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Benchmarking sep-CMA-ES on the BBOB-2009 Noisy Testbed

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ABSTRACT

A partly time and space linear CMA-ES is benchmarked on the BBOB-2009 noisy function test bed. This algorithm with a multistart strategy with increasing population size solves 10 functions out of 30 in 20-D.

Categories and Subject Descriptors

G.1.6 [Numerical Analysis]: Optimization—*global optimization, unconstrained optimization*; F.2.1 [Analysis of Algorithms and Problem Complexity]: Numerical Algorithms and Problems

General Terms

Algorithms

Keywords

Benchmarking, Black-box optimization, Evolutionary computation, Covariance matrix adaptation, Evolution strategy

1. INTRODUCTION

The sep-CMA-ES algorithm introduced in [7] is a variant of the covariance matrix adaptation evolution strategy (CMA-ES) [5] that is linear in time and space. This property combined with a faster learning rate makes sep-CMA-ES appropriate for separable function and larger dimensions. A mixed strategy of using sep-CMA-ES and CMA-ES is proposed here and benchmarked on a noisy function testbed.

2. ALGORITHM PRESENTATION

In its design, the sep-CMA-ES differs from the CMA-ES by two aspects: first, the covariance matrix is constrained to be diagonal at each of its update, second, the learning rate is increased by a factor of $\frac{n+3/2}{3}$, where n is the dimension of the search space¹. These modifications result

¹Please note that the factor for the learning rate is smaller than the one in [7].

in an algorithm that trades model complexity with a time and space scaling that is better than the original CMA-ES. The $(\mu/\mu_w, \lambda)$ -sep-CMA-ES has been shown to outperform $(\mu/\mu_w, \lambda)$ -CMA-ES on separable functions.

We propose here what would be the best of two worlds: to use sep-CMA-ES for the first few iterations and then switch to CMA-ES. At the time of the switch, all parameters are retained except for the learning rate that is decreased back to its default value. This implies the diagonal covariance matrix acquired using sep-CMA-ES is directly used by CMA-ES. This mixed strategy is therefore expected to be faster than CMA-ES on separable functions. Ongoing work has also shown that for some test functions the first iterations using sep-CMA-ES would not disadvantage the latter use of CMA-ES in any way. In other terms, the cost of initially using sep-CMA-ES would not induce a penalty in the cost of solving the function with CMA-ES afterwards. The author admits some functions could induce such a penalty.

As for the multistart strategy, we use the increasing population size IPOPOP-CMA-ES [1]. Though this approach has shown its limits [6], independent restart may improve the probability of the algorithm reaching a given target function value.

3. EXPERIMENTAL PROCEDURE

The Matlab implementation of the CMA-ES (version 3.23 beta) is used². We use the $(\mu/\mu_w, \lambda)$ -IPOPOP-CMA-ES variant with an initial default population size $\lambda = 4 + \lfloor 3 \ln(n) \rfloor$ increasing twice at each restart. Except the learning rate, all other algorithm parameters are set to their default values. The covariance matrix is constrained to be diagonal only for the first $1 + 100n/\sqrt{\lambda}$ iterations of the *first start*. A maximum of 8 independent restarts is conducted. Restarts occur after $100 + 300n\sqrt{n/\lambda}$ iterations or if any of the default stopping criterion is met. The initial stepsize has been set to 2 and the starting point has been chosen uniformly in $[-4, 4]^n$. The maximum number of function evaluations was set to 10^4 times the dimension. No parameter tuning was done, the CrE [3] is computed to zero.

4. RESULTS

Results from experiments according to [3] on the benchmarks functions given in [2, 4] are presented in Figures 1 and 2 and in Tables 1 and 2. From the results of this algorithm, the uniform noise model is the most difficult to deal

²Latest version available here:<http://www.lri.fr/~hansen/cmaesintro.html>

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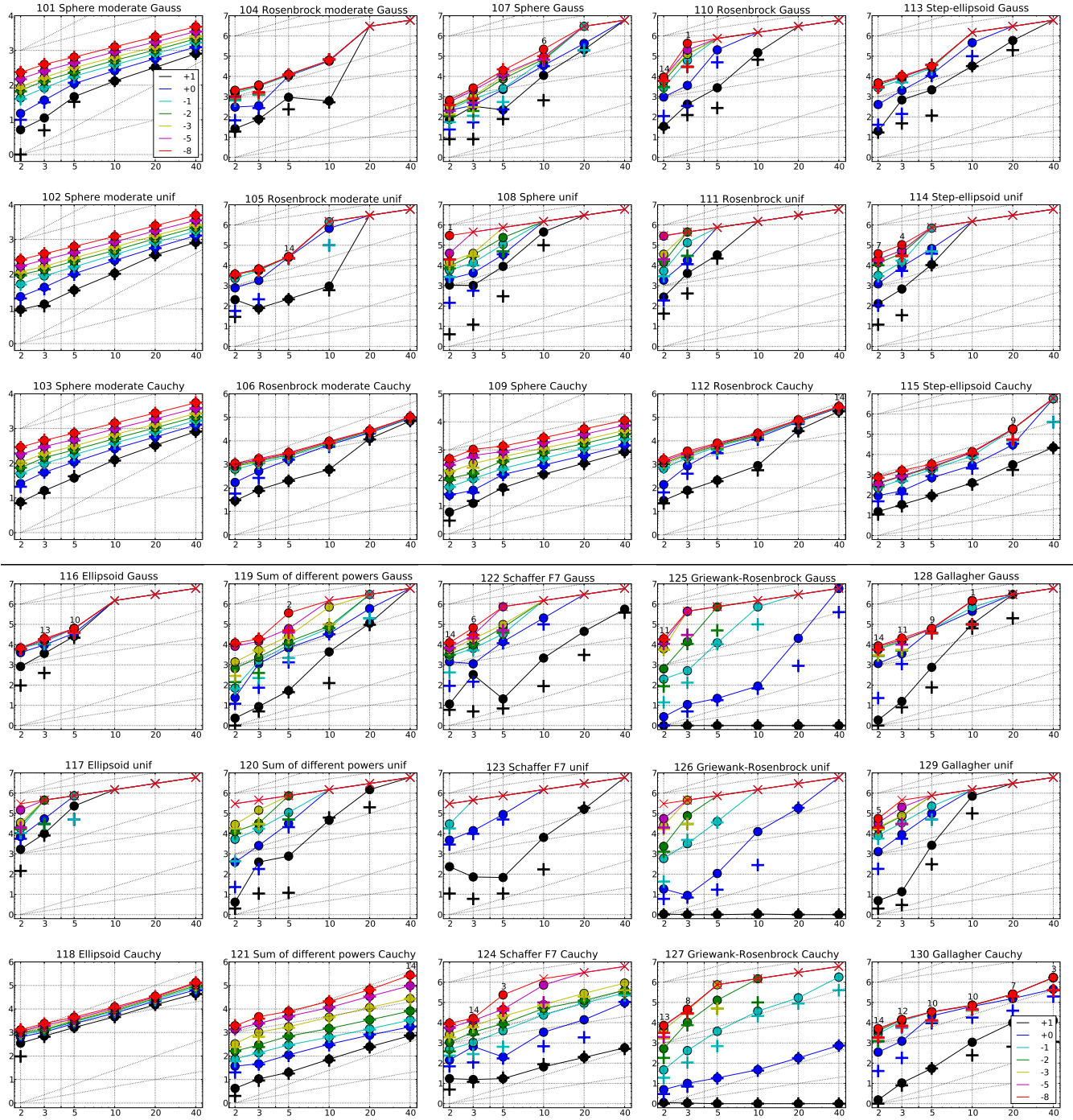


Figure 1: Expected Running Time (ERT, ●) to reach $f_{\text{opt}} + \Delta f$ and median number of function evaluations of successful trials (+), shown for $\Delta f = 10, 1, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-5}, 10^{-8}$ (the exponent is given in the legend of f_{101} and f_{130}) versus dimension in log-log presentation. The $\text{ERT}(\Delta f)$ equals to $\#FES(\Delta f)$ divided by the number of successful trials, where a trial is successful if $f_{\text{opt}} + \Delta f$ was surpassed during the trial. The $\#FES(\Delta f)$ are the total number of function evaluations while $f_{\text{opt}} + \Delta f$ was not surpassed during the trial from all respective trials (successful and unsuccessful), and f_{opt} denotes the optimal function value. Crosses (×) indicate the total number of function evaluations $\#FES(-\infty)$. Numbers above ERT-symbols indicate the number of successful trials. Annotated numbers on the ordinate are decimal logarithms. Additional grid lines show linear and quadratic scaling.

f_{101} in 5-D, N=15, mFE=738					f_{101} in 20-D, N=15, mFE=2654					f_{102} in 5-D, N=15, mFE=754					f_{102} in 20-D, N=15, mFE=2798						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	15	4.6e1	3.7e1	5.6e1	4.6e1	15	3.2e2	3.1e2	3.4e2	3.2e2	10	15	3.5e1	2.9e1	4.1e1	3.5e1	15	3.6e2	3.4e2	3.8e2	3.6e2
1	15	1.1e2	1.0e2	1.2e2	1.1e2	15	5.8e2	5.6e2	6.0e2	5.8e2	1	15	1.0e2	9.3e1	1.1e2	1.0e2	15	5.8e2	5.6e2	6.0e2	5.8e2
1e-1	15	1.8e2	1.7e2	1.9e2	1.8e2	15	8.0e2	7.8e2	8.2e2	8.0e2	1e-1	15	1.6e2	1.5e2	1.7e2	1.6e2	15	8.2e2	7.9e2	8.5e2	8.2e2
1e-3	15	3.2e2	3.1e2	3.3e2	3.2e2	15	1.3e3	1.2e3	1.3e3	1.3e3	1e-3	15	3.0e2	2.9e2	3.1e2	3.0e2	15	1.3e3	1.3e3	1.3e3	1.3e3
1e-5	15	4.4e2	4.3e2	4.5e2	4.4e2	15	1.7e3	1.7e3	1.8e3	1.7e3	1e-5	15	4.3e2	4.2e2	4.4e2	4.3e2	15	1.8e3	1.7e3	1.8e3	1.8e3
1e-8	15	6.4e2	6.2e2	6.6e2	6.4e2	15	2.5e3	2.4e3	2.5e3	2.5e3	1e-8	15	6.3e2	6.1e2	6.5e2	6.3e2	15	2.5e3	2.5e3	2.5e3	2.5e3
f_{103} in 5-D, N=15, mFE=1162					f_{103} in 20-D, N=15, mFE=3014					f_{104} in 5-D, N=15, mFE=23542					f_{104} in 20-D, N=15, mFE=200022						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	15	3.8e1	3.2e1	4.4e1	3.8e1	15	3.3e2	3.1e2	3.4e2	3.3e2	10	15	9.3e2	2.3e2	1.6e3	9.3e2	0	<i>17e+0</i>	<i>15e+0</i>	<i>18e+0</i>	1.3e5
1	15	1.1e2	9.9e1	1.2e2	1.1e2	15	5.7e2	5.5e2	5.9e2	5.7e2	1	15	1.1e4	8.4e3	1.3e4	1.1e4					
1e-1	15	1.8e2	1.7e2	1.9e2	1.8e2	15	7.9e2	7.7e2	8.1e2	7.9e2	1e-1	15	1.1e4	9.0e3	1.3e4	1.1e4					
1e-3	15	3.1e2	3.0e2	3.2e2	3.1e2	15	1.3e3	1.3e3	1.3e3	1.3e3	1e-3	15	1.2e4	1.0e4	1.4e4	1.2e4					
1e-5	15	4.8e2	4.6e2	5.1e2	4.8e2	15	1.9e3	1.9e3	1.9e3	1.9e3	1e-5	15	1.2e4	1.0e4	1.5e4	1.2e4					
1e-8	15	7.3e2	6.9e2	7.8e2	7.3e2	15	2.8e3	2.8e3	2.8e3	2.8e3	1e-8	15	1.3e4	1.1e4	1.5e4	1.3e4					
f_{105} in 5-D, N=15, mFE=50008					f_{105} in 20-D, N=15, mFE=200022					f_{106} in 5-D, N=15, mFE=5292					f_{106} in 20-D, N=15, mFE=34994						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	15	2.2e2	2.1e2	2.3e2	2.2e2	0	<i>18e+0</i>	<i>14e+0</i>	<i>19e+0</i>	1.3e5	10	15	2.1e2	1.9e2	2.2e2	2.1e2	15	1.2e4	1.2e4	1.3e4	1.2e4
1	14	2.5e4	2.2e4	3.0e4	2.4e4						1	15	1.6e3	1.3e3	1.9e3	1.6e3	15	2.2e4	2.1e4	2.3e4	2.2e4
1e-1	14	2.6e4	2.2e4	3.0e4	2.4e4						1e-1	15	2.2e3	1.9e3	2.5e3	2.2e3	15	2.4e4	2.3e4	2.5e4	2.4e4
1e-3	14	2.7e4	2.3e4	3.1e4	2.5e4						1e-3	15	2.7e3	2.4e3	2.9e3	2.7e3	15	2.5e4	2.5e4	2.6e4	2.5e4
1e-5	14	2.7e4	2.3e4	3.1e4	2.5e4						1e-5	15	2.9e3	2.6e3	3.2e3	2.9e3	15	2.6e4	2.6e4	2.7e4	2.6e4
1e-8	14	2.7e4	2.3e4	3.2e4	2.5e4						1e-8	15	3.2e3	2.9e3	3.4e3	3.2e3	15	2.8e4	2.7e4	2.9e4	2.8e4
f_{107} in 5-D, N=15, mFE=23686					f_{107} in 20-D, N=15, mFE=200022					f_{108} in 5-D, N=15, mFE=50008					f_{108} in 20-D, N=15, mFE=200022						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	15	2.2e2	9.1e1	3.6e2	2.2e2	13	2.1e5	1.8e5	2.5e5	1.8e5	10	15	9.0e3	4.9e3	1.4e4	9.0e3	0	<i>72e+0</i>	<i>28e+0</i>	<i>11e+1</i>	1.8e5
1	15	2.3e3	9.2e2	3.7e3	2.3e3	7	4.2e5	3.3e5	7.4e5	2.0e5	1	13	3.5e4	2.8e4	4.1e4	3.0e4					
1e-1	15	2.5e3	1.2e3	3.9e3	2.5e3	1	3.0e6	1.5e6	>3e6	2.0e5	1e-1	6	1.1e5	7.5e4	1.8e5	4.2e4					
1e-3	15	1.0e4	7.8e3	1.3e4	1.0e4	0	<i>11e-1</i>	<i>13e-2</i>	<i>14e+0</i>	2.0e5	1e-3	0	<i>20e-2</i>	<i>58e-4</i>	<i>23e-1</i>	2.2e4					
1e-5	15	1.3e4	1.0e4	1.6e4	1.3e4						1e-5										
1e-8	15	2.0e4	1.8e4	2.4e4	2.0e4						1e-8										
f_{109} in 5-D, N=15, mFE=1730					f_{109} in 20-D, N=15, mFE=6338					f_{110} in 5-D, N=15, mFE=50008					f_{110} in 20-D, N=15, mFE=200022						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	15	4.5e1	3.6e1	5.5e1	4.5e1	15	3.3e2	3.2e2	3.5e2	3.3e2	10	15	2.8e3	3.3e2	5.2e3	2.8e3	0	<i>60e+0</i>	<i>39e+0</i>	<i>40e+1</i>	1.8e5
1	15	1.3e2	1.2e2	1.5e2	1.3e2	15	6.3e2	6.1e2	6.5e2	6.3e2	1	3	2.1e5	1.2e5	6.2e5	5.0e4					
1e-1	15	2.2e2	2.0e2	2.4e2	2.2e2	15	1.1e3	1.1e3	1.2e3	1.1e3	1e-1	0	<i>21e-1</i>	<i>70e-2</i>	<i>33e-1</i>	1.1e4					
1e-3	15	5.7e2	5.2e2	6.2e2	5.7e2	15	2.3e3	2.2e3	2.4e3	2.3e3	1e-3										
1e-5	15	8.7e2	8.1e2	9.4e2	8.7e2	15	3.6e3	3.5e3	3.7e3	3.6e3	1e-5										
1e-8	15	1.4e3	1.3e3	1.4e3	1.4e3	15	5.6e3	5.5e3	5.7e3	5.6e3	1e-8										
f_{111} in 5-D, N=15, mFE=50008					f_{111} in 20-D, N=15, mFE=200022					f_{112} in 5-D, N=15, mFE=14628					f_{112} in 20-D, N=15, mFE=137776						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	12	3.4e4	2.6e4	4.2e4	2.9e4	0	<i>16e+2</i>	<i>52e+1</i>	<i>93e+2</i>	1.8e5	10	15	2.1e2	1.9e2	2.3e2	2.1e2	15	2.9e4	2.6e4	3.1e4	2.9e4
1	0	<i>40e-1</i>	<i>19e-1</i>	<i>43e+0</i>	2.8e4						1	15	4.3e3	3.1e3	5.4e3	4.3e3	15	6.4e4	5.5e4	7.3e4	6.4e4
1e-1											1e-1	15	5.7e3	4.6e3	6.8e3	5.7e3	15	7.0e4	6.1e4	7.9e4	7.0e4
1e-3											1e-3	15	6.7e3	5.6e3	7.8e3	6.7e3	15	7.4e4	6.5e4	8.3e4	7.4e4
1e-5											1e-5	15	7.3e3	6.2e3	8.5e3	7.3e3	15	7.6e4	6.7e4	8.5e4	7.6e4
1e-8											1e-8	15	8.0e3	6.9e3	9.2e3	8.0e3	15	7.9e4	7.1e4	8.8e4	7.9e4
f_{113} in 5-D, N=15, mFE=37944					f_{113} in 20-D, N=15, mFE=200022					f_{114} in 5-D, N=15, mFE=50008					f_{114} in 20-D, N=15, mFE=200022						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	15	2.2e3	8.0e2	3.6e3	2.2e3	5	5.9e5	4.2e5	9.9e5	2.0e5	10	15	1.1e4	7.8e3	1.5e4	1.1e4	0	<i>17e+1</i>	<i>92e+0</i>	<i>39e+1</i>	1.8e5
1	15	1.3e4	8.6e3	1.7e4	1.3e4	0	<i>21e+0</i>	<i>47e-1</i>	<i>87e+0</i>	1.8e5	1	8	6.8e4	5.0e4	9.9e4	3.7e4					
1e-1	15	2.6e4	2.3e4	3.0e4	2.6e4						1e-1	1	7.0e5	3.3e5	>7e5	5.0e4					
1e-3	15	3.1e4	2.8e4	3.4e4	3.1e4						1e-3	0	<i>99e-2</i>	<i>10e-2</i>	<i>38e-1</i>	2.5e4					
1e-5	15	3.1e4	2.8e4	3.4e4	3.1e4						1e-5										
1e-8	15	3.2e4	2.8e4	3.4e4	3.2e4						1e-8										
f_{115} in 5-D, N=15, mFE=7658					f_{115} in 20-D, N=15, mFE=200074					f_{116} in 5-D, N=15, mFE=50008					f_{116} in 20-D, N=15, mFE=200022						
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	
10	15	9.1e1	7.7e1	1.1e2	9.1e1	15	3.1e3	2.3e3	3.9e3	3.1e3	10	15	2.6e4	2.2e4	3.0e4	2.6e4	0	<i>13e+2</i>	<i>45e+1</i>	<i>36e+2</i>	1.8e5
1	15	7.1e2	5.9e2	8.3e2	7.1e2	15	3.0e4	2.6e4	3.4e4	3.0e4	1	14	3.6e4	3.2e4	4.1e4	3.3e4					
1e-1	15	1.8e3	1.4e3	2.3e3	1.8e3	9	1.7e5	1.2e5	2.6e5	9.2e4	1e-1	10	6.1e4	4.9e4	7.9e4	4.1e4					
1e-3	15	2.6e3	2.1e3	3.1e3	2.6e3	9	1.8e5	1.2e5	2.7e5	9.7e4	1e-3	10	6.2e4	5.0e4	8.0e4	4.2e4					
1e-5	15	2.6e3	2.1e3	3.0e3	2.6e3	9	1.8e5	1.2e5	2.8e5												

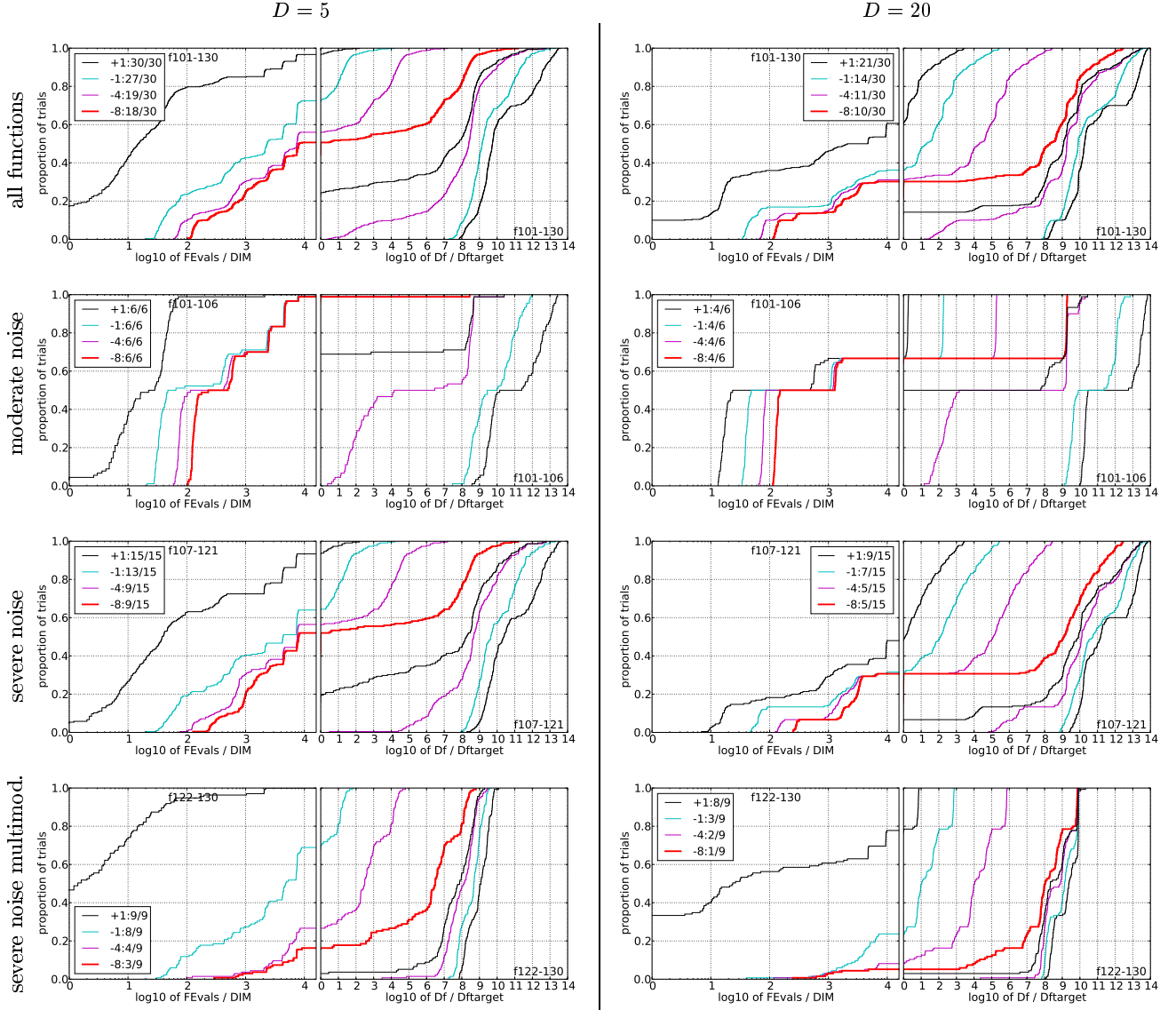


Figure 2: Empirical cumulative distribution functions (ECDFs), plotting the fraction of trials versus running time (left subplots) or versus Δf (right subplots). The thick red line represents the best achieved results. Left subplots: ECDF of the running time (number of function evaluations), divided by search space dimension D , to fall below $f_{\text{opt}} + \Delta f$ with $\Delta f = 10^k$, where k is the first value in the legend. Right subplots: ECDF of the best achieved Δf divided by 10^{-8} for running times of $D, 10D, 100D \dots$ function evaluations (from right to left cycling black-cyan-magenta). Top row: all results from all functions; second row: moderate noise functions; third row: severe noise functions; fourth row: severe noise and highly-multimodal functions. The legends indicate the number of functions that were solved in at least one trial. FEvals denotes number of function evaluations, D and DIM denote search space dimension, and Δf and Df denote the difference to the optimal function value.

f_{121} in 5-D, N=15, mFE=16756						f_{121} in 20-D, N=15, mFE=74630						f_{122} in 5-D, N=15, mFE=50008						f_{122} in 20-D, N=15, mFE=200022					
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}			
10	15	2.0e1	1.5e1	2.5e1	2.0e1	15	2.5e2	2.3e2	2.7e2	2.5e2	10	15	2.1e1	1.1e1	3.2e1	2.1e1	15	4.5e4	2.6e4	6.4e4	4.5e4		
1	15	1.1e2	9.7e1	1.3e2	1.1e2	15	7.7e2	7.2e2	8.2e2	7.7e2	1	15	1.4e4	1.0e4	1.8e4	1.4e4	0	<i>4.4e-1</i>	<i>1.7e-1</i>	<i>6.2e-1</i>	1.8e5		
1e-1	15	2.9e2	2.7e2	3.2e2	2.9e2	15	1.4e3	1.4e3	1.5e3	1.4e3	1e-1	14	3.3e4	2.8e4	4.0e4	3.1e4	.	.	.	.	.
1e-3	15	1.7e3	1.6e3	1.9e3	1.7e3	15	1.2e4	1.1e4	1.2e4	1.2e4	1e-3	7	9.8e4	7.1e4	1.6e5	4.5e4	.	.	.	.	.
1e-5	15	4.8e3	4.5e3	5.1e3	4.8e3	15	3.4e4	3.3e4	3.6e4	3.4e4	1e-5	1	7.4e5	3.7e5	>7e5	5.0e4	.	.	.	.	.
1e-8	15	7.9e3	7.1e3	8.8e3	7.9e3	15	6.6e4	6.4e4	6.8e4	6.6e4	1e-8	0	<i>1.6e-4</i>	<i>7.4e-6</i>	<i>7.0e-3</i>	4.0e4	.	.	.	.	.
f_{123} in 5-D, N=15, mFE=50008						f_{123} in 20-D, N=15, mFE=200022						f_{124} in 5-D, N=15, mFE=50058						f_{124} in 20-D, N=15, mFE=200086					
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}			
10	15	6.8e1	4.0e1	9.7e1	6.8e1	14	1.6e5	1.4e5	1.9e5	1.5e5	10	15	1.7e1	1.2e1	2.2e1	1.7e1	15	1.9e2	1.7e2	2.1e2	1.9e2		
1	7	8.8e4	6.3e4	1.4e5	4.0e4	0	<i>7.7e-1</i>	<i>4.9e-1</i>	<i>9.9e-1</i>	1.8e5	1	15	2.0e2	1.8e2	2.3e2	2.0e2	15	1.4e4	5.2e3	2.3e4	1.4e4		
1e-1	0	<i>1.0e-1</i>	<i>3.7e-2</i>	<i>2.6e-1</i>	3.5e4	.	.	.	.	.	1e-1	15	4.1e3	2.3e3	6.0e3	4.1e3	15	9.1e4	8.0e4	1.0e5	9.1e4
1e-3	.	.	.	.	.	.	.	.	.	.	1e-3	15	2.0e4	1.7e4	2.4e4	2.0e4	9	2.8e5	2.2e5	3.9e5	1.6e5
1e-5	.	.	.	.	.	.	.	.	.	.	1e-5	13	4.5e4	3.9e4	5.3e4	3.9e4	0	<i>4.1e-5</i>	<i>3.7e-6</i>	<i>4.4e-4</i>	1.8e5
1e-8	.	.	.	.	.	.	.	.	.	.	1e-8	3	2.4e5	1.4e5	7.2e5	4.4e4	.	.	.	.	.
f_{125} in 5-D, N=15, mFE=50008						f_{125} in 20-D, N=15, mFE=200022						f_{126} in 5-D, N=15, mFE=50008						f_{126} in 20-D, N=15, mFE=200022					
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}			
10	15	1.0e0	1.0e0	1.0e0	1.0e0	15	1.0e0	1.0e0	1.0e0	1.0e0	10	15	1.0e0	1.0e0	1.0e0	1.0e0	15	1.0e0	1.0e0	1.0e0	1.0e0		
1	15	2.2e1	1.7e1	2.7e1	2.2e1	15	2.0e4	7.8e3	3.3e4	2.0e4	1	15	1.1e2	5.4e1	1.7e2	1.1e2	13	1.8e5	1.5e5	2.2e5	1.5e5		
1e-1	15	1.2e4	8.1e3	1.7e4	1.2e4	0	<i>3.9e-2</i>	<i>4.7e-2</i>	<i>6.8e-2</i>	1.8e5	1e-1	12	4.0e4	3.0e4	5.3e4	2.8e4	0	<i>8.9e-2</i>	<i>6.1e-2</i>	<i>1.1e-1</i>	1.8e5		
1e-3	0	<i>2.8e-3</i>	<i>1.1e-3</i>	<i>7.0e-3</i>	4.0e4	.	.	.	.	.	1e-3	0	<i>8.5e-3</i>	<i>4.7e-3</i>	<i>1.1e-2</i>	3.5e4	.	.	.	.	.
1e-5	.	.	.	.	.	.	.	.	.	.	1e-5	.	.	.	.	.	.	.	.	.	.
1e-8	.	.	.	.	.	.	.	.	.	.	1e-8	.	.	.	.	.	.	.	.	.	.
f_{127} in 5-D, N=15, mFE=50058						f_{127} in 20-D, N=15, mFE=200022						f_{128} in 5-D, N=15, mFE=50008						f_{128} in 20-D, N=15, mFE=200022					
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}			
10	15	1.0e0	1.0e0	1.0e0	1.0e0	15	1.0e0	1.0e0	1.0e0	1.0e0	10	15	7.6e2	6.4e1	1.5e3	7.6e2	1	3.0e6	1.5e6	>3e6	2.0e5		
1	15	1.9e1	1.6e1	2.2e1	1.9e1	15	1.8e2	1.5e2	2.1e2	1.8e2	1	9	5.5e4	4.1e4	7.8e4	3.6e4	0	<i>6.5e+0</i>	<i>5.7e+0</i>	<i>7.1e+0</i>	1.8e5		
1e-1	15	3.7e3	1.8e3	5.9e3	3.7e3	10	1.7e5	1.3e5	2.3e5	1.2e5	1e-1	9	5.9e4	4.6e4	8.1e4	3.8e4	.	.	.	.	.
1e-3	1	7.4e5	3.7e5	>7e5	5.0e4	0	<i>8.3e-3</i>	<i>3.7e-3</i>	<i>1.5e-2</i>	8.9e4	1e-3	9	6.0e4	4.6e4	8.1e4	3.8e4	.	.	.	.	.
1e-5	0	<i>1.8e-3</i>	<i>1.6e-4</i>	<i>3.2e-3</i>	3.5e4	.	.	.	.	.	1e-5	9	6.0e4	4.6e4	8.3e4	3.8e4	.	.	.	.	.
1e-8	.	.	.	.	.	.	.	.	.	.	1e-8	9	6.4e4	5.0e4	8.9e4	3.9e4	.	.	.	.	.
f_{129} in 5-D, N=15, mFE=50008						f_{129} in 20-D, N=15, mFE=200022						f_{130} in 5-D, N=15, mFE=50124						f_{130} in 20-D, N=15, mFE=200086					
Δf	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}	#	ERT	10%	90%	RT _{succ}			
10	15	2.7e3	1.4e3	4.1e3	2.7e3	0	<i>6.9e+0</i>	<i>4.1e+0</i>	<i>7.9e+0</i>	1.8e5	10	15	5.5e1	4.3e1	6.7e1	5.5e1	15	9.9e3	5.4e3	1.5e4	9.9e3		
1	6	9.8e4	6.9e4	1.6e5	4.1e4	.	.	.	.	.	1	12	2.2e4	1.4e4	3.1e4	1.7e4	9	1.6e5	1.0e5	2.3e5	1.0e5
1e-1	3	2.3e5	1.3e5	7.0e5	4.1e4	.	.	.	.	.	1e-1	10	3.3e4	2.4e4	4.5e4	2.7e4	7	2.5e5	1.6e5	4.3e5	9.5e4
1e-3	0	<i>1.8e-1</i>	<i>4.2e-3</i>	<i>3.1e-1</i>	2.5e4	.	.	.	.	.	1e-3	10	3.4e4	2.4e4	4.5e4	2.7e4	7	2.5e5	1.6e5	4.4e5	9.6e4
1e-5	.	.	.	.	.	.	.	.	.	.	1e-5	10	3.4e4	2.4e4	4.6e4	2.7e4	7	2.6e5	1.6e5	4.3e5	9.6e4
1e-8	.	.	.	.	.	.	.	.	.	.	1e-8	10	3.5e4	2.5e4	4.6e4	2.8e4	7	2.6e5	1.6e5	4.3e5	9.7e4

Table 2: Shown are, for functions f_{121} - f_{130} and for a given target difference to the optimal function value Δf : the number of successful trials (#); the expected running time to surpass $f_{\text{opt}} + \Delta f$ (ERT, see Figure 1); the 10%-tile and 90%-tile of the bootstrap distribution of ERT; the average number of function evaluations in successful trials or, if none was successful, as last entry the median number of function evaluations to reach the best function value (RT_{succ}). If $f_{\text{opt}} + \Delta f$ was never reached, figures in *italics* denote the best achieved Δf -value of the median trial and the 10% and 90%-tile trial. Furthermore, N denotes the number of trials, and mFE denotes the maximum of number of function evaluations executed in one trial. See Figure 1 for the names of functions.

with since the performances of the mixed strategy seems to decrease compared to the other noise models. Furthermore, noise affects the scaling of this algorithm since it scales worse on functions f_{107} , f_{108} and f_{109} than on the same function with less noise f_{101} , f_{102} and f_{103} . On the Gauss noise model, which is second most severe, the algorithm can still solve f_{101} . Otherwise, it can only solve functions up to 10-D in the best case.

5. CPU TIMING EXPERIMENT

For the timing experiment, the proposed algorithm was run on f_8 and restarted until at least 30 seconds have passed (according to Figure 2 in [3]). The experiments were conducted with an Intel Core 2 6700 processor (2.66GHz) with Matlab R2008a on Linux 2.6.24.7. The results were 15, 13, 11, 9.7, 9.9, and 13 $\times 10^{-5}$ seconds per function evaluations in dimension 2, 3, 5, 10, 20, and 40 respectively.

6. CONCLUSION

The strategy of mixing CMA-ES with its time and space linear variant results in this algorithm. Tested on the BBOB-2009 noisy functions test bed, it could only solve all ten functions using the less severe Cauchy noise model in 20-D.

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