

# Design of a Surrogate Model Assisted $(\mu/\mu, \lambda)$ -ES

Jingyun Yang and Dirk V. Arnold  
Faculty of Computer Science, Dalhousie University  
Halifax, Nova Scotia B3H 4R2  
jingyun.yang@dal.ca, dirk@cs.dal.ca

## ABSTRACT

Surrogate models have been widely used to assist evolutionary algorithms (EAs) to avoid unnecessary objective function evaluations. The cost is reduced by substituting the true objective function evaluation with a cheap but inaccurate estimate using the surrogate model. The surrogate model is built on the knowledge gained in previous iterations. Using surrogate assisted  $(1+1)$ -ES for simple model and single steps have been studied, but the effect of actual inferior parent resulted from an inaccurate surrogate estimation and the corresponding poor step size are not well understood. We study the behaviour using a surrogate model assisted  $(\mu/\mu, \lambda)$ -ES using a population instead of a single offspring with the hope to possible address the issue. The behaviours of the two strategies are compared using several test functions.

## KEYWORDS

$(\mu/\mu, \lambda)$ -ES, Surrogate Model, Evolutionary algorithms(EAs), Gaussian Process

### ACM Reference format:

Jingyun Yang and Dirk V. Arnold. 2018. Design of a Surrogate Model Assisted  $(\mu/\mu, \lambda)$ -ES. In *Proceedings of* , , 6 pages.  
<https://doi.org/>

## 1 INTRODUCTION

*Evolution strategies (ESs)* have been widely utilized to solve optimization problems where the true objective function evaluation is computationally-intensive. Various attempts have been made to reduce the cost by extracting the information obtained from points evaluated in previous iterations. Such information yields insights into better mutation and recombination that help generate and select promising offspring. Cumulative step size adaptation (CSA) [20] builds an evolution path based on the history step size (mutation) of ESs, the population in the next iteration is generated based on the mutation adapted by the evolution path.

The history information could be used to construct a surrogate model, referred either as a local approximation or a global approximation to the true objective function [16]. There are a range of surrogate models and a survey of the development can be found by Jin [14] and Loshchilov [18]. Those algorithms are usually heuristic by

nature and the behaviour of each step is likely not well interpreted. Recent work in surrogate assisted EAs tend to use sophisticated algorithm where surrogates are combined or the model is updated online according to some heuristic. Comparison is often made by comparing the performance using the algorithm with and without model assistance where the behaviour of the surrogate is not well simulated. In this context, an approach that could simulate the surrogate would be helpful in understanding the surrogate behaviour, leading to potential modification for surrogate update or parameter-setting. A surrogate that models the objective function with desired precise gains benefit especially for algorithms that requires a large population size for good performance. The computational saving largely lies in the saved evaluations outshine the potential poor step resulted from relative inaccurate estimation of candidate solutions.

This paper intend to improve the understanding of the impact of population size on surrogate-assisted ESs' by analyzing using simple test functions with strong theoretical basis and established baselines. The paper is organized as follows: In Section 2 we give a brief review of related background, in Section 3 we propose a local surrogate model-assisted  $((\mu/\mu, \lambda) + (\mu/\mu, \lambda))$ -ES and study its behaviour on sphere functions. Based on the existing knowledge and step behaviour, in Section 4, we then propose a combined step size adaptation mechanism for the this algorithm, analyze the performance using several test functions and compare the result with a surrogate model-assisted  $(1+1)$ -ES [17]. The experimental result is followed by a discussion and future work in Section 5.

## 2 RELATED WORK

### 2.1 Surrogate Model

Using an approximate model to reduce computational cost can be traced back to 1960s [7]. Some successful surrogated models include but are not limited to Polynomial Regression (PR, response surface methodology) [11], Gaussian Process (GP, Kriging models) [13], Artificial neural networks [23]. There are two types of surrogate models, global surrogate model and local surrogate model. . ES using global surrogate model based on Kring was examined by Ratle [21]. Another ES using global surrogate model based on Artificial neural networks was constructed by Jin [15] which gives an imperial criterion on using the true objective function or the surrogate model to evaluate the offspring. Ulmer et al [24] and Buche et al [5] also applied GP as surrogate models in ES. But the performance of global surrogate models degrade as the dimension of the data increases, known as *curse of dimensionality*. Since the performance of ES is straightly affected by the surrogate model accuracy, online surrogates has been introduced by using a surrogate-adaptation mechanism that updated the model according to some heuristic. Loshchilov et al [12] uses . Online local surrogate models [25] can be constructed using methods like radial basis function (RBF) [8] to

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from [permissions@acm.org](mailto:permissions@acm.org).

© 2018 Association for Computing Machinery.  
ACM ISBN .  
<https://doi.org/>

replace the global surrogate model, where the surrogate model is updated online, giving a more accurate estimation compared with the global surrogate model.

There are various surrogate-assisted EAs integrating global and local surrogate models or using a combination of heuristics. These methods tend to be sophisticated for good performance, while few literatures have *systematically investigated* the surrogated-assisted  $(\mu/\mu, \lambda)$ -ES. One exception is what Chen and Zou [6] proposed but yet incomplete in terms of two aspects. Firstly, it uses a linear surrogate that cannot give a precise estimate when coordinate transform is applied, the precondition to solve a generalized optimization problem [17]. Secondly, it does not include a step size adaptation mechanism. Besides that, Ulmer et al [9] proposed a Model Assisted Steady-State Evolution Strategy (MASS-ES), which is a  $(\mu + \lambda)$ -ES that is a  $(1+1)$ -ES when we set  $\mu = \lambda = 1$ . But the behavior of step size adaptation is unclear given the proposed conditions.

There is a wealth of literatures for solving black box optimization using  $(1+1)$ -ES on unimodal test problems given the convergence property of convex functions. Kayhani and Arnold [17] proposed a surrogated-assisted  $(1+1)$ -ES that investigates the acceleration and single step behaviour of the algorithm using GP based local surrogate. In this algorithm, the local surrogate acts as a filter and is updated every time when a true objective function is made. Since  $(1+1)$ -ES generate a single offspring per iteration and is not as robust as  $(\mu/\mu, \lambda)$  especially in the presence of surrogate (bias due to choice of points), we argue that it is natural to ask to what degree the choice of population can benefit the ES in terms of robustness and acceleration.

## 2.2 Step size adaptation

The step size of  $(\mu/\mu, \lambda)$ -ES is commonly adapted using cumulative step size adaptation (CSA) proposed by Ostermeier et al [20]. In each iteration,  $(\mu/\mu, \lambda)$ -ES generate  $\lambda$  candidate solutions  $y_i \in \mathbb{R}^N, i = 1, \dots, \lambda$  from a parental population  $x_i \in \mathbb{R}^N, i = 1, \dots, \mu$  and the centroid of the parent population is  $x = 1/\mu \sum_{i=1}^{\mu} x_i$  where  $\mu < \lambda$ . The parental population is replaced by the best  $\mu$  candidate solutions generated by  $y_i = x + \sigma z$  where  $\sigma \in \mathbb{R}$  is a scalar referred to as the step size and  $z \in \mathbb{R}^N$  as the mutation. For a strategy with ideally adapted step size, each step should be uncorrelated. If the consecutive steps are negatively correlated, the step size should be decreased. In contrast, if the consecutive steps are positively correlated, the steps are pointing to the same direction. Then a number of small steps can be replaced by fewer large steps and therefore, the step size should increase.

To decide the correlation, information from previous steps and mutations are cumulated. By comparing the step size with its expected length under random selection, the step size is adapted according to its expected length. It increases if the length is less than expected and decrease otherwise.

Define the search path as

$$p_{k+1} \leftarrow (1 - c)p_k + \sqrt{\mu c(2 - c)}z, \quad (1)$$

where  $0 < c \leq 1$  is the proportion of history information retained and passed to the evolution path in the next iteration,  $\sqrt{\mu c(2 - c)}$  is a normalization constant that updates the evolution path from the

mutation of this iteration and  $z$  the mutation obtained by averaging the best  $\mu$  candidate solutions generated.

The step size is adapted

$$\sigma \leftarrow \sigma \exp \left( \frac{c}{d} \left( \frac{\|p\|}{E\|N(0, I)\|} \right) \right), \quad (2)$$

where  $E\|N(0, I)\|$  is the expected length of the search path  $p$  and can be approximated as  $E\|N(0, I)\| \approx \sqrt{n}(1 - 1/4n + 1/21n^2)$ . In Section 4, we use the well established parameters from Hansen's CMA tutorial [10] where  $c = (\mu + 2)/(N + \mu + 5)$ ,  $d = 1 + 2 \max \left( 0, \sqrt{(\mu - 1)/(N + 1) - 1} \right) + c$ .

Few

(*not step size adaptation COULD IN FUTURE WORK*) Covariance Matrix Adaptation (CMA) [19].

## 3 ANALYSIS

To understand the potential implications of using surrogate models in EAs with varying population size, in this section, we use a simple model that applies a surrogate to the population. Specifically, we propose an EA that, in each iteration, a population of new  $\lambda$  candidate solutions are generated and then evaluated by the surrogate instead of true objective function calls and a selection based on the inaccurate surrogate estimate is done followed by a true objective function evaluation for the centroid of the selected referred to as the parent for next iteration. We assume that the inaccurate estimate of the surrogate model is a Gaussian random variable with mean equals the true objective function value of the candidate solution with some variance that describes the accuracy of the surrogate model. So, we can apply the technique of analyzing ESs's behaviours in the presence of Gaussian noise [3]. The analysis could be extended to biased surrogate models where the distribution mean is different from the exact objective function value [17].....

Comparison based surrogate model

Consider the minimization of the quadratic sphere  $f : \mathbb{R}^N \rightarrow \mathbb{R}$  with  $f(x) = x^T x$  where the surrogate model assisted  $(\mu/\mu, \lambda)$ -ES is applied. This section will use the surrogate model described above to replace the true objective function calls of candidate solutions in each iteration, inaccurate but at vanishing cost. We first consider a simple iteration of the strategy. In each iteration, a population size of  $\lambda$  new candidate solutions  $y_i \in \mathbb{R}^N, i = 1, \dots, \lambda$  are generated from  $\mu$  parents  $x_i \in \mathbb{R}^N, i = 1, \dots, \mu$ , where  $\lambda > \mu$ . The parental population with size  $\mu$  are replaced by the best  $\mu$  candidate solutions  $y_{i:\lambda}, i = 1, 2, \dots, \mu$  evaluated by the surrogate model with fitness estimate  $f_e(y_{i:\lambda}) \leq f_e(y_{j:\lambda}), 1 \leq i < j \leq \lambda$  at vanishing cost. For each of the  $\lambda$  candidate solutions  $y_i = x + \sigma z$  where the parent  $x = \sum_{i=1}^{\mu} x_i / \mu$ , the centroid of the parental population is obtained through intermediate recombination,  $z \in \mathbb{R}^N$  is a standard normally distributed random vector,  $\sigma > 0$  is the step size of the strategy that the adaptation is discussed in Section 4. The strategy uses the surrogate model to obtain a fitness estimate of the candidate solution  $f_e(y_i), 1 \leq i \leq \lambda$  and by the assumption the estimate has mean  $f(y_i)$  with some standard deviation  $\sigma_e > 0$  (surrogate model error also as fitness noise [2]). Better surrogate model results in smaller model error  $\sigma_e$ . For the  $\lambda$  new candidate solutions  $f_e(y_i) < f_e(y_j), 1 \leq i < j \leq \lambda$  indicates the estimated objective function value of  $y_i$  is superior to  $y_j$  and therefore the

best  $\mu$  candidate solutions are selected, replacing the old parental population of size  $\mu$  (used for offspring generation in next iteration), while the other inferior candidate solutions are discarded. Therefore, in each iteration only one objective function call is made in evaluating the fitness of the parent (centroid of parental population). The surrogate essentially does a pre-selection for  $(\mu/\mu, \lambda)$ -ES over candidate solutions, avoiding the unnecessary objective function calls determined by the surrogate model.

Decomposition of  $z$ , first proposed by Rechenberg [22] can be used to study the expected step size of the strategy. We can decompose the vector  $z$  as a vector sum  $z = z_1 + z_2$ , where  $z_1$  is in the direction of the negative gradient of the objective function  $\nabla f(x)$ , while  $z_2$  orthogonal to  $z_1$ . We have  $z_1$  standard normally distributed, while  $\|z_2\|^2 \chi$ -distributed with  $N - 1$  degree of freedom and  $\|z_2\|^2/N \xrightarrow{N \rightarrow \infty} 0$  (see reference theorem [dirk's slides]). Denote  $\delta = N(f(x) - f(y))/(2R^2)$  where  $R = \|x\|$  is the distance to the optimal, we further introduce normalized step size  $\sigma^* = N\sigma/R$  and  $z_{\text{step}} = \sum_{i=1}^{\mu} z_{i;\lambda}$  (the averaged  $z$  taken by the best  $\mu$  candidate solutions). The normalized fitness advantage of  $y$  over  $x$  follows

$$\begin{aligned} \delta &= \frac{N}{2R^2} (x^T x - (x + \sigma z_{\text{step}})^T (x + \sigma z_{\text{step}})) \\ &= \frac{N}{2R^2} (-2\sigma x^T z_{\text{step}} - \sigma^2 \|z_{\text{step}}\|^2) \\ &\stackrel{N \rightarrow \infty}{=} \sigma^* z_{\text{step},1} - \frac{\sigma^{*2}}{2}, \end{aligned} \quad (3)$$

where  $z_{\text{step},1}$ , the component of  $z_{\text{step}}$  pointing to the negative gradient of  $f(x)$ , is normally distributed and  $\|z_{\text{step}}\|^2/N \xrightarrow{N \rightarrow \infty} 1$ . We further introduce  $\sigma_\epsilon^* = N\sigma_\epsilon/(2R^2)$ , the normalized surrogate model error (also referred to as the normalized fitness noise in Noise Sphere from Arnold and Beyer [2]). The estimate of true objective function value of  $y_i$  is  $f_\epsilon(y_i) = f(y_i) + \sigma_\epsilon z_\epsilon$ ,  $z_\epsilon \in \mathbb{R}$  is standard normally distributed.

The actual normalized fitness advantage of  $y$  using the surrogate model is

$$\delta_\epsilon = \delta + \sigma_\epsilon^* z_\epsilon \quad (4)$$

The expected value of the normalized change in objective function value

$$\begin{aligned} \Delta &= -\frac{N}{2} E [\log f(y) - \log f(x)] \\ &= -\frac{N}{2} E \left[ \log \frac{f(x^{t+1})}{f(x^t)} \right], \end{aligned} \quad (5)$$

where  $y^t$  is the centroid of parental population in timestamp  $t$ , the equation is normalized in terms of dimensionality.

Since the fitness of  $\lambda$  offspring generated are evaluated by the surrogate model with vanishing cost. The objective function evaluation per iteration is 1 instead of  $\lambda$  (for  $(\mu/\mu, \lambda)$ -ES), therefore the normalized progress rate when dimensionality  $N \rightarrow \infty$ , by substituting  $\lambda$  with 1 in equation (7) from [4] is

$$\eta = \frac{1}{1} E[\Delta] = \frac{\sigma^* c_{\mu/\mu, \lambda}}{\sqrt{1 + g^2}} - \frac{(\sigma^*)^2}{2\mu}, \quad (6)$$

where  $\vartheta = \sigma_\epsilon^*/\sigma^*$  is the noise-to-signal ratio, defined to measure the quality of surrogate model relative to the algorithm's step size,  $c_{\mu/\mu, \lambda}$  is the  $(\mu/\mu, \lambda)$ -progress coefficient derived by Arnold and Beyer [1] that follows

$$c_{\mu/\mu, \lambda} = \frac{\lambda - \mu}{2\pi} \left( \frac{\lambda}{\mu} \right) \int_{-\infty}^{\infty} e^{-x^2} [\Phi(x)]^{\lambda-\mu-1} [1 - \Phi(x)]^{\mu-1} dx, \quad (7)$$

where  $\Phi^{-1}$  is the inverse function of  $\Phi$ , the normal cumulative distribution function. The integral can be solve numerically.

To obtain the opt. expected fitness gain  $\eta_{opt}$  and its corresponding opt. normalized step size  $\sigma_{opt}^*$ , we take derivative of equation (6) over  $\sigma^*$  and get the following

$$\eta_{opt} = \frac{\sigma_{opt}^* c_{\mu/\mu, \lambda}}{\sqrt{1 + g^2}} - \frac{(\sigma_{opt}^*)^2}{2\mu} \quad (8)$$

$$\sigma_{opt}^* = \frac{\mu c_{\mu/\mu, \lambda}}{\sqrt{1 + g^2}} \quad (9)$$

The expected fitness gain against the normalized step size for  $(\mu/\mu, \lambda)$ -ES with population size  $\lambda = 10, 20, 40$  corresponding  $\mu = 3, 5, 10$  are plotted in Figure 1 from left to right respectively. The line shows the result obtained from Eqs. (6) (7). The dots represent the experimental result for unbiased Gaussian surrogate error for  $n \in \{10, 100\}$  obtained by averaging 100 runs. The result obtained for  $n \rightarrow \infty$  are considered to be cases with a large normalized step size with very small noise to signal ratio.

It can be inferred from Figure 1 that, for a fixed population size, the expected fitness gain decreases with an increasing noise-to-signal-ratio. The surrogate cannot severe its purpose and the performance without

Compared the result obtained by the surrogate assisted (1+1)-ES (Fig 1. [17]), there is indeed a

there is a significant increase in expected fitness gain as the population size  $\lambda$  increases, the

(log scale size)

graph – subplot(1, 3) seems better?

## 4 STEP SIZE ADAPTATION

### 4.1 Cumulative step size adaptation

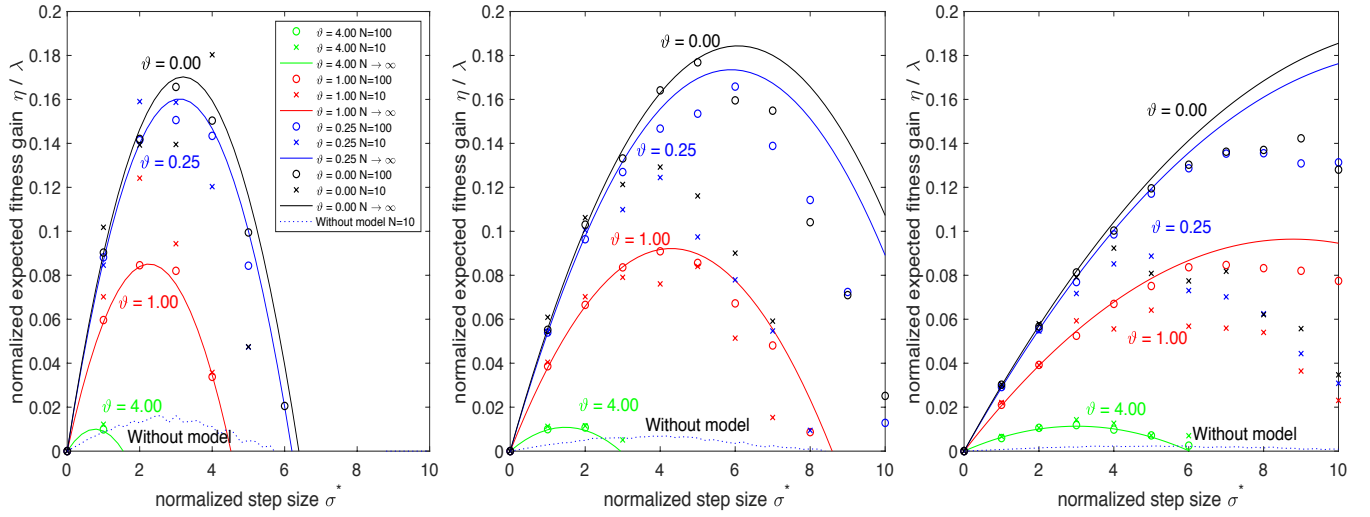
Even though the analysis in Section 3 suggests potential better performance for the surrogate-assisted  $(\mu/\mu, \lambda)$ -ES. There is no guarantee the step size of the strategy can be properly adapted and further the analysis is very inaccurate in terms of finite dimension. In this section we experimnt the surroagted model assisted  $((\mu/\mu, \lambda) + (\mu/\mu, \lambda))$ -ES using the cumulative step size adaptation (CSA)[20], commonly used in  $(\mu/\mu, \lambda)$ -ES and exploit the potential insight that it may offer. The strategy is evaluated by using a Gaussian Process based surrogate model replacing the simple model that simulates the surrogate behaviour in Section 3. Several test functions are used for testing the strategy.

(normalized step size)

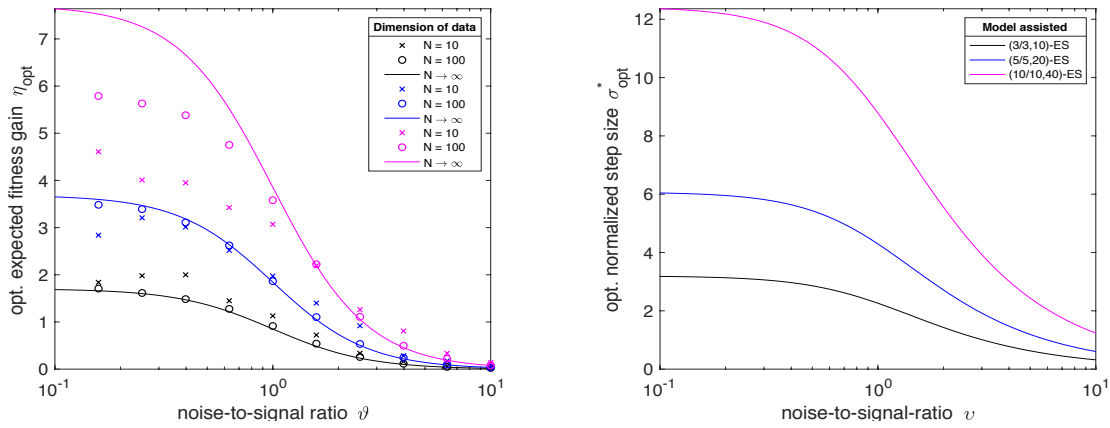
table(test functions)

Table for median of test results for surrogate model assisted  $(\mu/\mu, \lambda)$ -ES using CSA

histgram obojective function evaluations AND plot model error AND norma



**Figure 1:** The figures from left to right shows the expected single step behaviour of the surrogate model assisted  $(\mu/\mu, \lambda)$ -ES with unbiased Gaussian distributed surrogate error with  $\lambda = 10, 20, 40$  respectively where  $\mu = \text{ceil}(\lambda/4)$ . The solid lines are the results obtained analytically when  $n \rightarrow \infty$ , while the dotted line below illustrates the corresponding performance ( $n = 10$ ) of the  $(\mu/\mu, \lambda)$ -ES without model assistance. The dots represents the experimental result for  $n = 10$  (crosses) and  $n = 100$  (circles).



**Figure 2:** Opt. expected fitness gain and corresponding opt. normalized step size of the surrogate model assisted  $(\mu/\mu, \lambda)$ -ES plotted against the noise-to-signal ratio. The line and dots with colour black, blue green represent  $(3/3, 10)$ -ES,  $(3/3, 10)$ -ES,  $(3/3, 10)$ -ES. The solid line represents the results obtained analytically when  $n \rightarrow \infty$ .

Figure histogram for objective function evaluations and relative surrogate model error.

histgram success rate AND normalized convergence rate(3 sphere function)

Figure for success rate for surrogate assisted  $(\mu/\mu, \lambda)$ -ES with  $\lambda = 10, 20, 40$

## 4.2 Alternative

From Figure x, the success rate for all test functions are approximately 0.48, the strategy makes a bad step every other step. It comes natural to ask, how much we are to benefit if we can avoid or simply not take those bad steps.

Recent papers in surrogate model assisted ES consider (1+1)-ES, the step size of the strategy is successfully adapted using the

1/5-rule []. Then we probably can apply a similar criteria when encounter a bad step size.

Propose step size adaptation in terms of emergency.

table(test functions) Table for median of test results for surrogate model assisted  $(\mu/\mu, \lambda)$ -ES using CSA with emergency

Figure for success rate for surrogate assisted  $(\mu/\mu, \lambda)$ -ES with  $\lambda = 10, 20, 40$

## 5 CONCLUSIONS

In this paper, We proposed a local surrogate-assisted  $(\mu/\mu, \lambda) + (\mu/\mu, \lambda)$ -ES. The strategy uses a local surrogate model to optimize the candidate solution obtained in each iteration. The performance

**Table 1: Median test results.**

Test functions	Median number of objective function calls (with model assistance)			
	(1 + 1)-ES	(3/3, 10)-ES	(5/5, 20)-ES	(10/10, 40)-ES
linear sphere	503	4.65%	9.84%	19.17%
quadratic sphere	214	8.39%	18.31%	28.09%
cubic sphere	198	8.64%	14.51%	25.83%
Schwefel's function	1503	18.28%	31.58%	64.43%
quartic function	1236	7.37%	15.55%	32.48%

**Algorithm 1** A Surrogate Assisted  $(\mu/\mu, \lambda)$ -ES

```

1:  $c \leftarrow \frac{\mu+2}{n+\mu+5}$ 
2:  $d \leftarrow 1 + 2\max(0, \sqrt{\frac{\mu-1}{n+1}} - 1)$ 
3:  $p \leftarrow 0$ 
4: while not terminate() do
5:   for  $i = 1, 2, \dots, \lambda$  do
6:     Generate standard normally distributed  $z_i \in \mathbb{R}^N$ 
7:      $y_i \leftarrow x + \sigma z_i$ 
8:     Evaluate  $y_i$  using the surrogate model, yielding  $f_\epsilon(y_i)$ 
9:   end for
10:   $z = \frac{1}{\mu} \sum_{i=1}^{\mu} z_{i,\lambda}$ 
11:   $y = x + \sigma x$ 
12:  Evaluate  $y$  using true objective function, yielding  $f(y)$ 
13:  Update surrogate model
14:   $s \leftarrow (1 - c)s + \sqrt{c(2 - c)}\mu z$ 
15:   $\sigma \leftarrow \sigma \times \exp\left(\frac{c}{d} \frac{\|X\|}{E\|N(0, I)\|} - 1\right)$ 
16: end while

```

**Algorithm 2** Cumulative Step Size Adaptation with Emergency

```

1:  $c \leftarrow \frac{\mu+2}{n+\mu+5}$ 
2:  $d \leftarrow 1 + 2\max(0, \sqrt{\frac{\mu-1}{n+1}} - 1)$ 
3:  $p \leftarrow 0$ 
4:  $D \leftarrow 0.68$ 
5: while not terminate() do
6:   for  $i = 1, 2, \dots, \lambda$  do
7:     Generate standard normally distributed  $z_i \in \mathbb{R}^N$ 
8:      $y_i \leftarrow x + \sigma z_i$ 
9:     Evaluate  $y_i$  using the surrogate model, yielding  $\hat{f}(y_i)$ 
10:   end for
11:   $z = \frac{1}{\mu} \sum_{i=1}^{\mu} z_{i,\lambda}$ 
12:   $y = x + \sigma x$ 
13:  Evaluate  $y$  using true objective function, yielding  $f(y)$ 
14:  Update surrogate model
15:  if  $f(x) < f(y)$  (Emergency) then
16:     $\sigma \leftarrow \sigma D$ 
17:  else
18:     $s \leftarrow (1 - c)s + \sqrt{c(2 - c)}\mu z$ 
19:     $\sigma \leftarrow \sigma \times \exp\left(\frac{c}{d} \frac{\|X\|}{E\|N(0, I)\|} - 1\right)$ 
20:  end if
21: end while

```

is analyzed by adding different levels of Gaussian distributed noise and applying the strategy to sphere functions.

## REFERENCES

- [1] D. V. Arnold and H. -G. Beyer. 2000. Efficiency and mutation strength adaptation of the  $(\mu, \text{mu}, \lambda)$ -es in a noisy environment. In *Proceedings of the 6th International Conference on Parallel Problem Solving from Nature (PPSN VI)*. Springer-Verlag, London, UK, UK, 39–48. <http://dl.acm.org/citation.cfm?id=645825.669117>.
- [2] D. V. Arnold and H. -G. Beyer. 2004. Performance analysis of evolutionary optimization with cumulative step length adaptation. *IEEE Transactions on Automatic Control*, 49, 4, (Apr. 2004), 617–622.
- [3] D. V. Arnold and H. -G. Beyer. 2002. *Noisy optimization with evolution strategies*. Vol. 8. Springer Science & Business Media.
- [4] Dirk V. Arnold and Hans-Georg Beyer. 2001. Local performance of the  $(\mu/\mu, \lambda)$ -es in a noisy environment. In *Foundations of Genetic Algorithms 6*. W. N. Martin and W. M. Spears, (Eds.) Morgan Kaufmann, San Francisco, 127–141. <http://www.sciencedirect.com/science/article/pii/B9781558607347500901>.
- [5] D. Buche, N. N. Schraudolph, and P. Koumoutsakos. 2005. Accelerating evolutionary algorithms with gaussian process fitness function models. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 35, 2, (May 2005), 183–194.
- [6] Y. Chen and X. Zou. 2014. Performance analysis of a  $(1+1)$  surrogate-assisted evolutionary algorithm. In *Intelligent Computing Theory*. V. Bevilacqua D. Huang and P. Premaratne, (Eds.) Springer International Publishing, Cham, 32–40.
- [7] B. Dunham, D. Fridshal, R. Fridshal, and JH North. 1963. Design by natural selection. *Synthese*, 15, 1, 254–259.
- [8] K.C. Giannakoglou. 2002. Design of optimal aerodynamic shapes using stochastic optimization methods and computational intelligence. *Progress in Aerospace Sciences*, 38, 1, 43–76. <http://www.sciencedirect.com/science/article/pii/S0376042101000197>.
- [9] Y. Jin, (Ed.) 2005. *Model assisted evolution strategies. Knowledge Incorporation in Evolutionary Computation*. Springer Berlin Heidelberg, Berlin, Heidelberg, 333–355. [https://doi.org/10.1007/978-3-540-44511-1\\_16](https://doi.org/10.1007/978-3-540-44511-1_16).
- [10] N. Hansen. 2016. The cma evolution strategy: a tutorial. *arXiv preprint arXiv:1604.00772*.
- [11] W. J. Hill and W. G. Hunter. 1966. A review of response surface methodology: a literature survey. *Technometrics*, 8, 4, 571–590. eprint: <https://amstat.tandfonline.com/doi/pdf/10.1080/00401706.1966.10490404>. <https://amstat.tandfonline.com/doi/abs/10.1080/00401706.1966.10490404>.
- [12] M. Schoenauer I. Loshchilov and M. Sebag. 2012. Self-adaptive surrogate-assisted covariance matrix adaptation evolution strategy. In *Proceedings of the 14th annual conference on Genetic and evolutionary computation*. ACM, 321–328.
- [13] W. J. Welch J. Sacks, T. J. Mitchell, and H. P. Wynn. 1989. Design and analysis of computer experiments. *Statist. Sci.*, 4, 4, (Nov. 1989), 409–423. <https://doi.org/10.1214/ss/1177012413>.
- [14] Y. Jin. 2011. Surrogate-assisted evolutionary computation: recent advances and future challenges. *Swarm and Evolutionary Computation*, 1, 2, 61–70. <http://www.sciencedirect.com/science/article/pii/S2210650211000198>.
- [15] Y. Jin, M. Olhofer, and B. Sendhoff. 2002. A framework for evolutionary optimization with approximate fitness functions. *IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION*, 6, 481–494.
- [16] Y. Jin and B. Sendhoff. 2002. Fitness approximation in evolutionary computation - a survey. In *Proceedings of the 4th Annual Conference on Genetic and Evolutionary Computation (GECCO'02)*. Morgan Kaufmann Publishers Inc., New York City, New York, 1105–1112. <http://dl.acm.org/citation.cfm?id=2955491.2955686>.
- [17] A. Kayhani and D. V. Arnold. 2018. Design of a surrogate model assisted  $(1 + 1)$ -es. In *Parallel Problem Solving from Nature - PPSN XV - 15th International Conference, Coimbra, Portugal, September 8–12, 2018, Proceedings, Part I*, 16–28. [https://doi.org/10.1007/978-3-319-99253-2%5C\\_2](https://doi.org/10.1007/978-3-319-99253-2%5C_2).

- [18] I. Loshchilov. 2016. LM-CMA: an Alternative to L-BFGS for Large Scale Black-box Optimization. *Evolutionary Computation*, to appear.
- [19] S. D. Müller N. Hansen and P. Koumoutsakos. 2003. Reducing the time complexity of the derandomized evolution strategy with covariance matrix adaptation (cma-es). *Evol. Comput.*, 11, 1, (Mar. 2003), 1–18. <http://dx.doi.org/10.1162/106365603321828970>.
- [20] G. Andreas O. Andreas and H. Nikolaus. 1994. A derandomized approach to self-adaptation of evolution strategies. *Evol. Comput.*, 2, 4, (Dec. 1994), 369–380. <http://dx.doi.org/10.1162/evco.1994.2.4.369>.
- [21] A. Ratle. 2001. Kriging as a surrogate fitness landscape in evolutionary optimization. *Artif. Intell. Eng. Des. Anal. Manuf.*, 15, 1, (Jan. 2001), 37–49. <http://dx.doi.org/10.1017/S0890060401151024>.
- [22] I. Rechenberg. 1973. Evolutionsstrategie—optimierung technischer systeme nach prinzipien der biologischen evolution.
- [23] M. Smith. 1993. *Neural Networks for Statistical Modeling*. (1st ed.). Thomson Learning.
- [24] H. Ulmer, F. Streichert, and A. Zell. 2003. Evolution strategies assisted by gaussian processes with improved pre-selection criterion. In *in IEEE Congress on Evolutionary Computation, CEC 2003*, 692–699.
- [25] Z. Zhou, Y. S. Ong, P. B. Nair, A. J. Keane, and K. Y. Lum. 2007. Combining global and local surrogate models to accelerate evolutionary optimization. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 37, 1, (Jan. 2007), 66–76.