents

In many real-world problems, it is likely that the subcomponents of an objective function are different in nature, and hence their contribution to the global objective value may vary. In a recent study [28], it has been shown that the computational budget can be spent more efficiently based on the contribution of subcomponents to the global fitness. In the CEC'2010 benchmark suite for almost all of the functions the same base function is used to represent different subcomponents. The use of the same base function and equal sizes of subcomponents result in equal contribution of all subcomponents. This configuration does not represent the imbalance between the contribution of various subcomponents in many real-world problems.

By introducing nonuniform subcomponent sizes, the contribution of different subcomponents will be automatically different as long as they are of different sizes. However, the contribution of a subcomponent can be magnified or dampened by multiplying a coefficient with the value of each subcomponent function.

2.3 Functions with overlapping subcomponents

In the CEC'2010 benchmark suite, the subcomponents are disjoint subsets of the decision variables. In other words, the subcomponent functions do not share any decision variable. When there is no overlap between the subcomponents, it is theoretically possible to decompose a large-scale problem into an ideal grouping of the decision variables. However, when there is some degree of overlap between the subcomponents, there will be no unique optimal grouping of the decision variables. In this report, a new category of functions is introduced with overlapping subcomponents. This serves as a challenge for decomposition algorithms to detect the overlap and devise a suitable strategy for optimizing such partially interdependent subcomponents.

2.4 New transformations to the base functions

Some of the base functions used in the CEC'2010 benchmark suite are very regular and symmetric. Examples include Sphere, Elliptic, Rastrigin, and Ackley functions. For a better resemblance with many real-world problems, some non-linear transformations are applied on these base functions to break the symmetry and introduce some irregularity on the fitness landscape [13]. It should be noted that these transformations do not change the separability and modality properties of the functions. The three transformations that are applied are: ill-conditioning, symmetry breaking, and irregularities.

2.4.1 Ill-conditioning

Ill-conditioning refers to the square of the ratio between the largest direction and smallest direction of contour lines [13]. In the case of ellipsoid, if it is stretched in the direction of one of its axes more than other axes then we say that the function is ill-conditioned.

2.4.2 Irregularities

Most of the benchmark functions have regular patterns. It is desirable to introduce some degree of irregularity by applying some transformation.

2.4.3 Symmetry breaking

Some operators that generate genetic variations especially those based on a Gaussian distribution are symmetric and if the functions are also symmetric there is a bias in favor of symmetric operators. In order to eliminate such bias a symmetry breaking transformation is desirable.

3 Definitions

Definition 1. *A function* $f(\mathbf{x})$ *is partially separable with* m *independent subcomponents iff:*

$$\arg\min_{\mathbf{x}} f(\mathbf{x}) = \Big(\arg\min_{\mathbf{x}_1} f(\mathbf{x}_1, \dots), \dots, \arg\min_{\mathbf{x}_m} f(\dots, \mathbf{x}_m)\Big),$$

where $\mathbf{x} = \langle x_1, \dots, x_D \rangle^\top$ *is a decision vector of* D *dimensions,* $\mathbf{x}_1, \dots, \mathbf{x}_m$ *are disjoint sub-vectors of* $\mathbf{x}$*, and* $2 \leq m \leq D$*.*

As a special case of Definition 1, a function is *fully separable* if sub-vectors $\mathbf{x}_1, \dots, \mathbf{x}_m$ are 1-dimensional (i.e. $m = D$).

Definition 2. *A function* $f(\mathbf{x})$ *is fully-nonseparable if every pair of its decision variables interact with each other.*

Definition 3. *A function is* partially additively separable *if it has the following general form:*

$$f(\mathbf{x}) = \sum_{i=1}^{m} f_i(\mathbf{x}_i) \ ,$$

where $\mathbf{x}_i$ *are mutually exclusive decision vectors of* f_i*,* $\mathbf{x} = \langle x_1, \dots, x_D \rangle^\top$ *is a global decision vector of* D *dimensions, and* m *is the number of independent subcomponents.*

Definition 3 is a special case of Definition 1. Partially additively separable functions conveniently represent the modular nature of many real-world problems [43]. All of the partially separable function which are defined in this report follow the format presented in Definition 1.

4 Benchmark Problems

In this report we define four major categories of large-scale problems:

1. Fully-separable functions;
2. Two types of partially separable functions:
   (a) Partially separable functions with a set of non-separable subcomponents and one fully-separable subcomponents;
   (b) Partially separable functions with only a set of non-separable subcomponents and no fully-separable subcomponent.
3. Functions with overlapping subcomponents: the subcomponents of these functions have some degree of overlap with its neighboring subcomponents. There are two types of overlapping functions:
   (a) Overlapping functions with conforming subcomponents: for this type of functions the shared decision variables between two subcomponents have the same optimum value with respect to both subcomponent functions. In other words, the optimization of one subcomponent may improve the value of the other subcomponent due to the optimization of the shared decision variables.
   (b) Overlapping functions with conflicting subcomponents: for this type of functions the shared decision variables have a different optimum value with respect to each of the subcomponent functions. This means that the optimization of one subcomponent may have a detrimental effect on the other overlapping subcomponent due to the conflicting nature of the shared decision variables.
4. Fully-nonseparable functions.

The base functions that are used to form the separable and non-separable subcomponents are: Sphere, Elliptic, Rastrigin's, Ackley's, Schwefel's, and Rosenbrock's functions. These functions which are classical examples of benchmark functions in many continuous optimization test suites [13, 40, 41] are mathematically defined in Section 4.1. Based on the major four categories described above and the aforementioned six base functions, the following 15 large-scale functions are proposed in this report:

1. Fully-separable Functions
   (a) f_1: Elliptic Function
   (b) f_2: Rastrigin Function
   (c) f_3: Ackley Function
2. Partially Additively Separable Functions
   - Functions with a separable subcomponent:
     (a) f_4: Elliptic Function
     (b) f_5: Rastrigin Function
     (c) f_6: Ackley Function
     (d) f_7: Schwefels Problem 1.2
   - Functions with no separable subcomponents:
     (a) f_8: Elliptic Function
     (b) f_9: Rastrigin Function
     (c) f_{10}: Ackley Function
     (d) f_{11}: Schwefels Problem 1.2
3. Overlapping Functions
   (a) f_{12}: Rosenbrock's Function
   (b) f_{13}: Schwefels Function with Conforming Overlapping Subcomponents
   (c) f_{14}: Schwefels Function with Conflicting Overlapping Subcomponents
4. Non-separable Functions
   (a) f_{15}: Schwefels Problem 1.2

The high-level design of these four major categories is explained in Section 4.2.

4.1 Base Functions

4.1.1 The Sphere Function

$$f_{\text{sphere}}(\mathbf{x}) = \sum_{i=1}^{D} x_i^2 ,$$

where $\mathbf{x}$ is a decision vector of D dimensions. The sphere function is a very simple unimodal and fully-separable function which is used as the fully-separable subcomponent for some of the partially separable functions which are defined in this report.

4.1.2 The Elliptic Function

$$f_{\text{elliptic}}(\mathbf{x}) = \sum_{i=1}^{D} 10^{6\frac{i-1}{D-1}} x_i^2$$

4.1.3 The Rastrigin's Function

$$f_{\text{rastrigin}}(\mathbf{x}) = \sum_{i=1}^{D} \left[x_i^2 - 10\cos(2\pi x_i) + 10\right]$$

4.1.4 The Ackley's Function

$$f_{\text{ackley}}(\mathbf{x}) = -20\exp\left(-0.2\sqrt{\frac{1}{D}\sum_{i=1}^{D} x_i^2}\right) - \exp\left(\frac{1}{D}\sum_{i=1}^{D}\cos(2\pi x_i)\right) + 20 + e$$

4.1.5 The Schwefel's Problem 1.2

$$f_{\text{schwefel}}(\mathbf{x}) = \sum_{i=1}^{D}\left(\sum_{j=1}^{i} x_i\right)^2$$

4.1.6 The Rosenbrock's Function

$$f_{\text{rosenbrock}}(\mathbf{x}) = \sum_{i=1}^{D-1}\left[100(x_i^2 - x_{i+1})^2 + (x_i - 1)^2\right]$$

4.2 The Design

4.2.1 Symbols

The symbols and auxiliary functions are described in this section. The vectors are typeset in lowercase bold and represent column vectors (e.g. $\mathbf{x} = \langle x_1, \ldots, x_D\rangle^\top$). Matrices are typeset in uppercase bold (e.g. $\mathbf{R}$).

$\mathcal{S}$: A multiset containing the subcomponent sizes for a function. For example, $\mathcal{S} = \{50, 25, 50, 100\}$ means there are 4 subcomponents each with 50, 25, 50 and 100 decision variables respectively.

$|\mathcal{S}|$: Number of elements in $\mathcal{S}$. The number of subcomponents in a function.

$\mathcal{C}_i = \sum_{j=1}^{i} \mathcal{S}_i$: The sum of the first i items from $\mathcal{S}$. For convenience $\mathcal{C}_0$ is defined to be zero. $\mathcal{C}_i$ is used to construct the decision vector of different subcomponent functions with the right size.

D : The dimensionality of the objective function.

$\mathcal{P}$: A random permutation of the dimension indices $\{1, \ldots, D\}$

w_i : A randomly generated weight which is used as the coefficient of ith non-separable subcomponent function to generate the imbalance effect. The weights are generated as follows:

$$w_i = 10^{\,3\mathcal{N}(0,1)},$$

where $\mathcal{N}(0,1)$ is a Gaussian distribution with zero mean and unit variance.

$\mathbf{x}^{\text{opt}}$: The optimum decision vector for which the value of the objective function is minimum. This is also used as a shift vector to change the location of the global optimum.

T_{osz} : A transformation function to create smooth local irregularities [13].

$$T_{\text{osz}} : \mathbb{R}^D \to \mathbb{R}^D, x_i \mapsto \text{sign}(x_i)\exp(\hat{x}_i + 0.049(\sin(c_1\hat{x}_i) + \sin(c_2\hat{x}_i))), \text{ for } i = 1, \dots, D$$

$$\text{where } \hat{x}_i = \begin{cases} \log(|x_i|) & \text{if } x_i \neq 0 \\ 0 \text{ otherwise} & \end{cases}, \ \text{sgin}(x) = \begin{cases} -1 & \text{if } x < 0 \\ 0 & \text{if } x = 0 \\ 1 & \text{if } x > 0 \end{cases}$$

$$c_1 = \begin{cases} 10 & \text{if } x_i > 0 \\ 5.5 & \text{otherwise} \end{cases}, \text{and } c_2 = \begin{cases} 7.9 & \text{if } x_i > 0 \\ 3.1 & \text{otherwise.} \end{cases}$$

T^{β}_{asy} : A transformation function to break the symmetry of the symmetric functions [13].

$$T^{\beta}_{\text{asy}} : \mathbb{R}^D \to \mathbb{R}^D, x_i \mapsto \begin{cases} x_i^{1+\beta\frac{i-1}{D-1}\sqrt{x_i}} & \text{if } x_i > 0 \\ x_i & \text{otherwise} \end{cases}, \text{for } i = 1, \dots, D.$$

Λ^{α} : A D-dimensional diagonal matrix with the diagonal elements $\lambda_{ii} = \alpha^{\frac{1}{2}\frac{i-1}{D-1}}$. This matrix is used to create ill-conditioning [13]. The parameter α is the condition number.

$\mathbf{R}$: An orthogonal rotation matrix which is used to rotate the fitness landscape randomly around various axes as suggested in [36].

m : The overlap size between subcomponents.

$\mathbf{1}$ = $\langle 1, \dots, 1 \rangle^{\top}$ a column vector of all ones.

Except for applying some new transformations, the design of fully-separable and fully-nonseparable functions does not differ from that of CEC'2010 benchmarks. The general design of other categories of functions such as partially separable functions and overlapping functions are described in the next section.

4.2.2 Design of Partially Separable Functions

This type of functions has the following general form:

$$f(\mathbf{x}) = \sum_{i=1}^{|\mathcal{S}|-1} w_i f_{\text{nonsep}}(\mathbf{z}_i) + f_{\text{sep}}(\mathbf{z}_{|\mathcal{S}|}),$$

where w_i is a randomly generated weight to create the imbalance effect, and f_{sep} is either the Sphere function or the non-rotated version of Rastrigin's or Ackley's functions. To generate a non-separable version of these functions a rotation matrix may be used. The vector $\mathbf{z}$ is formed by transforming, shifting and finally rearranging the dimensions of vector $\mathbf{x}$. A typical transformation is shown below:

$$\mathbf{y} = \Lambda^{10} T^{0.2}_{\text{asy}}(T_{\text{osz}}(\mathbf{x} - \mathbf{x}^{\text{opt}})),$$

$$\mathbf{z}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]})$$

As it was described before the vector $\mathbf{x}^{\text{opt}}$ is the location of the shifted optimum which is used as a shift vector. The permutation set $\mathcal{P}$ is used to rearrange the order of the decision variables and $\mathcal{C}_i$ is used to construct each of the subcomponent vectors ($\mathbf{z}_i$) with the corresponding size ($\mathcal{S}_i$) specified in the multiset $\mathcal{S}$.

4.2.3 Design of Overlapping Functions with Conforming Subcomponents

The design of this type of functions is very similar to partially separable functions except for the formation of vector $\mathbf{z}_i$ which is performed as follows:

$$\mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}-(i-1)m+1]} : \mathcal{P}_{[\mathcal{C}_i-(i-1)m]})$$

The parameter m causes two adjacent subcomponents to have m decision variables in common. This parameter is adjustable by the user and can vary in the following range $1 \leq m \leq min\{\mathcal{S}\}$ The total number of decision variables for this type of functions is calculated as follows:

$$D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i - (m(|\mathcal{S}| - 1))$$

4.2.4 Design of Overlapping Functions with Conflicting Subcomponents

The overall structure of this type of functions is similar to partially separable functions except for the way the vector $\mathbf{z}_i$ is constructed:

$$\mathbf{y}_i = \mathbf{x}(\mathcal{P}_{[\mathcal{C}_{i-1}-(i-1)m+1]} : \mathcal{P}_{[\mathcal{C}_i-(i-1)m]}) - \mathbf{x}_i^{\text{opt}}$$

$$\mathbf{z}_i = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{y}_i)).$$

As it can be seen, each subcomponent vector $\mathbf{z}_i$ has a different shift vector. This generates a conflict between the optimum value of the shared decision variables between two overlapping subcomponents.

4.3 The Function Definitions

4.3.1 Fully-separable Functions

f_1: Shifted Elliptic Function

$$f_1(\mathbf{z}) = \sum_{i=1}^{D} 10^{6\frac{i-1}{D-1}} z_i^2 \tag{1}$$

- $\mathbf{z} = T_{\text{osz}}(\mathbf{x} - \mathbf{x}^{\text{opt}})$
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_1(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Unimodal;
- Separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number $\approx 10^6$).

f_2: Shifted Rastrigin's Function

$$f_2(\mathbf{z}) = \sum_{i=1}^{D} \left[z_i^2 - 10\cos(2\pi z_i) + 10\right] \tag{2}$$

- $\mathbf{z} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{x} - \mathbf{x}^{\text{opt}}))$
- $\mathbf{x} \in [-5, 5]^D$
- Global optimum: $f_2(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Multimodal;
- Separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number ≈ 10).

f_3: Shifted Ackley's Function

$$f_3(\mathbf{z}) = -20\exp\left(-0.2\sqrt{\frac{1}{D}\sum_{i=1}^{D} z_i^2}\right) - \exp\left(\frac{1}{D}\sum_{i=1}^{D}\cos(2\pi z_i)\right) + 20 + e \tag{3}$$

- $\mathbf{z} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{x} - \mathbf{x}^{\text{opt}}))$
- $\mathbf{x} \in [-32, 32]^D$
- Global optimum: $f_3(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Multimodal;
- Separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number ≈ 10).

4.3.2 Partially Additive Separable Functions I

f_4: 7-nonseparable, 1-separable Shifted and Rotated Elliptic Function

$$f_4(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|-1} w_i f_{\text{elliptic}}(\mathbf{z}_i) + f_{\text{elliptic}}(\mathbf{z}_{|\mathcal{S}|}) \tag{4}$$

- $\mathcal{S} = \{50, 25, 25, 100, 50, 25, 25, 700\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i}),\ i \in \{1, \ldots, |\mathcal{S}| - 1\}$
- $\mathbf{z}_{|\mathcal{S}|} = T_{\text{osz}}(\mathbf{y}_{|\mathcal{S}|})$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_4(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Unimodal;
- Partially Separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number $\approx 10^6$).

f_5: 7-nonseparable, 1-separable Shifted and Rotated Rastrigin's Function

$$f_5(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|-1} w_i f_{\text{rastrigin}}(\mathbf{z}_i) + f_{\text{rastrigin}}(\mathbf{z}_{|\mathcal{S}|}) \tag{5}$$

- $\mathcal{S} = \{50, 25, 25, 100, 50, 25, 25, 700\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i})),\ i \in \{1, \ldots, |\mathcal{S}| - 1\}$
- $\mathbf{z}_{|\mathcal{S}|} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{y}_{|\mathcal{S}|}))$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-5, 5]^D$
- Global optimum: $f_5(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Multimodal;
- Partially Separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number ≈ 10).

f_6: **7-nonseparable, 1-separable Shifted and Rotated Ackley's Function**

$$f_6(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|-1} w_i f_{\text{ackley}}(\mathbf{z}_i) + f_{\text{ackley}}(\mathbf{z}_{|\mathcal{S}|}) \tag{6}$$

- $\mathcal{S} = \{50, 25, 25, 100, 50, 25, 25, 700\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i})),\ i \in \{1, \ldots, |\mathcal{S}| - 1\}$
- $\mathbf{z}_{|\mathcal{S}|} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{y}_{|\mathcal{S}|}))$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-32, 32]^D$
- Global optimum: $f_6(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Multimodal;
- Partially Separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number ≈ 10).

f_7: **7-nonseparable, 1-separable Shifted Schwefel's Function**

$$f_7(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|-1} w_i f_{\text{schwefel}}(\mathbf{z}_i) + f_{\text{sphere}}(\mathbf{z}_{|\mathcal{S}|}) \tag{7}$$

- $\mathcal{S} = \{50, 25, 25, 100, 50, 25, 25, 700\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$

- $\mathbf{z_i} = T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i})),\ i \in \{1, \ldots, |\mathcal{S}| - 1\}$
- $\mathbf{z}_{|\mathcal{S}|} = T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{y}_{|\mathcal{S}|}))$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_3(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Multimodal;
- Partially Separable;
- Shifted;
- Smooth local irregularities;

4.3.3 Partially Additive Separable Functions II

f_8: 20-nonseparable Shifted and Rotated Elliptic Function

$$f_8(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|} w_i f_{\text{elliptic}}(\mathbf{z}_i) \tag{8}$$

- $\mathcal{S} = \{50, 50, 25, 25, 100, 100, 25, 25, 50, 25, 100, 25, 100, 50, 25, 25, 25, 100, 50, 25\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_8(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Unimodal;
- Partially Separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number $\approx 10^6$).

f_9: 20-nonseparable Shifted and Rotated Rastrigin's Function

$$f_9(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|} w_i f_{\text{rastrigin}}(\mathbf{z}_i) \tag{9}$$

- $\mathcal{S} = \{50, 50, 25, 25, 100, 100, 25, 25, 50, 25, 100, 25, 100, 50, 25, 25, 25, 100, 50, 25\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i})),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-5, 5]^D$
- Global optimum: $f_9(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Multimodal;
- Partially separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number ≈ 10).

f_{10}**: 20-nonseparable Shifted and Rotated Ackley's Function**

$$f_{10}(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|} w_i f_{\text{ackley}}(\mathbf{z}_i) \tag{10}$$

- $\mathcal{S} = \{50, 50, 25, 25, 100, 100, 25, 25, 50, 25, 100, 25, 100, 50, 25, 25, 25, 100, 50, 25\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = \Lambda^{10} T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i})),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-32, 32]^D$
- Global optimum: $f_{10}(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Multimodal;
- Partially separable;
- Shifted;
- Smooth local irregularities;
- Ill-conditioned (condition number ≈ 10).

f_{11}**: 20-nonseparable Shifted Schwefel's Function**

$$f_{11}(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|} w_i f_{\text{schwefel}}(\mathbf{z}_i) \tag{11}$$

- $\mathcal{S} = \{50, 50, 25, 25, 100, 100, 25, 25, 50, 25, 100, 25, 100, 50, 25, 25, 25, 100, 50, 25\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i = 1000$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}+1]} : \mathcal{P}_{[\mathcal{C}_i]}),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i})),\ i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_{11}(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Unimodal;
- Partially separable;
- Shifted;
- Smooth local irregularities;

4.3.4 Overlapping Functions

f_{12}: Shifted Rosenbrock's Function

$$f_{12}(\mathbf{z}) = \sum_{i=1}^{D-1} \left[100(z_i^2 - z_{i+1})^2 + (z_i - 1)^2\right] \tag{12}$$

- $D = 1000$
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_{12}(\mathbf{x}^{\text{opt}} + \mathbf{1}) = 0$

Properties:

- Multimodal;
- Separable;
- Shifted;
- Smooth local irregularities;

f_{13}: Shifted Schwefel's Function with Conforming Overlapping Subcomponents

$$f_{13}(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|} w_i f_{\text{schwefel}}(\mathbf{z}_i) \tag{13}$$

- $\mathcal{S} = \{50, 50, 25, 25, 100, 100, 25, 25, 50, 25, 100, 25, 100, 50, 25, 25, 25, 100, 50, 25\}$
- $\mathcal{C}_i = \sum_{j=1}^{i} \mathcal{S}_i, \;\; \mathcal{C}_0 = 0$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i - m(|\mathcal{S}| - 1) = 905$
- $\mathbf{y} = \mathbf{x} - \mathbf{x}^{\text{opt}}$
- $\mathbf{y}_i = \mathbf{y}(\mathcal{P}_{[\mathcal{C}_{i-1}-(i-1)m+1]} : \mathcal{P}_{[\mathcal{C}_i-(i-1)m]}), \; i \in \{1, \ldots, |\mathcal{S}|\}$
- $\mathbf{z_i} = T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y_i})), \; i \in \{1, \ldots, |\mathcal{S}|\}$
- $m = 5$: overlap size
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_{13}(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Unimodal;
- Non-separable;
- Overlapping;
- Shifted;
- Smooth local irregularities;

f_{14}**: Shifted Schwefel's Function with Conflicting Overlapping Subcomponents**

$$f_{14}(\mathbf{z}) = \sum_{i=1}^{|\mathcal{S}|} w_i f_{\text{schwefel}}(\mathbf{z}_i) \tag{14}$$

- $\mathcal{S} = \{50, 50, 25, 25, 100, 100, 25, 25, 50, 25, 100, 25, 100, 50, 25, 25, 25, 100, 50, 25\}$
- $D = \sum_{i=1}^{|\mathcal{S}|} \mathcal{S}_i - (m(|\mathcal{S}| - 1)) = 905$
- $\mathbf{y}_i = \mathbf{x}(\mathcal{P}_{[\mathcal{C}_{i-1}-(i-1)m+1]} : \mathcal{P}_{[\mathcal{C}_i-(i-1)m]}) - \mathbf{x}_i^{\text{opt}}$
- $\mathbf{x}_i^{\text{opt}}$: shift vector of size $|\mathcal{S}_i|$ for the ith subcomponent
- $\mathbf{z}_i = T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{R}_i \mathbf{y}_i))$
- $m = 5$: overlap size
- $\mathbf{R}_i$: a $|\mathcal{S}_i| \times |\mathcal{S}_i|$ rotation matrix
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_{14}(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Unimodal;
- Non-separable;
- Conflicting subcomponents;
- Shifted;
- Smooth local irregularities;

4.3.5 Fully Non-separable Functions

f_{15}**: Shifted Schwefel's Function**

$$f_{15}(\mathbf{z}) = \sum_{i=1}^{D} \left(\sum_{j=1}^{i} x_i \right)^2 \tag{15}$$

- $D = 1000$
- $\mathbf{z} = T_{\text{asy}}^{0.2}(T_{\text{osz}}(\mathbf{x} - \mathbf{x}^{\text{opt}}))$
- $\mathbf{x} \in [-100, 100]^D$
- Global optimum: $f_{15}(\mathbf{x}^{\text{opt}}) = 0$

Properties:

- Unimodal;
- Fully non-separable;
- Shifted;
- Smooth local irregularities;

5 Evaluation

5.1 General Settings

1. **Problems:** 15 minimization problems;
2. **Dimensions:** $D = 1000$;
3. **Number of runs:** 25 runs per function;
4. **Maximum number of fitness evaluations:** $\mathrm{Max\_FE} = 3 \times 10^6$;
5. **Termination criteria:** when Max_FE is reached.
6. **Boundary Handling:** All problems have the global optimum within the given bounds, so there is no need to perform search outside of the given bounds for these problems. The provided codes returns NaN if an objective function is evaluated outside the specified bounds.

Table 1 presents the time required for 10000 function evaluations (FEs) using the Matlab/Octave versions of the test suite. The test suite was tested in a single thread on an Intel(R) Core(TM)2 Duo CPU E8500 @3.16GHz using GNU Octave 3.2.3 on Ubuntu Linux 10.04.4 LTS.

Table 1: Runtime of 10,000 FEs (in seconds) on the benchmark functions.

Function	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
Runtime	4.69	6.35	1.14	4.81	6.56	1.37	3.55	5.34
Function	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	–
Runtime	7.90	1.84	9.98	0.95	9.94	10.35	24.40	–

The whole experiment with 3×10^6 FEs is thereby expected to take about 207 hours with the Matlab/Octave version on a computer with similar configurations. It is recommended that the participants perform parallel runs to reduce the runtime of a complete experiment.

5.2 Data To Be Recorded and Evaluation Criteria

Solution quality for each function when the FEs counter reaches:

- FEs1 = 1.2e+5
- FEs2 = 6.0e+5
- FEs3 = 3.0e+6

The best, median, worst, mean, and standard deviation of the 25 runs should be recorded and presented in a table as shown in Table 2. Participants are requested to present their results in a tabular form, following the example given in Table 2. Competition entries will be mainly ranked based on the median results achieved when FEs = 1.2e+5, 6.0e+5 and 3.0e+6. In addition, please also provide convergence curves of your algorithm on the following six selected functions: f_2, f_7, f_{11}, f_{12}, f_{13}, and f_{14}. For each function, a single convergence curve should be plotted using the average results over all 25 runs.

Note: The function values recorded at FEs1, FEs2, FEs3 for all 25 runs should be recorded in a plain text file and be submitted to the chair of the session via email [2].

[2] The file should be submitted as a ZIP archive to Dr. Xiaodong Li (`xiaodong.li@rmit.edu.au`)

Table 2: Experimental Results.

1000D		f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
1.2e5	Best	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx
	Median								
	Worst								
	Mean								
	StDev								
6.0e5	Best								
	Median								
	Worst								
	Mean								
	StDev								
3.0e6	Best								
	Median								
	Worst								
	Mean								
	StDev								

1000D		f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	–
1.2e5	Best	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx	x.xxe+xx
	Median								
	Worst								
	Mean								
	StDev								
6.0e5	Best								
	Median								
	Worst								
	Mean								
	StDev								
3.0e6	Best								
	Median								
	Worst								
	Mean								
	StDev								

6 Conclusion

In this report we have proposed a set of 15 large-scale benchmark problems as an extension to the existing CEC'2010 benchmark suite [42] for better evaluation of large-scale global optimization algorithms and to present some new challenges to the existing algorithms in order to boost the research in the field of LSGO.

The new features that are presented in this report are: (1) introducing imbalance between the contribution of subcomponents; (2) creating subcomponents with non-uniform subcomponent sizes; (3) introducing conforming and conflicting overlapping problems, and (4) applying several nonlinear transformations to the base functions. The primary goal in designing this new set of benchmark problems is to better represent a wider range of real-world large-scale optimization problems.

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