

## Two approaches for parallelizing the UEGO algorithm \*

P.M. ORTIGOSA, I. GARCÍA

pilar@iron.ualm.es, inma@iron.ualm.es

Department of Computer Architecture and Electronics, University of Almería, Spain.

M. JELASITY

jelasity@inf.u-szeged.hu

Research Group on Artificial Intelligence, MTA-JATE, Szeged, Hungary.

**Abstract.** In this work UEGO, a new stochastic optimization technique for accelerating and/or parallelizing existing search methods is described and parallelized. The skeleton of the algorithm is a parallel hillclimber. The separate hillclimbers work in restricted search regions (or clusters) of the search space. The volume of the clusters decreases as the search proceeds which results in a cooling effect similar to simulated annealing. Besides this, UEGO can be effectively parallelized because the amount of information exchanged among clusters (communication) is minimal. The purpose of this communication is to ensure that a hill is explored only by one hillclimber. UEGO makes periodic attempts to find new hills to climb. Two parallel algorithms of UEGO have been implemented and empirical results are also presented including an analysis of speedup.

**Keywords:** Global Optimization, Stochastic Methods, Parallelism, Evolutionary Algorithms.

### 1. Introduction

UEGO stands for *Universal Evolutionary Global Optimizer*. Though this method is not 'evolutionary' in the usual sense, we have kept the name for historical reasons. The predecessor of UEGO was GAS, a steady-state genetic algorithm with subpopulation support. GAS offers a solution to the so-called niche radius problem which is a common problem for many simple niching techniques such as *fitness sharing* [2, 3], *simple iteration* or the *sequential niching* [1]. This problem is related to functions that have multiple local optima and whose optima are unevenly spread throughout the search space. The solution of GAS involves a 'cooling' technique which enables the search to focus on the promising regions of the space, starting off with a relatively large radius that decreases as the search proceeds. For more details on GAS the reader should consult [7].

In [6] an introduction to the history, motivation behind developing UEGO and its evaluation for binary problem is given.

The common part of UEGO with GAS is the species creation mechanism and the 'cooling' method. However, the species creation and 'cooling' mechanisms have been logically separated from the present optimization algorithm, so it is possible to implement any kind of optimizers that work 'inside a species'. This allows the adaptation of the method to a large number of possible search domains using existing domain specific optimizers while enjoying the advantages of the old GAS-style subpopulation approach. In this paper, an algorithm called SASS, proposed by Solis and Wets ([10]), was applied as the optimizer algorithm.

\* In Franco Giannessi, Panos M. Pardalos and Tamás Rapcsák (eds): *Optimization Theory: Recent Developments from Mátraháza*, Applied Optimization series 59, Kluwer, 2001. This work was supported by the Ministry of Education of Spain (CICYT TIC99-0361) and by the Tempus Structural Joint European Project.

In the following sections the term *species* will be used instead of e.g. *cluster*, *zone*, *region*, *sub-domain*, etc. This may be strange, since in evolutionary computation this term normally refers to a population of similar individuals while here it denotes a subset of the search domain. This is not a major problem however; a species, in our sense, is nothing else but the set of all possible members that are similar according to some similarity measure which is application dependent. We think that the behavior of a species to be defined later has strong biological analogies.

### 1.1. Outline of the Paper

Section 2 describes UEGO; the basic concepts, the general algorithm and the theoretical tools used to set the parameters of the system based on a few user-given parameters. Sections 3 and 4 describe two parallel algorithms and show experimental results. Section 5 then provides a short summary.

## 2. Description of UEGO

In this section the basic concepts, the algorithm, and the setting of the parameters are outlined. In UEGO, a domain specific optimizer has to be implemented. Wherever we refer to 'the optimizer' in the paper, we mean this optimizer.

### 2.1. Basic Concepts

In the following part it will be assumed that the parameters of the function take values from the unit interval. This is easy to achieve for any function via normalization. With this assumption, some concepts (i.e. radius, attraction region) are easier to be understood.

A key notion in UEGO is that of a *species*. A species can be thought of as a window on the whole search space. This window is defined by its *centre* and a *radius*. The centre is a solution, and the radius is a positive number. Naturally, this definition assumes a *distance* defined over the search space. The role of this window is to 'localize' the optimizer, which is always called by a species and can 'see' only its window; so every new sample is taken from there. This means that the largest step made by the optimizer in a given species is no larger than the radius of the given species. If the value of a new solution is better than that of the old centre, the new solution becomes the centre and the window is moved.

The radius of a species is not arbitrary; it is taken from a list of decreasing radii, the *radius list*. The radii decrease in a regular fashion in geometrical progression. The first element of this list is always the diameter of the search space. This allows the largest species to always contain the whole space independently of its centre. The diameter is given by the largest distance between any of the two possible solutions according to the distance mentioned above. If the radius of a species is the *i*-th element of the list, then we say that the *level* of the species is *i*.

During the optimization process, a list of species is kept by UEGO. The algorithm is, in fact, a method for managing this *species-list* (i.e. creating, deleting and optimizing species); it will be described in Section 2.2.

**Algorithm 1** : *Description of UEGO strategy*

```

Begin UEGO
  init_species_list
  optimize_species( n[1] )
  for i = 2 to levels
    create_species( new[i]/length(species_list) )
    fuse_species( r[i] )
    shorten_species_list( max_spec_num )
    optimize_species( n[i]/max_spec_num )
    fuse_species( r[i] )
  end for
End UEGO

```

## 2.2. The Algorithm

Firstly, some parameters of UEGO will be dealt with; more details can be found in Section 2.3.

As we mentioned earlier, every species has a fixed level during its lifetime. However, species-level operators are allowed to change this level as will be described. The maximal value for the level is given by a parameter called `levels`. Every valid level  $i$  (i.e. for levels from  $[1, \text{levels}]$ ) has a corresponding radius value ( $r_i$ ) and two integers ( $new_i$ ,  $n_i$ ) which denote the number of function evaluations.  $new_i$  is used when new species are created at a given level while  $n_i$  is applied when optimizing individual species. To define the algorithm fully, one more parameter is needed: the maximal length of the above species list (`max_spec_num`). The basic algorithm is shown in Algorithm 1. Now, the set of procedures called by UEGO will be described.

`Init_species_list`. Create a species list consisting of a single species with a random centre at level 1.

`Create_species( evals )`. For every species on the list, create random pairs of solutions in the 'window' of the species, and for every such pair take the middle of the *section* connecting the pair. If the objective function value at the middle is worse than the values of the pair, then the members of the pair are inserted in the species list. Every new inserted species is assigned the actual level value (`i` in Algorithm 1).

The motivation behind this method is simple: to create species that are on different 'hills' so ensuring that there is a valley between the new species (see Figure 1).

Naturally this is a heuristic only. In higher dimensions it is possible (in fact typical) that many species are created even if the function is unimodal. This is an unlucky effect which is handled by the cooling process to ensure that at the beginning the algorithm does not create too many species capturing only the rough structure of the landscape. The parameter of this procedure is an upper bound for the number of function evaluations. Note that this algorithm needs a definition of *section* in the search space.

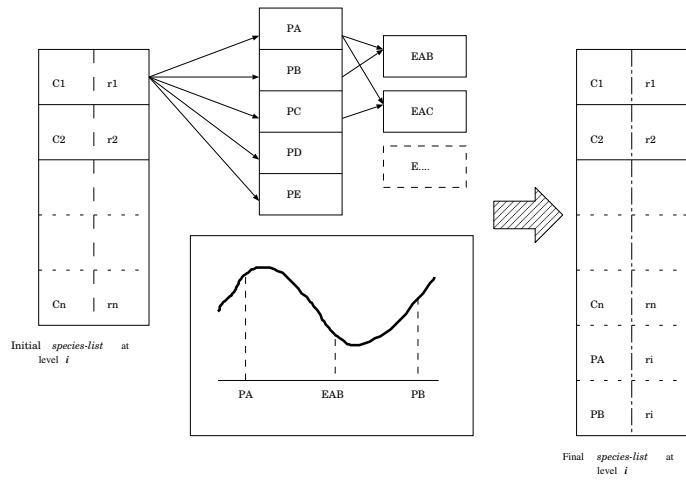


Figure 1. Species creation mechanism

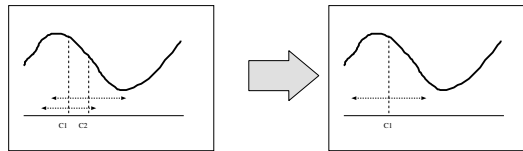


Figure 2. Fusion mechanism

`Fuse_species(radius)`. If the centres of any pair of species from the species list are closer to each other than the given radius, the two species are fused. The centre of the new species will be the one with the best function value, while the level will be the minimum of the levels of the original species to be fused (see Figure 2). Naturally this method does not ensure that no species will overlap after fusion though the amount of the overlapping regions is typically highly decreased.

`Shorten_species_list(max_spec_num)`. Delete species to reduce the list length to the given value. Higher level species are deleted first.

`Optimize_species(evals)`. Start the optimizer for every species with the given evaluation number (i.e. every single species in the actual list receives the given number of evaluations). See Section 2.1.

It is clear that if for some level  $i$  the species list is shorter than the allowed maximal length, `max_spec_num`, the overall number of function evaluations will be smaller than  $n_i$  (see Algorithm 1, `optimize_species`).

Finally, let us make a remark about a possible parallel implementation. The most time-consuming parts of the basic algorithm is the creation and optimization of the species. Note that these two steps can be done independently for every species, so each species can be assigned to a different processor. Notice also that a species is defined by its centre and its level, so the amount of information used in communications is really small.

### 2.3. Parameters of UEGO

The most important parameters are those that depend on the level ( $i$ ): the radii ( $r_i$ ) and two function evaluation numbers for species creation ( $new_i$ ) and optimization ( $n_i$ ) (see Algorithm 1). In this section a method is described that determines the value of these parameters, using a few easy-to-understand parameters provided by the user.

We will now make use of the notation introduced in Section 2.2. The user-given parameters are listed below. Short notations (in brackets) that will be used in equations in the subsequent sections are also given.

**evals ( $N$ ):** The maximal number of function evaluations the user allows for the whole optimization process. Note that the actual number of function evaluations may be less than this value.

**levels ( $l$ ):** The maximal level value (see Algorithm 1).

**threshold ( $\nu$ ):** The meaning of this parameter will be explained later.

**max\_spec\_num ( $M$ ):** The maximal length of the species list.

**min\_r ( $r_l$ ):** The radius that is associated with the maximal level, i.e. levels.

The parameter setting algorithm to be described can use any four of the above five values while the remaining parameters are set automatically.

**Speed of the optimizer.** Before presenting the parameter setting method, the notion of the *speed* of the optimizer must be introduced. As explained earlier, the optimizer cannot make a larger step in the search space than the current radius of the species. Furthermore, if the centre of a species is far from the local optima, then these steps will be larger while if the centre is already close to a local optimum then the steps will be very small. Given a certain number of evaluations, it is possible to measure the distance the given species moves during the optimization process assuming that the species is suboptimal. This distance can be approximated (as a function of the radius and evaluations) for certain optimizers using ideal landscapes (such as linear functions) with the help of mathematical models or experimental results. This naturally leads to a notion of speed that will characterize a given domain (assuming e.g. a linear landscape) and will depend on the species radius. Speed will be denoted by  $v(r)$ . As we will not give any actual approximations here, the reader should refer to [7].

The parameter-setting method is based on intuitive and reasonable *principles*. These principles are now described below.

**Principle of equal chance.** At a level, every species moves a certain distance from its original centre due to optimization. This principle ensures that every species will receive

the number of evaluations that is enough to make it move at least a fixed distance, assuming that the speed of this motion is  $v(r)$ . A species will not necessarily move so far but the definition of speed is such that if the species is far from the local optima, then it will move approximately the given distance. This common distance is defined by  $r_1\nu$ . The meaning of `threshold` can now be given: it directly controls the distance a species is allowed to cover, so it actually controls the probability that a species will eventually represent a local optimum: the further a species can go, the higher the probability of reaching a local optimum is (and the more expensive the optimization is). Recall that  $r_1$  is always the diameter of the search space. Now, the principle can be formalized:

$$\frac{v(r_i)n_i}{M} = r_1\nu \quad (i = 2, \dots, l) \quad (1)$$

**Principle of exponential radius decreasing.** This principle is quite straightforward; given the smallest radius and the largest one ( $r_l$  and  $r_1$ ) the remaining radii are expressed by the exponential function:

$$r_i = r_1 \left(\frac{r_l}{r_1}\right)^{\frac{i-1}{l-1}} \quad (i = 2, \dots, l). \quad (2)$$

**Principle of constant species creation chance.** This principle ensures that even if the length of the species list is maximal, there is a chance of creating at least two more species for each old species. It also makes a strong simplification, namely, all the evaluations should be set to the same constant value.

$$new_i = 3M \quad (i = 2, \dots, l) \quad (3)$$

**Decomposition of  $N$ .** Let us define  $new_1 = 0$  for the sake of simplicity since  $new_1$  is never used by UEGO. The decomposition of  $N$  results in the trivial equation

$$\sum_{i=1}^l (n_i + new_i) = (l-1)3M + \sum_{i=1}^l n_i = N \quad (4)$$

making use of (3) in the process. One more simplification is possible; set  $n_1 = 0$  whenever  $l > 1$ . Note that if  $l = 1$  then UEGO is simply the optimizer.

Expressing  $n_i$  from (1) and substituting it for (4), we can write

$$(l-1)3M + \sum_{i=2}^l \frac{Mr_1\nu}{v(r_i)} = N \quad (5)$$

Using (2) as well, it is quite evident that the unknown parameters in (5) are just the user given parameters and due to the monotony of this equation in every variable, any of the parameters can be given using effective numerical methods, provided that the other parameters are known. Using the above principles, the remaining important parameters ( $n_i$ ,  $new_i$  and  $r_i$ ) can be calculated as well. Note, however, that some of the configurations set by the user may be unfeasible.

#### 2.4. Preparing experiments

The optimizer used by UEGO was the hill climber suggested in [10] (SASS) where the parameter  $\rho_{ub}$  (maximal step size) was set to the value of the species radius from which the optimizer is called and the accuracy of the search was set to  $\min(\rho_{ub}/10^3, 10^{-5})$ . The rest of parameters of the algorithm was set as the authors suggested in [10]. No fine tuning of the parameters of the optimizer was carried out.

In [6] and [8] several experiments with test functions were made, and those experiments showed that UEGO was a reliable global optimization method for finding not only the global maximum/maxima, but also several local optima. They also allowed confirmation that both the clustering technique and the level-based “cooling” technique showed some advantages over their predecessors. Comparisons to other algorithms showed that UEGO was competitive, at least on the examined test problems.

Table 1. Set of Test Functions

	Function	Domain	N. Optima.	Refer.
F1	$\sum_{i=1}^{10} \frac{1}{(k_i \cdot (x - a_i))^2 + c_i}$	[0, 10]	8	[7]
F2	$\sum_{i=1}^5 i \cdot \sin((i+1)x + i)$	[-10, 10]	> 20	[11]
F3	$-\sin(x_1^2 + 2x_2^2) \cdot e^{-x_1^2 - x_2^2}$	$[-3, 3]^2$	> 30	[11]
F4	$-\sin^2(\pi y_1) - \sum_{i=1}^2 (y_2 - 1)^2 (1 + \sin^2(\pi y_{i+1})) - (y_3 - 1)^2$ where $y_i = 1 + (x_i - 1)/4$	$[-10, 10]^4$	> 1000	[11]
F5	$-\sin^2(\pi y_1) - \sum_{i=1}^3 (y_i - 1)^2 (1 + 10 \sin^2(3\pi y_{i+1})) - (y_4 - 1)^2$ where $y_i = 1 + (x_i - 1)/4$	$[-10, 10]^4$	> 100	[11]
F6	$2.5 \cdot \prod_{i=1}^n \sin(x_i - \pi/2) + \prod_{i=1}^n \sin(5(x_i - \pi/2))$	$[0, \pi]^n$	> 100	[12]
F7	$0.5 \cdot \sum_{i=1}^n (x_i - 2)^2$	$[-1, 1]^{20}$	> 200	[5]
F8	$0.5 \cdot \sum_{i=1}^n (x_i + 0.5)^2$	$[-1, 1]^{20}$	> 200	[5]
F9	$10 \cdot \sum_{i=1}^n x_i^2$	$[-1, 1]^{20}$	> 200	[5]
F10	$0.5 \cdot \sum_{i=1}^n (x_i - 8)^2$	$[-1, 1]^{20}$	> 200	[5]
F11	$0.5 \cdot \sum_{i=1}^n i(x_i - 2)^2$	$[-1, 1]^{20}$	> 200	[5]

The goal of this work is to evaluate two different parallel implementations of UEGO but not the sequential version which is studied in [8]. Table 1 shows the set of test functions used for evaluating both parallel versions of UEGO where the name, dimension and number of local optima of each function can be seen. The last column shows the references where the test functions can be found.

Due to the stochastic nature of UEGO, all the numerical results given in this work are average values of one hundred executions.

### 3. Parallel Strategy: Synchronous Global Model (PSUEGO)

Regarding the parallelization of UEGO, it seems that the most convenient model is the centralized one where a master-worker communication is required (see Figure 3). It is interesting to remark that the most time-consuming parts of the basic sequential algorithm is the creation and optimization of the species, therefore, these two steps can be carried out independently for every species, so each species can be assigned to a different processor.

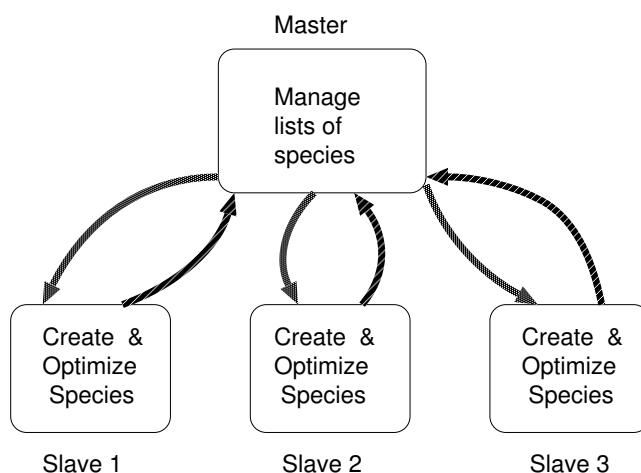


Figure 3. Parallel Strategy: Global Model

### 3.1. Description of PSUEGO strategy

The first parallel strategy is a synchronous algorithm where the slave processors carry out the creation and optimization procedures (see Figure 4), while the master processor manages the global species list (fuse, delete, etc.).

In order to run the "optimize" and "create.species" procedures, the slave processors need to receive from the master processor only the two parameters of a species (i.e. its centre and its radius), so the amount of information involved in the communication procedure is quite small.

The **optimize** and **create.species** procedures do not need any additional information; each procedure depends on a species only and does not depend on other parameters or species. For this reason, these procedures can be run independently on several slave processors at the same time.

Algorithms 2 and 3 show a description of the master and the slave processor algorithms.

The master processor, (see Algorithm 2), initializes the species list. In this parallel version, the **init.species.list** procedure does not create a single individual. Instead, it creates  $NP$  individuals randomly where  $NP$  is the number of slave processors. These  $NP$  individuals will be the centres of the first  $NP$  species, which will be included in the species list. Once the species list has been initialized, the master processor sends one species to each slave processor, so all species can be optimized simultaneously. Later, the master processor receives the optimized species from the slave processors and starts the iterative optimization process. The value of the level increases in each iteration (as was previously mentioned, **levels** is a user parameter that indicates the maximum number of levels).

At every iteration the master processor sends species from the species list to the slave processors. Then, when a slave processor generates a new species list, it sends this sub-



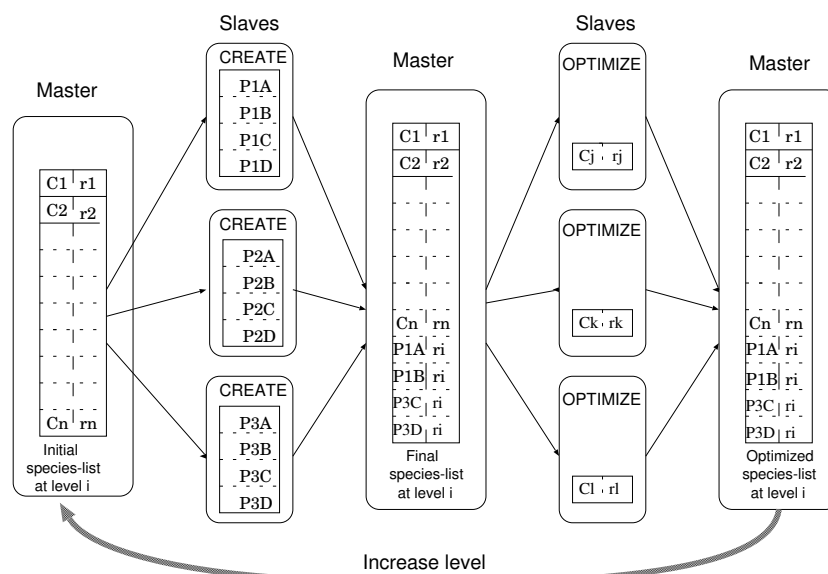


Figure 4. PSUEGO strategy

list back to the master processor. The master processor receives the sublist from a slave processor and sends another species (if there is a species from the species list that has not been sent yet) to the slave processor. Once the master processor has received all the sublists from the slave processors, it joins (**join** procedure) them to the previous species list and executes the **fuse\_species** and **shorten\_species** procedures. Then, the master processor distributes the species among the slave processors in the same way as in the previous case. When the master processor receives all the optimized species, it executes the **fuse\_species** procedure and finally the level is increased starting a new iteration.

### 3.2. Evaluation and results of PSUEGO

For analyzing the performance of this synchronous parallel version of UEGO (PSUEGO), the set of test functions described in Table 1 was used. All experiments were run 100 times, and results are the average value of 100 executions. Experiments were done on a Cray T3E using up to 33 processors.

Results have been obtained by using some of the tools available at Cray T3E (PAT program). These numerical results showed that in this parallel strategy the computational load was not well balanced; some processors worked more than others. In addition, due to the synchronization procedures, processors spent a large amount of time waiting for information, so they were quite frequently idle. Table 2 shows the percentage of idle time for every test function for several values of the number of processors. Results show that this percentage ranges from 16% to 50%.

**Algorithm 2** : *Description of MASTER\_PSUEGO strategy*

```

Begin MASTER_PSUEGO
  init_species_list
  SEND species to be optimized to slaves
  RECEIVE optimized species from slaves
  for i = 2 to levels
    while there are any species not sent
      SEND species (to create more new ones) to slaves
      RECEIVE lists of created species from slaves
    end while
    join new lists to the old list of species
    fuse_species
    shorten_species_list
    while there are any species not sent
      SEND species to be optimized to slaves
      RECEIVE optimized species from slaves
    end while
    fuse_species
  end for
End MASTER_PSUEGO

```

**Algorithm 3** : *Description of SLAVE\_PSUEGO strategy*

```

Begin SLAVE_PSUEGO
  RECEIVE species from master
  optimize_species
  SEND optimized species to master
  for i = 2 to levels
    while there is any species not sent in master
      RECEIVE species from master
      create_species
      SEND lists of created species to master
    end while
    while there is any species not sent in master
      RECEIVE species from master
      optimize_species
      SEND optimized species to master
    end while
  end for
End SLAVE_PSUEGO

```

Table 2. Percentage of idle time for PSUEGO for several processors.

Function	% Idle time						
	NP=2	NP=3	NP=4	NP=5	NP=9	NP=17	NP=33
F1	49	34	26	20	18	23	36
F2	49	34	25	20	20	28	26
F3	49	36	27	21	18	21	38
F4	49	34	26	21	19	23	36
F5	49	35	28	21	18	21	36
F6	49	38	25	16	19	28	38
F7	49	36	27	21	18	17	35
F8	49	34	26	20	20	29	36
F9	49	33	26	20	19	16	35
F10	50	34	28	21	18	26	36
F11	49	34	26	21	18	21	33

## PSUEGO

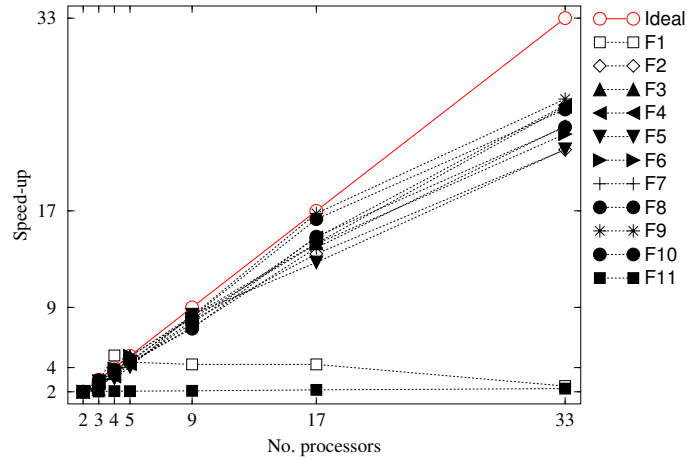


Figure 5. Speedup of PSUEGO for the set of test functions described in Table 1

As a consequence of the unbalanced workload and the synchronization procedures, PSUEGO does not exhibit a very good performance. This fact is shown in Figure 5, where the values of *speedup* versus the number of processors ( $NP$ ) were depicted. The *speedup* for  $NP$  processors is defined by:  $speedup = \frac{t_1}{t_{NP}}$  where  $t_1$  is the execution time when the algorithm is run, using a single processor (sequential case), and  $t_{NP}$  is the execution time, using  $NP$  processors.

#### 4. Parallel Strategy: Asynchronous Global Model (PAUEGO)

The second parallel strategy (PAUEGO) is intended to solve some of the previous problems. In this new implementation the load has been balanced forcing the master processor to optimize and create species while the slave processors are working. Another change is the reduction in the number of synchronization points. Now the master processor can start to carry out the synchronous operations over the species before receiving all the information, so the idle time for slave processors can be considerably reduced.

##### 4.1. Description of PAUEGO strategy

Algorithms 4 and 5 describe the master and slave strategies for PAUEGO algorithm. The first difference from PSUEGO is in the initialization phase. Now, every slave processor has a species initialization procedure, i.e. every slave processor chooses two or more individuals as centres of new species to optimize. When a slave processor has optimized all its species, it creates new species and the new species sublist is sent to the master processor. On the other hand, the master processor only initializes a single individual as the centre of a single species (it does not choose NP individuals like in PSUEGO), optimizes it and creates new species. Once this new sublist has been created, the master processor is prepared to receive any information (sublists of species) from any slave processor. If the master processor does not receive any sublist, it begins to fuse species saved in the current list of species. This fusion process stops when the master processor receives a sublist from a slave processor, and goes on when no more information is received. Once the master processor has received all sublists created by the slave processors and has applied the *fuse* procedure, the iterative loop starts.

The iterative part of PAUEGO for slave processors does not have any modification compared to the iterative part of PSUEGO. However, for PAUEGO, the master processor always checks the arrival of information (a newly created sublist of species or an optimized species) from slave processors and it sends a new species on information arrival. In addition, the master processor contributes to the optimization process by creating, fusing and optimizing species. The processes executed by the master processor are always interrupted when new information arrives, and they are resumed later.

##### 4.2. Evaluation and results of PAUEGO

For the analysis of the performance of PAUEGO, a set of experiments using the same set of test functions (see Table 1), was performed.

From the experiments we can conclude that the percentage of idle time for PAUEGO is much smaller than for PSUEGO as it can be seen in Table 3. For the asynchronous version, the percentage of idle time is no greater than 4% (which only appears for some test functions using up to 33 processors), while the same bound was 50% in the synchronous case.

Another conclusion based on the results is that the computational load is much more balanced: every processor executes a similar number of operations. Table 4 shows an

**Algorithm 4** : Description of MASTER\_PAUEGO strategy

```

Begin MASTER_PAUEGO
  init_species_list and optimize_species
  create_species
  RECEIVE a new species's sublist from each slave
  while there are any species to be received
    if any slave processor has sent a sublist
      RECEIVE the sublist from the slave
    else fuse_species
  end while
  for  $i = 2$  to levels
    while there are any species not sent
      SEND species to slave
      if any slave processor has sent a sublist
        RECEIVE the sublist from the slave
      else fuse_species
    end while
    shorten_species_list
    while there are any species not sent
      SEND species to be optimized to slave
      while any optimized species has been sent
        optimize a not yet optimized species
        fuse_species
      end while
      RECEIVE optimized species from slave
    end while
  end for
End MASTER_PAUEGO

```

example of the results achieved for test function F10 using up to 9 processors. Similar results were obtained for all test functions and number of processors.

In Table 4, first column (**PE**) indicates the processor identifier number where the identifier 0 corresponds to the master processor. The **cycles** column shows the number of cycles consumed by each processor during the execution. The **operations** column shows the number of operations made by each processor. It can be seen that the differences in the number of operations are quite small. The **oper/sec** column indicates the number of operation per second, and it is directly related to the workload balance. Data in this column show that approximately all the processors execute the same number of operations. The **dcache** column shows the cache misses, and the **miss/sec** column the average value of cache misses per second. It can be seen from here that the master processor has much fewer misses than the slave processors.

Figure 6 shows the *speedup* for PAUEGO versus the number of processors. It can be seen that the *speedup* is closer to the ideal case, mainly for a small number of processors. Ap-

**Algorithm 5** : Description of SLAVE\_PAUEGO strategy

```

Begin SLAVE_PAUEGO
  init_species_list and optimize_species
  while there is any species to send to master
    create_species
    SEND lists of created species to master
  end while
  for  $i = 2$  to levels
    while there is any species not sent in master
      RECEIVE species from master
      create_species
      SEND lists of created species to master
    end while
    while there is any species not sent in master
      RECEIVE species from master processor
      optimize_species
      SEND optimized species to master
    end while
  end for
End SLAVE_PAUEGO

```

Table 3. Percentage of idle time for PAUEGO for several processors.

Function	% idle time						
	NP=2	NP=3	NP=4	NP=5	NP=9	NP=17	NP=33
F1	0	1	1	2	2	3	4
F2	0	0	1	1	1	1	2
F3	0	0	1	2	2	2	4
F4	0	0	0	1	1	2	2
F5	0	1	1	0	1	1	2
F6	1	1	1	2	2	3	4
F7	0	1	1	0	1	1	2
F8	0	0	1	1	0	1	2
F9	0	0	1	1	0	1	1
F10	0	0	1	1	2	2	3
F11	0	0	1	0	1	2	2

plying PAUEGO to a problem more expensive from computation point of view, the *speedup* would be better due to the overlapping of communication and computation times.

Table 4. Results from an execution of PAUEGO for F10 test function using up 9 processors. Processor 0 is the master processor.

PE	cycles	operations	ops/sec	dcache	misses/sec
0	42368.98	2645.99	28.11	0.83	0.01
1	42227.79	2659.16	28.34	14.59	0.16
2	38129.47	2393.44	28.25	15.85	0.19
3	42306.36	2645.33	28.14	13.53	0.14
4	38244.14	2379.04	28.00	13.50	0.16
5	42542.94	2622.72	27.74	10.79	0.11
6	38443.14	2367.07	27.71	10.74	0.13
7	38223.73	2360.04	27.79	12.09	0.14
8	38218.41	2360.70	27.80	12.05	0.14

### PAUEGO

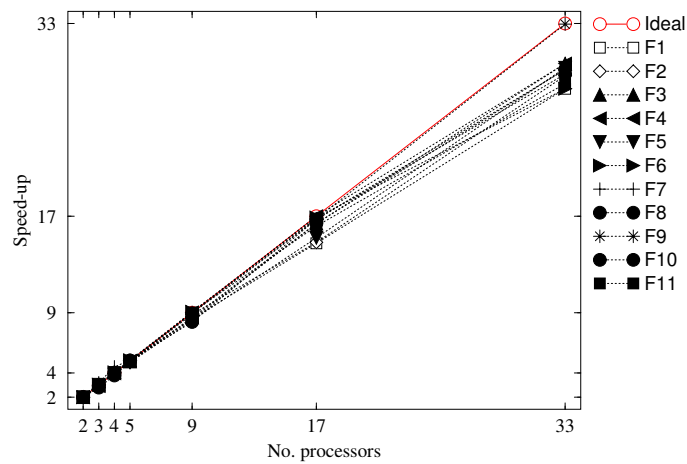


Figure 6. Speedup of PAUEGO for the set of test functions described in Table 1

## 5. Summary

In this paper, a new general technique (UEGO) for accelerating existing search methods has been described and two parallel implementations have been evaluated.

The first parallel strategy is a synchronous algorithm where the slave processors carry out the creation and optimization procedures while the master processor manages the global species list (fuse, delete, etc.). The main drawback of this strategy is that, due to points of synchronization, the slave processors are idle for a considerable amount of time, so the parallel program is inefficient. Another problem is that the load is not balanced, the master processor spends a long time waiting for information from the slave processors.

The second parallel strategy is intended to solve some of the previous problems. In this new implementation the load has been balanced, forcing the master to optimize and create species, while the slave processors are working. Another change was the reduction in the number of points of synchronization. Now the master processor can start to carry out the synchronous operations over the species before receiving all the information from the slaves processors, so the idle time for slaves was considerably reduced.

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