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Precision Constrained Optimization by Exponential Ranking

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Abstract—Demonstrative results of a probabilistic constraint handling approach that is exclusively using evolutionary computation are presented. In contrast to other works involving the same probabilistic considerations, in this study local search has been omitted, in order to assess the necessity of this deterministic local search procedure in connection with the evolutionary one. The precision stems from the non-linear probabilistic distance measure that maintains stable evolutionary selection pressure towards the feasible region throughout the search, up to micro level in the range of 10^{-10} or beyond. The details of the theory are revealed in another paper [1]. In this paper the implementation results are presented, where the non-linear distance measure is used in the ranking of the solutions for effective tournament selection. The test problems used are selected from the existing literature. The evolutionary implementation without local search turns out to be already competitively accurate with sophisticated and accurate state-of-the-art constrained optimization algorithms. This indicates the potential for enhancement of the sophisticated algorithms, as to their precision and accuracy, by the integration of the proposed approach.

Keywords—evolutionary algorithm; multiobjective optimization; constrained optimization; probabilistic modeling

I. INTRODUCTION

Evolutionary algorithms have become the most prominent approach for solving optimization problems during the three decades of their emergence. The advancements have been surprisingly rapid, presumably due to the simplicity of the original concept and its broad applicability that includes situations where insight into a problem is minimal. Today the evolutionary computation literature encompasses many advanced optimization algorithms having the spirit of genetic algorithms in essence. Updated surveys are reported in the literature from time to time, e.g. [2, 3]. The development process of the methodology may be broadly categorized as follows. The hallmarks of the first half are the developments along single objective optimization, and those of the second half were multiobjective optimizations in Pareto sense. As to the latter there are a number of excellent text books contributing to the advancement of evolutionary multiobjective optimization [4-6]. During both periods the main focus was on solving unconstrained problems; however, within each period, gradually more and more attention was paid to constrained optimization. Since multiobjective optimization

can be formulated as a single objective with constraints, where the constraints are the rest of the objectives subject to minimization, constrained optimization with a single objective function in some sense is a general case, and this is the case in this work. A widely used method for constrained optimization is the penalty function method. Penalty function method penalizes a solution, which deteriorates the fitness of a solution when it violates constraints. This penalization is accomplished by adding a value to the objective function value in proportion to the amount of constraint violation, where the proportionality factor is known as the penalty parameter. A strategy that did not require a penalty parameter in evolutionary constrained optimization was proposed by Deb in 2000 [7], which is superseded by another research with the penalty parameter [8]. In this approach during the tournament selection process an infeasible solution is always treated as inferior compared to a feasible one, or as inferior to a solution that violates the constraints to a lesser extent. Coello [9] proposed a self-adaptive penalty approach by using a co-evolutionary model to adapt the penalty factors. However, in general determination of a right penalty parameter still remained an issue.

Within the methodological framework of the penalty parameter approach, local search in combination with evolutionary computation (EC) has shown to be effective for solving constrained optimization problems [8]. In this combination the local search is an alternative for selection pressure in precision demanding problems. The role of EC in the joint evolutionary-classical approach is not the search for a feasible solution, but to produce a suitable starting condition for the effective execution of the local search, so that the actual reaching of feasible solution is essentially due to the local search and not due to the evolutionary computation. In an earlier study the effectiveness of local-search based evolutionary constrained optimization was enhanced by introducing a probabilistic distance metric into the evolutionary component of the method [10]. From the mentioned joint-evolutionary works, as their effectiveness is essentially due to local search, one can get the impression that a deterministic procedure, such as local search, is rather imperative in order to enable EC for constrained optimization.

The motivation of this work is to assess the necessity of local search in connection with EC for constrained optimization by studying if EC without any deterministic component alone can be used for precision optimization. The hypothesis is that the probabilistic treatment used to enhance the local-search based algorithm in [10] might by itself be sufficient to enable evolutionary algorithm to reach feasible solutions, which would make usage of local search unnecessary. Such finding would exemplify that EC is not inevitably forced to take a subordinate role to a deterministic procedure for precision demanding optimization, and this novel insight might stimulate new EC centered research in the constrained optimization area. Accordingly, in this paper the probabilistic approach is implemented without local search and its convergence in this basic form is investigated. The approach is based on a probabilistic model of the random solutions that serves to derive a nonlinear distance measure for grading the constraint satisfaction performance of every population member. While the details of the probabilistic distance measure are revealed in another paper [1], this paper presents the implementation results in order to verify the theoretical considerations. In the present work the nonlinear distance measure is used to rank the genetic population members for effective tournament selection. The exponential ranking procedure ensures the same high selection pressure towards the feasible region throughout the search process, up to micro level in the range of 10^{-10} or beyond. This implies precision in the algorithm's convergence behavior. The exponential nonlinear ranking (NR) procedure itself does involve the non-dominated sorting technique for the tournament selection, and this integrated procedure has been used in the local-search based method in [10]. In contrast to this, in the present implementation without local search, NR is used in alternating sequence with the conventional, namely non-probabilistic ranking, as it is used in the original non-dominated sorting (NS) technique of the well-known NSGA-II algorithm [11]. For this reason the algorithm developed for this paper is named NS-NR algorithm.

The organization of the paper is as follows. In section two, formulation of general multiobjective optimization problem as constraint single objective problem by weighting method are presented. In section three, probabilistic modeling of the random solutions for exponential ranking implementation in evolutionary algorithm is described. In section four, several implications of the exponential ranking are highlighted. In section five a demonstrative computer experiment is given and it is followed by discussion and conclusions.

II. WEIGHTING METHOD FOR MULTIObjective OPTIMIZATION

A. Problem Formulation

Although some basic information about the probabilistic treatment used in the NS-NR approach is given in [1], some basic information is also included here for the stand-alone representation and completeness of this paper.

The formulation in this research stems from the considerations known as *weighting method* [12-14]. In this method each objective is associated with a weighting coefficient and the weighting sum of the objectives is minimized. In this way, the multiple objective functions are transformed into a single objective function. We assume that the weighting coefficients w_i are real numbers such that $0 \leq w_i$ for all objectives $i=1, \dots, k$ so that a weighting problem can be stated as

$$\min \sum_{i=1}^k w_i f_i(\mathbf{x}) \text{ subject to } \mathbf{x} \in S \quad (1)$$

In the constraint handling presented in this work a single objective is involved which is subject to minimization. Therefore the problem can be stated as

$$\min f(\mathbf{x}) \text{ subject to } \mathbf{g}(\mathbf{x}) = [g_1(\mathbf{x}), g_2(\mathbf{x}), \dots, g_m(\mathbf{x})]^T \leq 0 \quad (2)$$

We assume that the feasible region is of the form

$$S = \{\mathbf{x} \in R^n \mid \mathbf{g}(\mathbf{x}) = [g_1(\mathbf{x}), g_2(\mathbf{x}), \dots, g_m(\mathbf{x})]^T \geq 0\} \quad (3)$$

One notes that in this formulation every constraint function $g_i(\mathbf{x}) = -v_i(\mathbf{x})$ where v denotes the actual degree of violation of a constraint, and this degree is a non-negative number for a violated constraint. Hence the functions $g_i(\mathbf{x})$ have a negative value for a violated constraint, whereas $\langle g_i(\mathbf{x}) \rangle$, has a positive value for a violated constraint, as $\langle \alpha \rangle$ is the *bracket operator* that is equal to $-\alpha$ if $\alpha < 0$, and zero otherwise. Therefore, the sum of violations $\langle g_i(\mathbf{x}) \rangle$ is another objective subject to minimization. That is, the problem formulation becomes a problem of two objective functions that are both subject to minimization. In this case, the formulation of the problem using weighting method becomes

$$\min w_1 G(\mathbf{x}) + w_2 f(\mathbf{x}) \quad (4)$$

where $G(\mathbf{x}) = f_1(\mathbf{x})$ and $f(\mathbf{x}) = f_2(\mathbf{x})$, and for k number of constraints $G(\mathbf{x})$ is given by

$$G(\mathbf{x}) = \sum_{i=1}^k \mu_i \langle g_i(\mathbf{x}) \rangle \quad (5)$$

where μ are non-negative values that are not all zero. Thus, the problem definition becomes explicitly,

$$\min \sum_{i=1}^k \mu_i \langle g_i(\mathbf{x}) \rangle + f(\mathbf{x}) = G(\mathbf{x}) + f(\mathbf{x}) \quad (6)$$

$$S = \{\mathbf{x} \in R^n \mid \langle \mathbf{g}(\mathbf{x}) \rangle = [\langle g_1(\mathbf{x}) \rangle, \langle g_2(\mathbf{x}) \rangle, \dots, \langle g_m(\mathbf{x}) \rangle]^T \geq 0\}$$

where $w_1 = \mu_i$, $w_2 = 1$. Without deviating from generality, this formulation of the problem is equivalent to a single objective problem with the objective $f(\mathbf{x})$ and the constraints denoted by $\langle g_i(\mathbf{x}) \rangle$. Such an approach is known as *ε -Constraint* method [14, 15]. Here one of the objective functions is selected to be optimized and all the other objective functions are converted into constraints by setting an upper bound to each of them. The problem to be solved is now of the form

minimize $f_l(\mathbf{x})$; subject to $f_j(\mathbf{x}) \leq \varepsilon_j$ for all $j=1, 2, \dots, k$, $j \neq l$; $\mathbf{x} \in S$, where $l \in \{1, \dots, k\}$. Naturally, inequalities can be converted to equalities by taking $\varepsilon_j = 0$ for all $j=1, 2, \dots, k$, $j \neq l$.

B. Issues of the penalty function approach

Conventionally, (6) is written in the form

$$\min P(\mathbf{x}, R) = f(\mathbf{x}) + \sum_{j=1}^J R_j \langle g_j(\mathbf{x}) \rangle \quad (7)$$

where function $\langle g_j(\mathbf{x}) \rangle$ is considered to be a *penalty function* and the parameters R_j are the associated *penalty parameters*; Since each individual R_j is not known, conventionally a common penalty parameter R is defined so that (7) becomes

$$\min P(\mathbf{x}, R) = f(\mathbf{x}) + R \sum_{j=1}^J \langle g_j(\mathbf{x}) \rangle \quad (8)$$

or taking $f_2(\mathbf{x}) = f(\mathbf{x})$ and the summation of the $\langle g_j(\mathbf{x}) \rangle$ functions as $f_1(\mathbf{x})$, we can write

$$P_{opt} = \min \{f_2(\mathbf{x}) + R f_1(\mathbf{x})\} \quad (9)$$

To solve the optimization problem given by (9) with the weighting method, one can consider some options as follows.

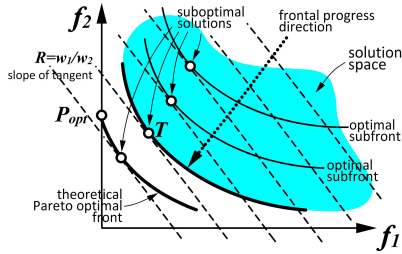


Fig. 1. Approach to the final optimal solution by means of constant penalty parameter R .

a) R is a constant. In this case, the development of the optimal front is illustrated in figure 1. The final development is the theoretical front and the solution is denoted with the point T which is far from the optimal point denoted by P_{opt} . As result of this option some gradient-based search algorithm is necessary that tails up evolutionary computation to reach the optimal point if it is realizable at all due to the chance of getting trapped in some local optima. During the Pareto front formation the most of the attention of the chromosomes goes to the penalty function rather than the objective function. As result of this, the convergence is essentially due to the constraints and therefore there is a significant progress along that line, while the single objective is de facto subsumed under the constraints. This situation makes determination of R very critical and precarious at the same time.

b) To determine the penalty parameter with adaptation by means of an extrapolation polynomial. In this case, a polynomial is fitted to the optimal front and its extrapolated intersection with the objective function axis is used for the slope of the tangent which is the reasonable estimation of the penalty parameter R . However, in this case, search algorithm tends to move to the straightforward solution, which is the gradual diminishing of the slope as illustrated in figure 2. As result of this option the penalty parameter takes smaller values during the search and may eventually vanish. In

the extreme, R goes to zero and problem turns out to be a single objective optimization omitting the constraints.

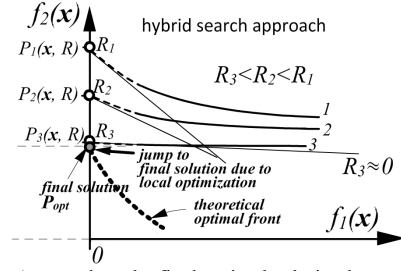


Fig. 2. Approach to the final optimal solution by means of penalty function approach, where R is the penalty parameter being estimated through curve fitting

C. Analysis of penalty function parameter

Let us assume that optimal theoretical front compromises the solutions for the objectives $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$, where objective $f_1(\mathbf{x})$ admits to be minimally zero. For the analysis viewpoint we assume that Pareto front is symmetrical with respect to $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$, and the front is an envelope of a line crossing the $f_1(\mathbf{x})$ axis at the point t and crossing the $f_2(\mathbf{x})$ axis at the point $P_{opt}t$; t is a parameter related to parametric representation of a line tangent to the Pareto front, and it is represented by

$$\frac{f_2(\mathbf{x})}{t} + \frac{f_1(\mathbf{x})}{P_{opt} - t} = 1 \quad (10)$$

In (10), P_{opt} is the optimum solution, where $f_2(\mathbf{x}) = P_{opt}$ and $f_1(\mathbf{x}) = 0$, which represents the satisfaction of the constraint. From (10), we obtain

$$f_2(\mathbf{x}) = \frac{t}{t - P_{opt}(\mathbf{x})} f_1(\mathbf{x}) + t \quad (11)$$

We can define the slope

$$r = \frac{t}{t - P_{opt}(\mathbf{x})} \quad (12)$$

as a *kernel* penalty parameter representing the varying part

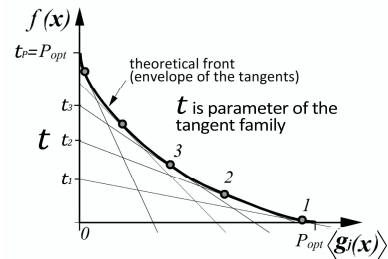


Fig. 3. The envelope of tangent and the new penalty parameter r

of the general penalty parameter R in (8), and for each constraint we consider $r = r_j$. The envelope of the tangent in (10) is shown in figure 3. In words, r is the gain in $f_2(\mathbf{x})$ per unit decrease in $f_1(\mathbf{x})$ at the point of tangent F and within infinitesimally small interval of $f_1(\mathbf{x})$. Incidentally, the envelope of the tangent is determined by the following condition [1]

$$t = f_2(\mathbf{x}) + \sqrt{f_2(\mathbf{x})f_1(\mathbf{x})} \quad (13)$$

$$p(\langle g_j \rangle) = \frac{1}{\langle g_j \rangle} \int_0^{\langle g_j \rangle} e^{-\frac{g_j}{\langle g_j \rangle}} dg_j = 1 - e^{-\frac{\langle g_j \rangle}{\langle g_j \rangle}} \quad (21)$$

For $\langle g_j \rangle = 0$ violation is zero and for $\langle g_j \rangle = \infty$, violation is 1, i.e., 100% for a finite mean value of $\langle g_j(\mathbf{x}) \rangle$. Explicitly $p(\langle g_j \rangle)$ is the probability of a violation in the range between zero and $\langle g_j \rangle$. It is a monotonically increasing function complying with the boundary conditions of $\langle g_j(\mathbf{x}) \rangle$ which varies between zero and infinity. It is interesting to note that for zero constraint violation the exponential probability density is at its maximum and probability of violation at its minimum. The probability $p(\langle g_j \rangle)$ is an appropriate measure for the magnitude or effectiveness of a violation, and it can be considered as a *probabilistic distance function* or a *metric* measuring the distance from the zero violation, fulfilling all the conditions to be a distance measure [16, 17]. The important implication of the premise (21) will be seen shortly.

The optimization problem with constraints is formulated in this work as follows.

$$P(\mathbf{x}) = f(\mathbf{x}) + \sum_{j=1}^J c_j r_j(\langle g_j \rangle) \langle g_j(\mathbf{x}) \rangle \quad (22)$$

where c_j is a penalty parameter belonging to the constraints and is a constant during the search process. $r_j(\langle g_j \rangle)$ is a penalty parameter also varying during the search process and belonging to each constraint. Therefore r_j is called as *convergence parameter*, being related to the convergence properties of the search, which in general means that it is a function of $\langle g_j(\mathbf{x}) \rangle$. For each constraint, separately, we can write

$$f_{1j}(\mathbf{x}) = c_j r_j(\langle g_j \rangle) \langle g_j(\mathbf{x}) \rangle \quad (23)$$

and from (12) and (13)

$$r_j = \frac{f_2(\mathbf{x}) + \sqrt{f_2(\mathbf{x})f_{1j}(\mathbf{x})}}{f_2(\mathbf{x}) + \sqrt{f_2(\mathbf{x})f_{1j}(\mathbf{x})} - P_{opt}(\mathbf{x})} \quad (24)$$

In (23) $r_j(\langle g_j \rangle) \langle g_j \rangle$ is replaced by $p_j(\langle g_j \rangle)$, in the form

$$r_j(\langle g_j \rangle) \langle g_j \rangle = p_j(\langle g_j \rangle) \quad (25)$$

Hence (22) becomes

$$P(\mathbf{x}) = f(\mathbf{x}) + \sum_{j=1}^J c_j p_j(\langle g_j(\mathbf{x}) \rangle) \quad (26)$$

The absolute value of r_j in (25) is due to the bracket operator mentioned with respect to (7). Justification of (25) can be seen by the limiting values, as follows. For $\langle g_j \rangle$ goes to infinity, then $p_j(\langle g_j \rangle)$ is indeterminate due to (21) where the mean value of $\langle g_j \rangle$ goes to infinity also. The product $p_j = r_j(\langle g_j \rangle) \langle g_j \rangle$ is computed using (12), noting that $\langle g_j \rangle$ is equal to f_{2j} , and as $\langle g_j \rangle$ goes to infinity P_{opt} also goes to infinity. Therefore taking $P_{opt} = \langle g_j \rangle$ in (12) and from (25)

$$\lim_{\langle g_j \rangle \rightarrow \infty} r_j(\langle g_j \rangle) \langle g_j \rangle = \lim_{\langle g_j \rangle \rightarrow \infty} \frac{t}{t - \langle g_j \rangle} \langle g_j \rangle \quad (27)$$

Due to (13), t is finite and therefore

$$\lim_{\langle g_j \rangle \rightarrow \infty} r_j(\langle g_j \rangle) \langle g_j \rangle = \lim_{\langle g_j \rangle \rightarrow \infty} \frac{\langle g_j \rangle}{\langle g_j \rangle} \quad (28)$$

which is indeterminate. Then (27)

$$\lim_{\langle g_j \rangle \rightarrow \infty} r_j(\langle g_j \rangle) \langle g_j \rangle \quad (29)$$

becomes indeterminate too. It is to note that c_j in (22) could be varying and a balanced strategy could be $c_j = f(\mathbf{x}) / \langle g_j \rangle$.

For $\langle g_j \rangle$ is equal to zero, $p_j(\langle g_j \rangle)$ in (21) goes to zero. In this case, the penalty term $r_j(\langle g_j \rangle) \langle g_j \rangle$ becomes zero, as it should be.

In view of (25), r_j is given by

$$r_j = f(\langle g_j \rangle) = p_j(\langle g_j \rangle) / \langle g_j \rangle \quad (30)$$

The new formulation (30) yields favourable, far reaching implications which are presented below. From (6), where we define

$$\sum_{j=1}^J \mu_j \langle g_j \rangle = G = \sum_{j=1}^J p(\langle g_j \rangle) \quad (31)$$

where μ is the weighting parameter. J is the number of constraints; The probability $p(\langle g_j \rangle)$ controls the penalty parameter R in (8); namely the penalty parameter is absorbed in $p(\langle g_j \rangle)$ in the form $c_j r_j$ while c_j is a constant being dependent on the associated constraint. The importance of this nonlinear transformation, namely $p(\langle g_j \rangle)$ is mainly due to its use for ranking the population members during the genetic search. In (26), $p(\langle g_j \rangle)$ can admit several interpretations as follows.

- On one hand it is a penalty function obtained by a nonlinear interpolation applied to $\langle g_j \rangle$. In this process, the probabilistic considerations apparently are exercised as a nonlinear transformation to the penalty function $\langle g_j(\mathbf{x}) \rangle$ to obtain another penalty function $p(\langle g_j \rangle)$ in order to bring $\langle g_j(\mathbf{x}) \rangle$ from an infinite range to a finite range namely, between zero and unity.
- As another interpretation, the penalty function $p(\langle g_j \rangle)$ is the probability of a random variable G , namely cumulative probability of an exponentially distributed random variable.
- Yet another interpretation is to consider $p(\langle g_j \rangle)$ as another stochastic variable Y_j obtained from a function of stochastic variable $X_j = g_j$.

The last interpretation is highlighted in this work so that several essential implications can be derived. For this aim first we consider the premise given by (21). The implication of this premise can be seen as follows.

Let us define

$$p(\langle g_j \rangle) = H(\langle g_j \rangle) \quad (32)$$

where $H(\langle g_j \rangle)$ is a function of random variable given by (21), $\langle g_j \rangle$ being the random variable in question.

$$\begin{aligned} p(\langle g_j \rangle) &= H(\langle g_j \rangle) = \int_0^{\langle g_j \rangle} \lambda_j e^{-\lambda_j \langle g_j \rangle} d\langle g_j \rangle \\ &= 1 - e^{-\lambda_j \langle g_j \rangle} \end{aligned} \quad (33)$$

where

$$\lambda_j = \frac{1}{\langle \bar{g}_j \rangle} \quad (34)$$

The probability density of this random variable is exponential density function given by (16). The probability density $f_p(p)$ of a new random variable p is given by

$$f_p(p) = \frac{f_{\langle g_j \rangle}(\langle g_j \rangle)}{\left| \frac{dH(\langle g_j \rangle)}{d\langle g_j \rangle} \right|_{\langle g_j \rangle = H^{-1}(p)}} \quad (35)$$

that gives the obvious result

$$f_p(p) = 1 \quad 0 \leq p \leq 1 \quad (36)$$

which is a uniform pdf. That is, (21) implies the uniform probability density of p . The important implication of this result will be presented in the following section.

IV. IMPLICATIONS OF THE PROBABILISTIC MODELING

A. Adaptive Zooming for Ranking with Precision

Adaptive zooming for ranking with precision is accomplished by accurate computation of $p(\langle g_j \rangle)$ in the range zero and unity as probabilistic distances, even though the actual constraint $\langle g_j(x) \rangle$ values may be close to the minimal point as much as the computer precision can allow, say at the range of 10^{-10} . To illustrate this, a sketch

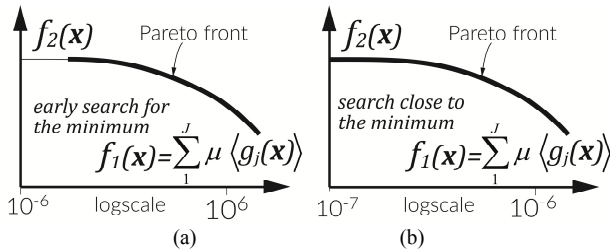


Fig. 5. Sketch of formation of the Pareto front at the early stage (a); at the last stage of the GA search (b).

of the Pareto front at the early stage of the genetic search is shown in figure 5a. A sketch of the Pareto front at the last stage of the genetic search is given in figure 5b. The shape of the curves is because of the log scale.

The probabilistic distance to the minimum is illustrated as a typical example in figure 6a by the indicated area where the computation of the shaded area is very precarious during the tournament selection process due to the issue of both exact parameterization of the exponential pdf in the existing range and the finite machine precision as well as the finite genotype coding. This situation is circumvented in figure 6b

by taking simply $p(\langle g_j \rangle)$ as the probability distance to the minimum. The indicated shaded areas in

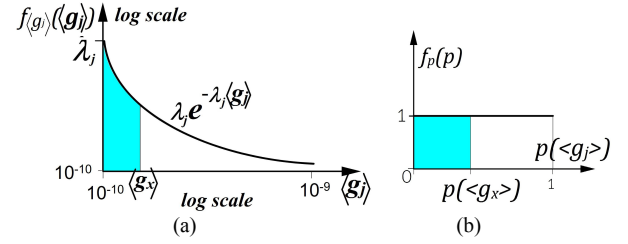


Fig. 6. Mathematical lense; pdf of the violations in the objective functions space (a); in the probabilistic space (b)

figures 6a and 6b are the same. This means if the constraint $\langle g_j(x) \rangle$ can be close to the optimal point in a micro scale, say in the range of 10^{-10} , as shown in figure 6a the penalty function $p(\langle g_j \rangle)$ takes place always in a macro scale in the range of between 0 and unity, as shown in figure 6b. This situation is equivalent to applying a commensurate magnifying glass to the space formed by actual objective function and the constraints functions to carry out the convergence process without being effected by any scale of convergence happening in this $\langle g_j \rangle$ space.

B. Effective Tournament Selection

Following the non-dominated sorting procedure as described in [11], an adaptive *threshold of productive chromosomes* is devised both in the non-dominated sorting (NS) stage as well as non-linear ranking (NR) stage of the NS-NR algorithm. It is based on the sum of the mean of the constraint violations $\langle g_T \rangle$ given by

$$\langle g_T \rangle = n_{bj} \sum_{j=1}^J \langle \bar{g}_j \rangle = \sum_{j=1}^J \frac{n_{bj}}{\lambda_j} \quad (37)$$

where $n_{bj} = \ln 2 / \lambda_j$ which is a constant. Referring to figure 7, the tournament selection, i.e., productive chromosomes selection is accomplished as follows.

- If the violations of a pair of population members are larger than the threshold, then the solution which has smaller violation wins the competition
- If the violations of a pair of population members are smaller than the threshold, then the solution with rank properties in terms of Pareto rank and crowding during the NS stage, or in terms of $P(\langle g_j \rangle, \mathbf{x})$ rank during NR stage, wins the tournament.

TABLE I

RESULTS FROM THE NS-NR APPROACH DESCRIBED IN THIS WORK FOR 30 RUNS ON THE BENCHMARK PROBLEMS DESCRIBED IN [1]

fcn	optimal	best	median	mean	st. dev.	worst	feas. runs	gen
g1	-15.00000	-14.99992	-14.99942	-14.99889	1.15E-03	-14.99550	30	560
g2	-0.803619	-0.803489	-0.792984	-0.794303	7.46E-03	-0.772063	30	760
g3	-1.000500	-1.000499	-1.000492	-1.000492	3.02E-06	-1.000486	30	420
g4	-30665.539	-30665.539	-30665.539	-31665.538	2.72E-04	-30525.789	30	540
g5	5126.498	5126.568	5177.187	5257.630	1.70E+02	5681.150	21	390
g6	-6961.814	-6961.8138	-6881.8553	-6781.8316	2.27E+02	-6028.6813	30	300
g7	24.306209	24.317060	24.734179	24.806833	4.32E-01	25.905036	30	1140
g8	-0.095825	-0.0958224	-0.0956730	-0.0929779	1.19E-02	-0.0291209	30	390
g9	680.63006	680.63497	680.65640	680.66532	2.67E-02	680.73702	30	540

- c) If the violations of a pair of population members are at either side of the threshold, then the elite population member that is the chromosome with violation lower than the threshold is selected irrespective to its rank in the NS or NR procedures.

The case illustrated in figure 7 where horizontal axis refers to NS (non-dominated sorting) procedures and vertical axis refers to NR (nonlinear ranking) procedures; $n_{bj} = \ln 2 / \lambda_j$ is the median of the exponential pdf as shown in figure 7b. For $n_{bj} = \ln 2 / \lambda_j$, its counterpart in terms of the probabilistic distance is $n_{pj} = 0.5$ which is, in contrast to n_{bj} , a constant. Thus, the constant probabilistic distance measure provides an adaptive threshold for productive chromosomes throughout the generations, in any scale permitted by the machine or genotype precision. By means of this particular tournament selection procedure, the dominance of the average violation by the stiff constraints, that is, by the members with high violations, is prevented; namely, during two consecutive generations the progressive diminishing of

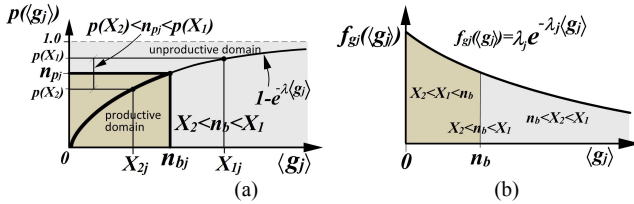


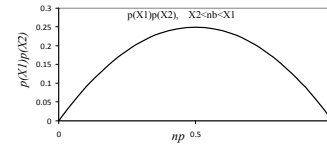
Fig. 7. Illustration of the threshold assessment for the tournament selection in both NS and NR procedures.

the average is aimed against the contingent average increase that may occur especially during the advanced

stages of the convergence. In the tournament selection, the domains considered separately are illustrated in figure 7b. The smaller total mean of the constraint violations implies improved convergence to the optimum. Referring to figure 7b, the probability P_j of the event relevant to the case (c) above is given by

$$P_j = P(\langle g_j \rangle) = P(X1_j) - P(X2_j) = e^{-\lambda_j n_{bj}} - e^{-2\lambda_j n_{bj}} \quad (38)$$

The variation of P_j with respect to n_{bj} is illustrated in figure 8, in terms of its counterpart p_j which has a maximum at $n_{pj} = 0.5$ for $n_{bj} = \ln 2 / \lambda_j$.

Fig. 8. Plot of the probability that two solutions occur on different sides of the threshold n_{bj} vs n_{pj}

It is to note that, the plot remains the same throughout the generations, although the same plot

in the actual violations domain, that is, in the $\langle g_j \rangle$ domain corresponds to a family of plots with respect to the parameter λ_j . Implementation of (35) in the NS-NR algorithm is as follows. Should the case (c) arise, the chromosome at the productive domain wins in the tournament selection.

C. Fast and robust convergence

With the probabilistic distance providing nonlinear ranking we obtain robust progress for convergence at each

TABLE II

COMPARISON OF THE BEST VALUES OF SOLUTIONS OBTAINED BY THE NS-NR APPROACH, AND FOUR EXISTING STATE OF THE ART APPROACHES

fcn	optimal	BEST				
		NS-NR	SR	HM	ASCHEA	SMES
g1	-15.00000	-15.000	-15.000	-14.7886	-15.0	-15.000
g2	-0.803619	-0.803489	-0.803515	-0.7995	-0.785	-0.803601
g3	-1.000500	-1.000499	-1.000*	-0.9997	-1.0*	-1.000*
g4	-30665.539	-30665.539	-30665.539	-30664.5*	-30665.5*	-30665.539
g5	5126.498	5126.568	5126.497	—	5126.5	5126.599
g6	-6961.814	-6961.8138	-6961.814	-6952.1	-6961.81	-6961.814
g7	24.306209	24.317060	24.307	24.620	24.3323	24.327
g8	-0.095825	-0.0958224	-0.095825	-0.0958250	-0.095825	-0.095825
g9	680.63006	680.63497	680.630	680.91	680.630	680.632

* the accuracy of the results provided in the literature is restricted to the printed one

TABLE III

COMPARISON OF THE MEAN VALUES OF SOLUTIONS OBTAINED BY THE NS-NR APPROACH, AND FOUR EXISTING STATE OF THE ART APPROACHES

fcn	optimal	M E A N				
		NS-NR	SR	HM	ASCHEA	SMES
g1	-15.00000	-14.99889	-15.000*	-14.7082	-14.84	-15.000
g2	-0.803619	-0.794303	-0.781975	-0.791671	-0.59	-0.785238
g3	-1.000500	-1.000492	-1.000*	-0.9989	-0.99989	-1.000*
g4	-30665.539	-31665.538	-30665.539	-30655.3	-30665.5	-30665.539
g5	5126.498	5257.630	5128.881	—	5141.65	5174.492
g6	-6961.814	-6781.8316	-6875.940	-6342.6	-6961.81	-6961.284
g7	24.306209	24.806833	24.374	24.826	24.66	24.475*
g8	-0.095825	-0.0929779	-0.095825	-0.089157	-0.095825	-0.095825
g9	680.63006	680.66532	680.656	681.16	680.641	680.643

*the accuracy of the results provided in the literature is restricted to the printed one

generation. To see this, from (25)

$$r_j = \frac{p(\langle g_j \rangle)}{\langle g_j \rangle} = \frac{1 - e^{-\lambda_j \langle g_j \rangle}}{\langle g_j \rangle} \quad (39)$$

In the limiting case, i.e., convergence to the minimum, r_j becomes λ_j with the implication seen by (34); namely

$$\lim_{\langle g_j \rangle \rightarrow 0} r_j = \frac{p(\langle g_j \rangle)}{\langle g_j \rangle} = \lim_{\langle g_j \rangle \rightarrow 0} \lambda_j e^{-\lambda_j \langle g_j \rangle} = \lambda_j \quad (40)$$

V. COMPUTER EXPERIMENTS

A. General analyses of the precision convergence behavior

Experiments have been carried out for a number of benchmark problems that are due to Michalewicz and Schoenauer [18]. The results from 30 runs of the algorithm are given in table 1, where the best known optimum is indicated as well as the performance of the NS-NR algorithm. The results are compared with four other algorithms in table 2, namely *stochastic ranking* [19], *homomorphous mapping* method in [20], *adaptive segregational Constraint Handling Evolutionary Algorithm (ASCHEA)* [21], and *A Simple Multimembered Evolution Strategy to Solve Constrained Optimization Problems (SMES)* [22]. From tables 2 and 3 it is seen that for the test problems considered, the NS-NR approach presented performs comparable with the most accurate algorithms in the literature, while it does not outperform them.

B. Detailed analysis of the precision convergence behavior

Computer experiments have been carried out using problem g2 in tables 1-3. The problem is due to [18]. The problem consists of a single objective with two constraints, subject to minimization, as given by (38)-(40).

$$\text{Minimize } f(\mathbf{x}) = - \frac{\sum_{i=1}^n \cos^4(x_i) - 2 \prod_{i=1}^n \cos^2(x_i)}{\sqrt{\sum_{i=1}^n i x_i^2}} \quad (41)$$

subject to

$$g_1(\mathbf{x}) = 0.75 - \prod_{i=1}^n x_i \leq 0 \quad (42)$$

$$g_2(\mathbf{x}) = \sum_{i=1}^n x_i - 7.5n \leq 0 \quad (43)$$

where $0 \leq x_i \leq 10$ ($i=1, \dots, 20$)

The best known optimum is

$$f(\mathbf{x}^*) = -0.80361910412559,$$

and the corresponding best variable values are

$$\begin{aligned} x_1^* &= 3.16246061572185; & x_2^* &= 3.12833142812967; \\ x_3^* &= 3.09479212988791; & x_4^* &= 3.06145059523469; \\ x_5^* &= 3.02792915885555; & x_6^* &= 2.99382606701730; \\ x_7^* &= 2.95866871765285; & x_8^* &= 2.92184227312450; \\ x_9^* &= 0.49482511456933; & x_{10}^* &= 0.48835711005490; \\ x_{11}^* &= 0.48231642711865; & x_{12}^* &= 0.47664475092742; \\ x_{13}^* &= 0.47129550835493; & x_{14}^* &= 0.46623099264167; \\ x_{15}^* &= 0.46142004984199; & x_{16}^* &= 0.45683664767217; \\ x_{17}^* &= 0.45245876903267; & x_{18}^* &= 0.44826762241853; \\ x_{19}^* &= 0.44424700958760; & x_{20}^* &= 0.44038285956317. \end{aligned}$$

The algorithm is executed with the following settings: *population size*=200; *amount of generations*=150; *C*=100; the *ratio of NS-NR procedures*=15/1; *crossover probability*=0.95; *Simulated Binary Crossover parameter nc*=1.0 [23]; *mutation probability*=0.05; *polynomial mutation parameter nm*=30 [24]. The results are shown in figures 9-12 using a logarithmic scale for the horizontal axis, which shows the total violation G . From the figures it is observed how the initial population gradually approaches towards the optimal solution. It is emphasized that an iteration of the algorithm consists of 15 Pareto-ranking based generations, followed by one probabilistic selection based generation. After 20 iterations the best feasible solution is found to be

$$f(\mathbf{x}) = -0.78835569614655$$

The population is seen in figure 9. The independent variables of this solution take:

$$\begin{aligned} x_1 &= 3.15921556367926; & x_2 &= 3.05012203191546; \\ x_3 &= 2.99548557106111; & x_4 &= 2.95357956839086; \\ x_5 &= 2.92853530781215; & x_6 &= 0.698330997346738; \\ x_7 &= 0.614737364075027; & x_8 &= 0.519294561838674; \\ x_9 &= 0.58315252010638; & x_{10} &= 0.537394783817692; \\ x_{11} &= 3.08268488604599; & x_{12} &= 2.99193702518271; \\ x_{13} &= 0.484713624884173; & x_{14} &= 0.555232075943147; \\ x_{15} &= 0.528189166194421; & x_{16} &= 0.494161231861299; \end{aligned}$$

$x_{17}=0.520658955898436;$ $x_{18}=0.481302236763824;$
 $x_{19}=0.429724286200153;$ $x_{20}=0.622919069113193.$

The peculiarity of the problem is essentially due to being highly non-linear, non-polynomial, and non-quadratic, -cubic, -quartic etc. the case being rather unconventional as to the examples subjected to evolutionary optimization and reported in the literature.

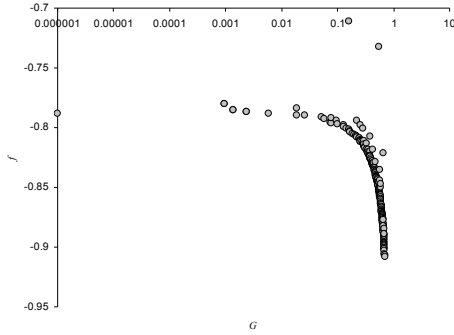


Fig. 9. Population after 20 iterations; horizontal axis shows the total violation G in (31) on a log scale.

After 40 iterations the best feasible solution is found to be

$$f(x) = -0.792566404183618$$

The population is seen in figure 10.

The independent variables of this solution take:

$x_1=3.16743077373371;$ $x_2=3.11153072964855;$
 $x_3=3.01156091583299;$ $x_4=3.00139459382801;$
 $x_5=2.96475180352977;$ $x_6=0.565947284057509;$
 $x_7=0.563461933159754;$ $x_8=0.597508576558864;$
 $x_9=0.543083970329823;$ $x_{10}=0.540363082224514;$
 $x_{11}=3.14939132194;$ $x_{12}=3.06891156366092;$
 $x_{13}=0.525006033808484;$ $x_{14}=0.525568247419281;$
 $x_{15}=0.528180782619807;$ $x_{16}=0.506898293813612;$
 $x_{17}=0.519975812107105;$ $x_{18}=0.486729641493575;$
 $x_{19}=0.478952387684703;$ $x_{20}=0.588533808993732.$

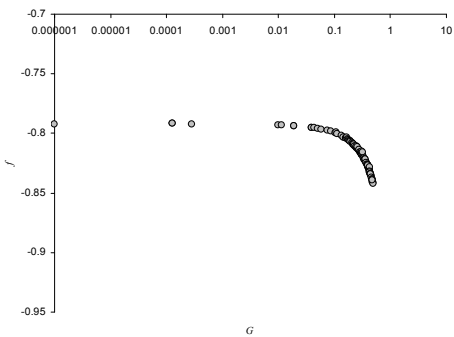


Fig. 10. Population after 40 iterations; horizontal axis shows the total violation G in (31) on a log scale.

After 80 iterations the best feasible solution is found to be

$$f(x) = -0.792890774207573$$

The population is seen in figure 11. The independent variables of this solution take:

$x_1=3.17471604947351;$ $x_2=3.10424069114897;$
 $x_3=3.02171047480553;$ $x_4=2.99308771595274;$
 $x_5=2.956410882173;$ $x_6=0.572505793511525;$
 $x_7=0.578665087235283;$ $x_8=0.554640545448787;$
 $x_9=0.566156238605148;$ $x_{10}=0.532405930514882;$
 $x_{11}=3.13679137497742;$ $x_{12}=3.0736263213087;$
 $x_{13}=0.528911605332599;$ $x_{14}=0.524193903602574;$
 $x_{15}=0.522282107205052;$ $x_{16}=0.507956068541584;$
 $x_{17}=0.508096753566494;$ $x_{18}=0.489204567842735;$
 $x_{19}=0.496488585809298;$ $x_{20}=0.587803667973163.$

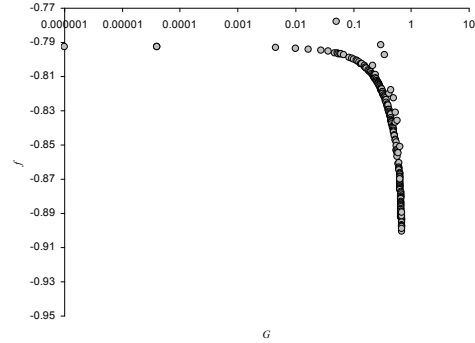


Fig. 11. Population after 80 iterations; horizontal axis shows the total violation G in (31) on a log scale.

After 150 iterations the best feasible solution is found to be

$$f(x) = -0.792895505756498$$

The population is seen in figure 12. The independent variables of this solution take:

$x_1=3.16841088942857;$ $x_2=3.10424069114897;$
 $x_3=3.02209237383018;$ $x_4=2.99311722179003;$
 $x_5=2.96241217056916;$ $x_6=0.572505793511525;$
 $x_7=0.578665087235283;$ $x_8=0.542375069637347;$
 $x_9=0.566156238605148;$ $x_{10}=0.532405930514882;$
 $x_{11}=3.13679137497742;$ $x_{12}=3.0749798869538;$
 $x_{13}=0.528911605332599;$ $x_{14}=0.524715025053636;$
 $x_{15}=0.522282107205052;$ $x_{16}=0.507956068541584;$
 $x_{17}=0.508096753566494;$ $x_{18}=0.489204567842735;$
 $x_{19}=0.496488585809298;$ $x_{20}=0.599643520402106.$

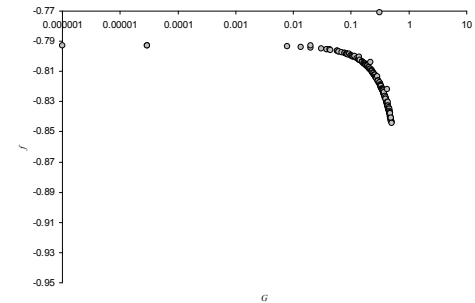


Fig. 12. Population after 150 iterations; horizontal axis shows the total violation G in (31) on a log scale.

CONCLUSIONS

Effectiveness of evolutionary optimization for constrained optimization is investigated. The results from the experiments demonstrate that precision optimization can be obtained by evolutionary computation alone without the involvement of local search. The feasible solutions are

reached with precision by a small yet significant modification of the ranking procedure of the evolutionary algorithm, namely using an exponential ranking. The validity of the theoretical considerations has been properly demonstrated. Due to the adaptive feature of the probabilistic model, in the exponential ranking process, the assessment of constraint violation is continuously done in a probabilistic scale between zero and unity. This is in contrast to conventional penalty parameter approaches, where the product of penalty parameter and constraint violation becomes precarious as the constraint violation tends to vanish. In this way, the same precision of the product is preserved, being independent of the level of convergence to the optimum. This means the exponential ranking method forms a dynamic “lens,” the magnifying power of which is commensurate with the scale of convergence. As consequence, convergence is accomplished accurately and systematically with precision at any range of both, the machine, computing and genotype coding precision. This is demonstrated from the experimental analysis of the convergence progress throughout the optimization process, thereby matching of the results with the theoretical considerations. Comparison of the results from the presented evolutionary precision optimization with state of the art algorithms revealed another important conclusion. Although the proposed algorithm does not outperform the existing researches in the literature, it is to note that the algorithm is a very basic one and minimally differs from conventional evolutionary algorithm, in contrast to the sophisticated algorithms. Strikingly, despite its very basic nature it performs competitive with the state of the art algorithms. This demonstrates that forming the ranking with the probabilistic nonlinearity is an outstandingly efficient measure to reach precision optimization. This means stable convergence with a precision convergence accuracy. This is an important conclusion, since it implies that the precision of existing constrained evolutionary optimization algorithms can be enhanced by inserting the probabilistic distance measure approach of this work.

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