

NICHING TECHNIQUES BASED ON SEXUAL CONFLICT IN CO-EVOLUTIONARY MULTI-AGENT SYSTEM

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Abstract: Evolutionary algorithms often suffer from premature loss of population diversity what limits their adaptive capacities in dynamic environments and leads to location of single solution in case of multi-modal fitness landscapes. Niching techniques for evolutionary algorithms are aimed at locating more than one optima of multi-modal functions. Sexual selection resulting from sexual conflict and co-evolution of female mate choice and male display trait is considered to be one of the ecological interactions responsible for speciation. This paper introduces the co-evolutionary multi-agent system with speciation by sexual conflict and its formal model. Such system is applied to multi-modal function optimization and the results from runs against commonly used test functions are presented.

Keywords: evolutionary algorithms, multi-agent systems, co-evolution, niching

1. INTRODUCTION

Evolutionary algorithms (EAs) have demonstrated in practice efficiency and robustness as global optimization techniques. However, they often suffer from premature loss of population diversity what results in premature convergence and may lead to locating local optima instead of a global one. What is more, both the experiments and theoretical analysis show that for multi-modal problem landscapes a simple EA will inevitably locate a single solution (Mahfoud, 1995). If we are interested in finding multiple solutions of comparable fitness, some multi-modal function optimization techniques (*niching methods*) should be used. Niching techniques (Mahfoud, 1995) are aimed at forming and stably maintaining species that are located in different optima of multi-modal fitness landscape (niches) throughout the search process.

The understanding of species formation processes (*speciation*) still remains the greatest challenge for evolutionary biology. The biological models of speciation include *allopatric models* (which require geographical separation of subpopulations) and *sympatric models* (where speciation takes place within one population without physical barriers) (Gavrilets, 2003). Sympatric speciation may be caused by different kinds of co-evolutionary interactions including *sexual selection*.

Sexual selection results from co-evolution of female mate choice and male display trait where females evolve to reduce direct costs associated with mating and keep them on optimal level and males evolve to attract females to mating (*sexual conflict*) (Gavrilets, 2003). The proportion of two sexes (females and males) in population is almost always 1 : 1. This fact combined with higher females' reproduction costs causes, that in the majority of cases, females choose males

in the reproduction process according to some males' features. In fact, different variants of sexual conflict are possible. For example there can be higher females' reproduction costs, equal reproduction costs (no sexual conflict), equal number of females and males in population, higher number of males in population (when the costs of producing a female are higher than producing a male), higher number of females in population (when the costs of producing a male are higher than producing a female) (Krebs and Davies, 1993).

In the following sections the previous work on sexual selection as a population diversity and speciation mechanism for evolutionary algorithms is presented. Next, the formal model of co-evolutionary multi-agent system based on the sexual conflict, in which females' reproduction costs are higher than males', is presented. In such a system two sexes co-evolve: females and males. Female mate choice is based on values of some important features of selected individuals. Also the operator of grouping individuals into reproducing pairs is introduced. Such system is applied to multi-modal function optimization and compared to other techniques.

2. PREVIOUS RESEARCH ON SEXUAL SELECTION AS A SPECIATION MECHANISM

Sexual selection is considered to be one of the ecological mechanisms responsible for sympatric speciation (Gavrilets, 2003). Gavrilets (2003) presented a model, which exhibits three general dynamic regimes. In the first one there is endless co-evolutionary chase between the sexes where females evolve to decrease the mating rate and males evolve to increase it. In the second regime females' alleles split into two clusters both at the optimum distance from the males' alleles and males get trapped between the two female clusters with relatively low mating success. In the third regime males answer the diversification of females by splitting into two clusters that evolve toward the corresponding female clusters. As a result, the initial population splits into two species that are reproductively isolated.

Todd and Miller (1997) showed that natural selection and sexual selection play complementary roles and both processes together are capable of generating evolutionary innovations and biodiversity much more efficiently. Sexual selection allows species to create its own optima in fitness landscapes. This aspect of sexual selection can result in rapidly shifting adaptive niches what allows the population to explore different regions of phenotype space and to escape from local optima. The authors also presented the model of sympatric speciation via sexual selection.

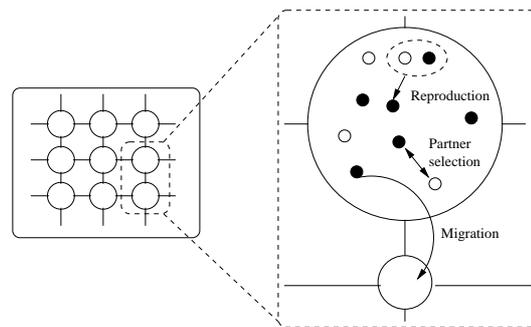


Fig. 1. Co-evolutionary multi-agent system with sexual selection used in experiments

Sánchez-Velazco and Bullinaria (2003) proposed *gendered selection strategies for genetic algorithms*. They introduced sexual selection mechanism, where males are selected on the basis of their fitness value and females on the basis of the so called *indirect fitness*. Female's indirect fitness is the weighted average of her fitness value, age, and the potential to produce fit offspring (when compared to her partner). For each gender different mutation rates were used. The authors applied their algorithm to Traveling Salesman Problem and function optimization.

Sexual selection as a mechanism for multi-modal function optimization was studied by Ratford, Tuson and Thompson (1997). In their technique sexual selection is based on the so called *seduction function*. This function gives a low measure when two individuals are very similar or dissimilar and high measure for individuals fairly similar. The Hamming distance in genotype space was used as a distance metric for two individuals. The authors applied their mechanism alone and in combination with crowding and spatial population model. Although in most cases their technique was successful in locating multiple optima in multi-modal domain, the strong tendency to lose all optima except one after several hundreds simulation steps was observed.

As it was presented here, sexual selection is the biological mechanism responsible for biodiversity and sympatric speciation. However it was not widely used as maintaining genetic diversity, speciation and multi-modal function optimization mechanism for evolutionary algorithms. It seems that sexual selection should introduce open-ended evolution, improve adaptive capacities of EA (especially in dynamic environments) and allow speciation (the formation of species located in different optima of multi-modal fitness landscape) but this is still an open issue and the subject of ongoing research.

3. CO-EVOLUTIONARY MULTI-AGENT SYSTEM WITH SEXUAL SELECTION

The main idea of *evolutionary multi-agent system (EMAS)* is the modeling of evolution process in *multi-agent system (MAS)* (Cetnarowicz *et al.*, 1996). The basic EMAS model allows the evolution of only one species. The model of *co-evolutionary multi-agent system (CoEMAS)* allows modeling of biological speciation mechanisms based on co-evolutionary interactions (including sexual selection), competition for limited resources, and geographical isolation (Dreżewski, 2003). Systems based on CoEMAS model can be applied, for example, to multi-modal function optimization (Dreżewski, 2004) and multi-objective optimization.

The system presented in this paper is the CoEMAS with sexual conflict (SCoEMAS). The mechanisms used in such system include: sexual conflict and co-evolution of sexes (higher female reproduction costs), sexual selection based on the mutual location of agents in fitness landscape (females choose males), and forming reproducing pairs.

3.1 SCoEMAS

The SCoEMAS may be described as 4-tuple:

$$SCoEMAS = \langle E, S, \Gamma, \Lambda \rangle \quad (1)$$

where E is the environment of the SCoEMAS, S is the set of species ($s \in S$) that co-evolve in SCoEMAS, Γ is the set of resource types that exist in the system, the amount of type γ resource will be denoted by r^γ , Λ is the set of information types that exist in the system, the information of type λ will be denoted by i^λ . There are four information types ($\Lambda = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4\}$) and one resource type ($\Gamma = \{\gamma\}$) in SCoEMAS.

3.2 Environment

The environment of SCoEMAS may be described as 3-tuple:

$$E = \langle T^E, \Gamma^E = \Gamma, \Lambda^E = \{\lambda_1, \lambda_2\} \rangle \quad (2)$$

where T^E is the topography of environment E , Γ^E is the set of resource types that exist in the environment, Λ^E is the set of information types that exist in the environment. The topography of the environment is given by:

$$T^E = \langle D, l \rangle \quad (3)$$

where D is directed graph with the cost function c defined: $D = \langle V, F, c \rangle$, V is the set of vertices, F is the set of arches. The distance between two

nodes is defined as the length of the shortest path between them in graph D .

The l function makes it possible to locate particular agent in the environment space:

$$l : A \rightarrow V \quad (4)$$

where A is the set of agents, that exist in SCoEMAS.

Vertice v is given by:

$$v = \langle A^v, \Gamma^v = \Gamma^E, \Lambda^v = \Lambda^E \rangle \quad (5)$$

A^v is the set of agents that are located in the vertice v . Agents can collect two types of informations from the vertice. The first one includes all vertices that are connected with the vertice v and the second one includes all female agents (of sex *fem*) that are located in the vertice v :

$$i^{\lambda_1} = \{u : u \in V \wedge \langle u, v \rangle \in F\} \quad (6)$$

$$i^{\lambda_2} = \{a^{fem} : a^{fem} \in A^{ind_i, fem} \cap A^v\} \quad (7)$$

where $A^{ind_i, fem}$ is the set of agents of sex *fem* and species ind_i ($ind_i \in S$).

3.3 Species

The set of species is given by:

$$S(t) = \{ind_1(t), \dots, ind_{ns}(t)\} \quad (8)$$

where ns is the number of species, that exist in the system in time t . The changes in the number of species result from the mutual location of agents in the fitness landscape.

Each of the species is defined as follows:

$$ind = \langle A^{ind}, SX^{ind}, Z^{ind}, C^{ind} \rangle \quad (9)$$

where A^{ind} is the set of agents that belong to species ind . There are two sexes within each species: females *fem* and males *mal* ($SX^{ind} = \{fem, mal\}$). The set of actions for species ind is defined as follows:

$$Z^{ind} = \{die, get, unlink, seekfem, accept, clone, rec, mut, givef, givem, migr\} \quad (10)$$

The set of relations of species ind_i with other species that exist in the SCoEMAS is given by:

$$C^{ind_i} = \left\{ \frac{ind_i, get-}{\rightarrow} \right\} \quad (11)$$

The $\frac{ind_i, get-}{\rightarrow}$ relation models the intra- and inter-species competition for limited resources:

$$\frac{ind_i, get-}{\rightarrow} = \left\{ \langle ind_i, ind_j \rangle : ind_i, ind_j \in S, \right. \\ \left. j = 1, \dots, ns \right\} \quad (12)$$

where *get* is the action of taking resource from the environment and the “-” sign indicates that action *get* performed by individuals of species ind_i has the negative effect on the fitness of individuals that belongs to the same and other species.

3.4 Female sex

The *fem* sex of species *ind* is defined as follows:

$$fem = \langle A^{fem}, Z^{fem}, C^{fem} \rangle \quad (13)$$

where A^{fem} is the set of agents of sex *fem* ($A^{fem} \subseteq A^{ind}$). The set of actions that agent a^{fem} can perform is defined as follows:

$$Z^{fem} = \{die, get, unlink, accept, clone, rec, mut, givef, migr\} \quad (14)$$

where *die* is the action of removing agent from the system (when it runs out of resource), *get* action allows agent to get some resource from the environment (the resource γ is given to the agents proportionally to their fitness values), *unlink* is the action of quitting from the reproducing pair formed with the individual of sex *mal*, *accept* is the action of accepting the agent of sex *mal* as a partner for reproduction (agent a^{mal} is accepted when it is located in the same niche as the agent a^{fem} , here the modified version of *hill-valley* function is used (Ursem, 1999), and there is greater probability of accepting agents closer in phenotypic space to the a^{fem} agent, according to Euclidean metric). *clone*, *rec*, and *mut* actions are responsible for, respectively, child creation, mutation with self-adaptation (Bäck *et al.*, 1997) and intermediate recombination (Booker *et al.*, 1997) of its genotype. *givef* action gives some resource of type γ to the child. *migr* action allows the migration within the environment.

The set of relations with sex *mal* is defined as follows:

$$C^{fem} = \left\{ \frac{fem, accept+}{givef-, givem-} \right\} \quad (15)$$

$$\frac{fem, accept+}{givef-, givem-} \rightarrow = \{ \langle fem, mal \rangle \} \quad (16)$$

where *accept* is the action of choosing individual a^{mal} for reproduction (which has the positive effect on its fitness) by agent a^{fem} . The action *accept* results in performing action *givef* and *givem* by, respectively, agent a^{fem} and a^{mal} . These actions transfer some amount of resource γ to the child, what results in decreasing the fitness of agents a^{fem} and a^{mal} . The relation $\frac{fem, accept+}{givef-, givem-} \rightarrow$ models the sexual conflict over the rate of reproduction because *givef* action results in much stronger decrease of fitness than *givem* action.

3.5 Male sex

The *male* sex is defined analogically as the *fem* sex, see equation (13). The set of actions that agent a^{mal} can perform is defined as follows:

$$Z^{mal} = \{die, get, unlink, seekfem, givem, migr\} \quad (17)$$

where *die*, *get*, *unlink*, and *migr* actions are defined analogically as in the case of *fem* sex. *seekfem* is the action that sends messages to female agents located in the vertice $v = l(a^{mal})$, when agent a^{mal} is ready for reproduction (the amount of resource is above the given level). *givem* action is analogical as *givef* action of *fem* sex, and the only difference is that males give four times less resource to child than females. There are no relations with *fem* sex ($C^{mal} = \emptyset$).

3.6 Female agent

Agent a of sex *fem*, that belongs to some species $ind \in S$ ($a \equiv a^{ind, fem}$) is defined as follows:

$$a = \langle GN^a, Z^a, \Gamma^a = \Gamma, \Lambda^a, PR^a \rangle \quad (18)$$

where GN^a is the genotype (consisted of real-valued vector of objective variables and vector of standard deviations used in mutation with self-adaptation). The set of agent's actions $Z^a = Z^{fem}$, see equation (14). The set of informations used by agent a $\Lambda^a = \{\lambda_1, \lambda_3, \lambda_4\}$. Information of type λ_3 is defined as follows:

$$i^{\lambda_3} = \{a_i^{mal} : \text{agent } a \text{ is paired with } a_i^{mal} \text{ agent}\} \quad (19)$$

Information of type λ_4 includes the time t_{pair} of forming pair with agent a_i^{mal} :

$$i^{\lambda_4} = \{t_{pair}\}, \quad (20)$$

PR is the set of agent's profiles with the order relation \trianglelefteq defined:

$$PR^a = \{pr^{res}, pr^{rep}, pr^{mig}\} \quad (21a)$$

$$pr^{res} \trianglelefteq pr^{rep} \trianglelefteq pr^{mig} \quad (21b)$$

where pr^{res} is the resource profile (this is also the profile, which goal has the higher priority), pr^{rep} is the reproductive profile, and pr^{mig} is the migration profile. Within pr^{res} profile all strategies connected with type γ resource are realized ($\langle die \rangle$, $\langle get \rangle$). Within pr^{rep} profile all strategies connected with the reproduction process ($\langle unlink \rangle$, $\langle accept, clone, rec, mut, givef \rangle$) are realized. These strategies use informations i^{λ_3} and i^{λ_4} . Within pr^{mig} profile the migration strategy ($\langle migr \rangle$), which uses information i^{λ_1} , is realized.

3.7 Male agent

Agent a of sex *mal*, that belongs to some species $ind \in S$ ($a \equiv a^{ind, mal}$) is defined analogically as $a^{ind, fem}$, see (18). Genotype GN^a is defined identically as in the case of $a^{ind, fem}$ agent. The set of agent's actions $Z^a = Z^{mal}$, see equation (17). The set of information used by agent a $\Lambda^a = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4\}$.

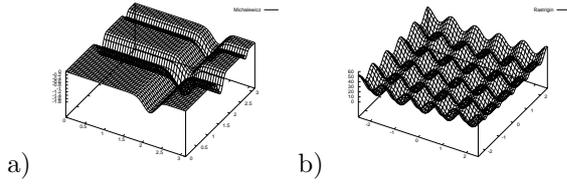


Fig. 2. Michalewicz (a) and Rastrigin (b) test functions

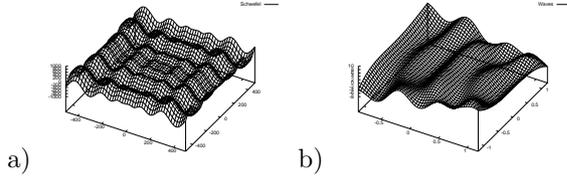


Fig. 3. Schwefel (a) and Waves (b) test functions

Information of type λ_3 includes agent a_i^{fem} with which agent a forms pair, analogically as in case of female agent — see (19). Information of type λ_4 includes the time of forming reproducing pair with agent a_i^{fem} , see (20).

The set of profiles and pr^{res} and pr^{mig} profiles are defined analogically as in the case of female agent, see (21).

Within pr^{rep} profile all strategies connected with the reproduction process are realized ($\langle unlink \rangle$ and $\langle seekfem, givem \rangle$). These strategies use informations i^{λ_2} , i^{λ_3} and i^{λ_4} .

4. SIMULATION EXPERIMENTS

First simulation experiments were aimed at testing if *SCoEMAS*, which model was presented in previous section, is able to form and stably maintain species located in the minima of multi-modal fitness landscape. Also, the comparison to deterministic crowding (DC) niching technique (Mahfoud, 1995) and EMAS without any niching mechanisms was made.

Four widely used multi-modal test functions: Michalewicz, Rastrigin, Schwefel and Waves (see fig. 2 and 3) were used as the fitness landscapes in the experiments (Potter, 1997; Ursem, 1999).

Figures 4 and 5 show the location of agents in fitness landscape (Rastrigin function) during the typical experiment with *SCoEMAS*. At the beginning there are 50 females (represented with triangles) and 50 males (represented with squares). It can be seen that as the simulation goes on the individuals reproduce and locate themselves near the minima in multi-modal domain. What is more the subpopulations are stable, and do not disappear throughout the simulation.

Figures 6 and 7 show the average number of located minima from 20 simulations. The minima

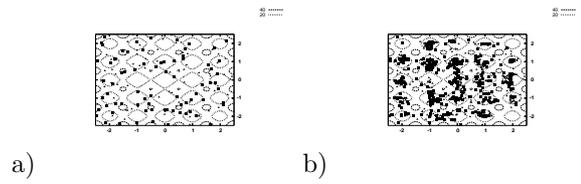


Fig. 4. The location of individuals in *SCoEMAS* during the 0th (a) and 50th (b) simulation step (Rastrigin function)

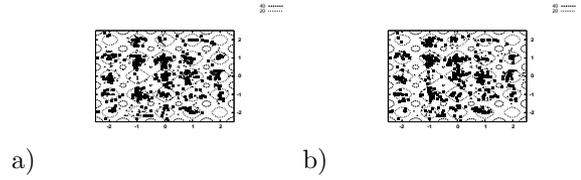


Fig. 5. The location of individuals in *SCoEMAS* during the 500th (a) and 5000th (b) simulation step (Rastrigin function)

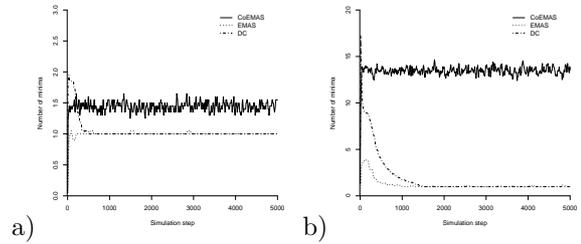


Fig. 6. The number of located minima of Michalewicz (a) and Rastrigin (b) function

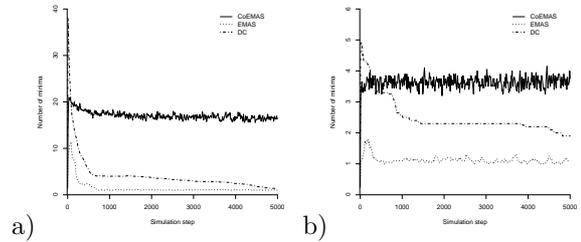


Fig. 7. The number of located minima of Schwefel (a) and Waves (b) function

was classified as located when there was at least one individual closer than 0.03 for Michalewicz function, 0.05 for Rastrigin function, 10.0 for Schwefel function, and 0.025 for Waves function. All the experiments were carried out for three techniques: *SCoEMAS*, EMAS, and DC.

The *SCoEMAS* stood relatively well when compared to other techniques. In all cases it formed and stably maintained species during the whole experiment. Although DC quickly located even greater number of minima than other techniques, there was quite strong tendency to lose almost all of them during the rest part of experiment. Simple EMAS, without any niching mechanisms was not able to stably populate more than one

minima. It turned out that in the case of multi-modal landscape it works just like simple EA.

Presented results indicate that simple EMAS can not be applied to multi-modal function optimization without introducing special mechanisms such as co-evolution. DC technique has some limitations — it has the strong tendency to lose minima during the simulation (this fact was also observed in (Watson, 1999)). CoEMAS with sexual selection is able to form and stably maintain species but still more research is needed.

5. CONCLUDING REMARKS

The idea of *co-evolutionary multi-agent system (CoEMAS)* allows us to model many ecological interactions between species, such as predator-prey and host-parasite co-evolution, mutualism, sexual conflict and co-evolution of sexes, etc.

In this paper sample CoEMAS with sexual conflict and resulting co-evolution of two sexes was presented. This system was applied to multi-modal function optimization. It properly formed and stably maintained species of agents located in the minima of multi-modal fitness landscapes. SCoEMAS was able to detect and stably maintain more minima than EMAS without niching mechanism and deterministic crowding niching technique.

Future research will include the comparison of other variants of sexual conflict (different costs of reproduction for each sex, different costs of producing female and male individual, resulting in different proportions of individuals of each sex in population). Also, more detailed comparison to other classical niching techniques and the parallel implementation of systems based on CoEMAS model with the use of MPI are included in future research plans.

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