Far East J. Appl. Math. **20**(1) (2005), 33-46

GENETIC ALGORITHMS RESEARCH AND APPLICATION BASED ON THE MECHANICS OF NATURAL SELECTION

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Abstract

There are many reformed approaches for genetic algorithms, but they all belong to static reformed methods. In this paper, a new dynamic reformed method ---NGA (GA based on natural selection theory), which is the introduction of niche "costae escarole" theory into genetic algorithms as a simple extension, is presented. In this method, the individuals with a larger niche as the members of the next generation, which considers not only the change of individuals at present, but also the development trend of individuals in the future, are chosen. A comparative analysis is made with respect to the selection mechanism and Schema theorem of NGA over classical GAs. It also proves that this method converges to the optimal solution with probability one. Two examples are given to illustrate the applications of the method. The simulation results show excellent self-learning capability of NGA.

2000 Mathematics Subject Classification: 68T05.

Key words and phrases: niche, genetic algorithms, costae escarole theory, fuzzy T-S systems.

The work was supported by the National Natural Science Key Foundation of China (60234010), Doctor Foundation in University of China (2004287005) and National Defense Foundation Research of China (K1603060318).

Received February 25, 2005

1. Introduction

Genetic algorithms (GAs) are globally optimal search algorithms, which use the selection, crossover and mutation operators to generate individuals of the new generation based on the mechanics of natural selection. Recently, they have been widely applied to the solution of various optimization problems. Compared with other algorithms, GAs have many unique properties:

(1) The operation plants of GA are not parameters themselves, but the coded individuals and we do not have to make any assumptions about continuity and differentiability, as long as the function is computational;

(2) Due to GAs' inherent parallel ability, they work well for global optimization;

(3) GAs employ the optimal search method of probability;

(4) Because of the flexibility of GAs, they are particularly suitable to the identification of structure and parameters for complex systems, such as neural networks and fuzzy systems.

However, there are still a lot of disadvantages to GAs, they are displayed in the following three aspects:

(1) There are difficulties in the selection and control of the algorithms' parameters;

(2) There exist some premature problems;

(3) The algorithms lack a definite leading factor, in other words they are deceptive.

Currently, the improvement research of GA is basically conducted with respect to these three difficulties [1, 3-12, 14-16]. For example, there is Fuzzy-GA [18] with the introduction of human thinking and ubiquitous fuzziness of objective things; GA [14] with the introduction of model of population growth; GA [16] imitating the phenomenon of division of labor in society; GA [8] employing the tactics that two generations of father and son that compete each other; GA [10] based on the selection of population area; GA [1] with the substitute tactics of adaptive generation gap; GA [11] with the introduction of age structure; GA [9] on the basis of the fuzzy self-adaptive tactics of mutation operator; GA [4, 12, 15] based on the improvement of ecological model of sub-generation, in which the ecological model is introduced, and GA [3, 5] in which niche and species are introduced to overcome the "premature" problem produced because of lacking population's diversity.

All of the reformed methods mentioned above utilize one respect of natural characteristics of population in evolution. But they only consider the current state or quantity of individuals in the selection of individuals of the sub-generation and ignore the development trend of individuals, and they still use the static reformed method. Actually, the development of individuals varies with environment and evolves towards the direction more adaptive to their development by gradual adaptation and accumulation. Therefore, the static reformed evolutionary tactics is incomplete and does not accord with the dynamic characteristics of organism evolution. The "costae escarole" theory of niche introduced in this paper is a dynamic reformed method, in which we choose the size of niche of individuals as the criterion of natural selection strategy and employ the tactics of reserving individuals with the largest niche to select the members of new generation, in order to improve the performance of GAs.

2. The "Costae Escarole" Theory of Niche

Niche includes two respects: one is the state of organism individuals, that is, the quantities of individuals or the adaptation capability of individuals; the other is the real influence of individuals on ecological environment or the ability to occupy the new ecological environment.

Consider an ecosystem with n individual organisms and define the niche of i-th organism as follows:

$$N_i = \frac{s_i + A_i p_i}{\sum_{i=1}^{n} (s_i + A_i p_i)},$$

where s_i is the state of i-th organism, denoting the state of individual, A_i is the measure transition coefficient, and p_i is the "escarole" of i-th organism individual, denoting the change rate of i-th organism ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, n$), $N_i \in [0, 1]$.

A bigger N_i indicates that the individual is more adaptable to the environment, has stronger increasing, prospering and evolving of its power, and plays a bigger role in the ecosystem. On the contrary, a smaller N_i demonstrates that the individual adapts less to the environment, and plays a smaller role in the ecosystem.

The "costae escarole" theory of niche has described the generality of ecosystem synthetically and the trend of individual change and development. It also has disclosed the extension of the niche of individuals and the competition among organisms and the inherent mechanism of formation and evolution of organism diversity.

In this paper, we incorporate the essential characteristics of biological heredity and evolution into GA, and choose the size of an individual's niche as the selection criterion to reform GA. The approach has considered not only the current state of individuals, but also the development trend of individuals as well as the function of this trend to the environment. It can remedy the disadvantages of the past reform methods, which only utilized the current state of individual.

3. GA Based on the Costae Escarole Theory of Niche

3.1. Niche-GA algorithm

(1) Initialization: Creating the initial population $N = \{n_1, n_2, \ldots, n_k\}$ randomly, where k is the size of the initial population.

(2) Creating two sequences of "costae" and "escarole" respectively:

for each individual n_i ($i = 1, 2, \ldots, k$), two sequences are created according to

$$\frac{dN}{dt} = r\left(1 - \frac{N}{K}\right)N, \tag{1}$$

the sequence of "costae": $s_1, s_2, \ldots, s_k$;

the sequence of "escarole": $p_1, p_2, \ldots, p_k$.

(3) Calculating the niche of each individual

$$n_i : N_i = \frac{s_i + A_i p_i}{\sum_{i=1}^{n} (s_i + A_i p_i)} \quad (i = 1, 2, ..., k).$$

(4) Select: combination of the arrangement of individuals according to their niche and tactics of reserving the individuals with the largest niche.

Arrange N_i and choose individuals with relatively larger niche as the members of sub-generation and employ the tactics of reserving the largest niche.

3.2. Comparative analysis of Niche-GA and SGA

3.2.1. Comparison of selection mechanisms

The performance of SGA depends largely on the selection mechanism of the sub-generation, that is, how to choose the replaced individuals to improve the efficiency of algorithms and the quality of solutions. In [17], Zhang et al. have studied this, analyzed the diversity of population by using GA and described the diversity of population with population variance and entropy. They also have pointed out that with the evolution of GA, improper operation of selection will cause the decrease of variance and entropy, lead to the decrease of population diversity and the premature phenomenon will appear. The dynamic selection mechanism proposed in this paper can avoid this phenomenon effectively.

The fundamental difference between NGA and SGA is the selection mechanism. In SGA, individuals that are more adaptable are selected to be the members of the new generation. This may easily lead to the problem that individuals from the same population are largely reproduced, which may further result in the problem of inbreeding and prematurity.

In Niche-GA, individuals with larger niches are chosen as the members of the next generation, and tactics of reserving the largest niche are employed. Hence, tactics of population selection based on the size of niche of individuals actually reflect the expansion of niche of each individual, namely, simulate the principle of natural competition to implement the evolution process of selecting the superior and eliminating the inferior, and make the individuals with a bigger influence on environment left and increase quickly. A bigger niche shows not only the higher adaptability of the individual, but also the development trend of adaptability of the individual. In other words, the tactics describe the development of the quantity and change rate of individuals' adaptability synthetically. Therefore, compared to SGA, NGA accords more with the natural selection law.

3.2.2. Comparison of schema theorem

Schema theorem of SGA:

$$m(H, t+1) = m(H, t) \cdot \frac{f(H)}{\bar{f}} \cdot \left[1 - p_c \cdot \frac{\delta(H)}{l-1} - o(H) \cdot p_m\right], \tag{2}$$

where

$m(H, t)$: quantity of samples with the H schema in the populations of t generation,

$f(H)$: Average fitness of populations with H schema in the t generation,

$\bar{f} = \frac{f(t)}{m}$: Average fitness of populations in the t generation, where $f(t) = \sum_i f_i$ is the sum of fitness of current populations.

In SGA, f_i is the fitness of individuals, which is designed in the solution process based on the problem at hand.

Schema theorem of Niche-GA

$$m(H, t+1) = m(H, t) \cdot \frac{f(H)}{\bar{f}} \cdot \left[1 - p_c \cdot \frac{\delta(H)}{l-1} - o(H) \cdot p_m\right]$$

$$= m(H, t) \cdot \frac{f(H) \cdot m(s_i + A_i p_i)}{\sum_{k=1}^{n} (s_k + A_k p_k)} \left[1 - p_c \cdot \frac{\delta(H)}{l-1} - o(H) \cdot p_m\right]. \tag{3}$$

In Niche-GA, the individual fitness is defined as below:

$$f_i = \frac{s_i + A_i p_i}{\sum_{k=1}^{n} (s_k + A_k p_k)}.$$

In SGA, the individual fitness f_i is corresponding to the above s_i, however, in Niche-GA, the change rate p_i of the fitness of i individual is added to the fitness of individuals and the transition coefficient A_i is used for adjustment so that the evolution process can proceed in balance.

3.2.3. Analysis of convergence of Niche-GA

Schema theorem has qualitatively estimated the growth law in the evolution process of schema with more excellent structure, but failed to present the convergence probability of GA to the best solution. According to the theory of Markov chain, in [13], Zhou and Sun have proved that SGA converges to the best solution with the probability less than one. At the same time, they have also proved that GA, utilizing the tactics of reserving the fittest individuals, converges to the best solution with the probability one. The selection mechanism of Niche-GA in this paper is to reserve fittest individuals, so we have the following conclusions.

Theorem. *GAs based on the selection mechanism of Niche-GA can always converge to the global optimum with probability one.*

Proof. Assume that $P^+(t) = (A(t), P(t))$, where $A(t)$ denotes the individual in the current population with the largest niche $N_i(t)$, and that after the successive function of selection, crossover and mutation operators, the population is transformed from one certain state $i \in I$ into the state $j \in I$. Suppose that the probabilities of the above three operators are s_{ij}, c_{ij}, m_{ij} respectively, and that the corresponding matrices are: $S = \{s_{ij}\}$, $C = \{c_{ij}\}$, $M = \{m_{ij}\}$ respectively, then we can obtain the transition matrix of population: $R = \{r_{ij}\}$,

$$A(t+1) = \max\{A(t), N_0\},$$

where N_0 is the individual with the largest niche $N_i(t)$ in the population $A(t+1)$. Hence, $\{P^+(t), t \geq 0\}$ is still a Markov chain, and we have $P^+(t) = P^+(0)(R^+)^t$.

Suppose the state comprising the optimal solution in the state set of individuals is I_0, and then the probability of state transition is

$$r_{ij}^+ > 0 \quad (\forall\, i \in I, \forall\, j \in I_0),$$

$$r_{ij}^+ = 0 \quad (\forall\, i \in I, \forall\, j \notin I_0).$$

That is, the state transition probability from arbitrary state to the state comprising the optimal solution is positive, while the state transition probability from the state of containing the optimal solution to the state of non-containing the optimal equals zero.

Hence, for $\forall\, i \in I, \forall\, j \notin I_0$, we have

$$(r^+)_{ij}^t \to 0, \quad (t \to \infty),$$

$$P_j^+(\infty) = 0, \quad (j \notin I_0).$$

Therefore, the algorithm can always find the best solution with probability one.

3.2.4. Analysis of the fitness function

In SGA, the operation of selecting the superior and eliminating the inferior is implemented mainly according to the adaptability of individuals. It is proved that in application the general fitness function does not work well, for example, in the minimum problem, the objective function $f(X)$ is transformed to the fitness function $F(X)$ in the search space with the following formula:

$$F(X) = \begin{cases} C_{\max} - f(X), & \text{if } X < C_{\max} \\ 0, & \text{if } X \geq C_{\max} \end{cases}$$

and sometimes the $F(X)$ converges faster, and sometimes slower. Therefore, the transition of fitness scaling is often needed based on the problem at hand.

In Niche-GA, the fitness function is defined as the size of the niche of individuals, that is,

$$F(X) = N_i(t) = \frac{s_i + A_i p_i}{\sum_{k=1}^{n} (s_k + A_k p_k)}.$$

Hence, this method is applicable to any kinds of problems and there is no need making the transition of fitness scaling.

4. Examples and Simulations

Example 1. In this example, two functions are chosen as the test functions:

$$f_1 = 0.5 + \frac{\sin\sqrt{x_1^2 + x_2^2} - 0.5}{[1.0 + 0.001(x_1^2 + x_2^2)]^2}, \quad -100 \le x_1,\, x_2 \le 100;$$

$$f_2 = x_1^2 + 2x_2^2 - 0.3\cos(3\pi x_1) - 0.4\cos(4\pi x_2) + 0.7, \quad -4 \le x_1,\, x_2 \le 4,$$

where f_1 is a multi-model function with a big change rate, and its size is symmetrical to the origin, furthermore, the closer it is to the origin, the faster it changes. f_2 is a function with a small change rate, so the general gradient descent method does not work well for it.

In the computation, we use Matlab for programming. Given the initial population, we create the "costae" sequence and the "escarole" sequence based on the Niche-GA, calculate the niche N_i of each individual, arrange them according to the size of their niche, choose the individuals with a larger niche as the members of sub-generation, and employ the strategy of reserving the individuals with the largest niche. For f_1, we choose the size of the initial population as $N = 120$, the crossover probability as 0.9, and the mutation probability as 0.0025; for f_2, we choose the size of the initial population $N = 120$, the crossover probability as 0.860, and the mutation probability as 0.0014. The calculation results are depicted in Figure 1. They show the superiority of improved Niche-GA over classical GA in terms of faster convergence and higher precision.

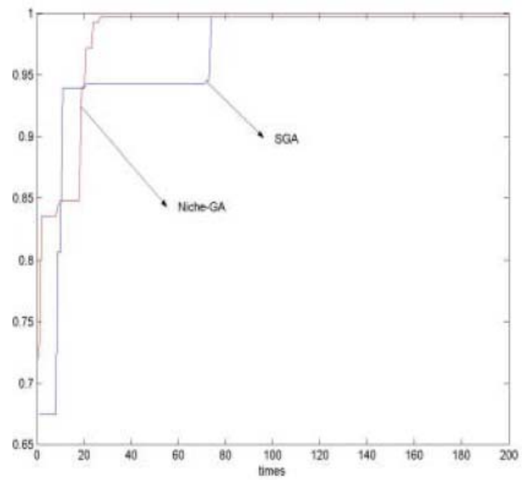

Figure 1a. The simulate curve of the optimized computation of function f_1

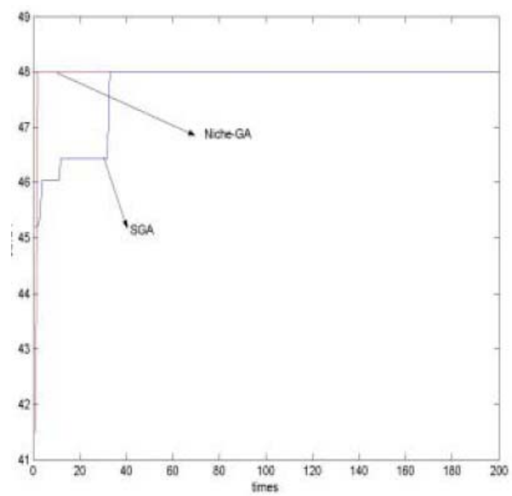

Figure 1b. The simulate curve of the optimized computation of function f_2

Example 2. Optimization of fuzzy T-S systems.

In this example, in order to verify the effectiveness of the algorithm in the optimization design of fuzzy T-S systems, we apply the Niche-GA algorithm to optimize and control a nonlinear process. The model we are going to study is as follows:

$$y(k) = 0.8y(k-1) - 0.6y(k-2) + 0.4x(k-1) + 0.2x(k-2),$$

$$x(k-1) = u(k-1) + 0.3u^2(k-1).$$

Fuzzy T-S systems with the following fuzzy rules:

$$R^i: \text{ If } x_1 \text{ is } X_1^i \text{ and } x_n \text{ is } X_n^i, \text{ then } y_i = a_1^i x_1 + a_2^i x_2 + \cdots + a_n^i x_n;$$

where R^i denotes the i-th fuzzy rule, X_p^i denotes the fuzzy set of the i-th fuzzy rule, and x_i, y_j are the input variable and the output variable of the i-th rule respectively, for $i = 1, 2, \ldots, m$. Using the "center of gravity" defuzzification method, we can obtain the output of the fuzzy system:

$$f(x) = \frac{\sum_{j=1}^{m} y_j \cdot \left(\prod_{i=1}^{n} \mu_{X_i}^{j}(x_i) \right)}{\sum_{j=1}^{m} \prod_{i=1}^{n} \mu_{X_i}^{j}(x_i)}.$$

Choosing the Gauss-type membership function: $\mu_{X_i}^{j}(x_i) = \exp\left(-\left(\frac{x_i - x_i^j}{\delta_i^j} \right)^2 \right)$ to be the membership function of the fuzzy logic system, we can obtain the fuzzy logic system with the following form:

$$f(x) = \frac{\sum_{j=1}^{m} y_j \cdot \exp\left(-\left(\frac{x_i - x_i^j}{\delta_i^j} \right)^2 \right)}{\sum_{j=1}^{m} \prod_{i=1}^{n} \exp\left(-\left(\frac{x_i - x_i^j}{\delta_i^j} \right)^2 \right)}, \quad (i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m). \tag{4}$$

The above (4) can be written as:

$$f(x) = \theta^T \xi(x), \tag{5}$$

where $\theta = (y_1, \ldots, y_m)^T$ is the parameter vector, and $\xi(x) = (\xi^1(x), \xi^2(x),$

..., $\xi^m(x))^T$ is the vector of fuzzy basis functions defined as follows:

$$\xi^j(x) = \frac{\prod_{i=1}^{n} \mu_{X_i}^j(x_i)}{\sum_{j=1}^{m} \prod_{i=1}^{n} \mu_{X_i}^j(x_i)}, \quad j = 1, 2, \ldots, m. \tag{6}$$

There are a total of two input variables to the T-S fuzzy controller that take on the following values: {NM, NS, ZERO, PS, PM}, in order to construct the T-S fuzzy system with 25 rules, we have to design the following parameters: the 20 input parameters of the fuzzy set, the total 50 parameters of the consequent rules. We use the proposed Niche-GA method to optimize the antecedence and consequent parameters of the T-S fuzzy system's rules.

Let the tracking function $u(k) = \sin(2\pi k/25)$. Then the tracking function and the tracking error are depicted in Figure 2 and Figure 3 respectively, by constructing the optimal fuzzy system.

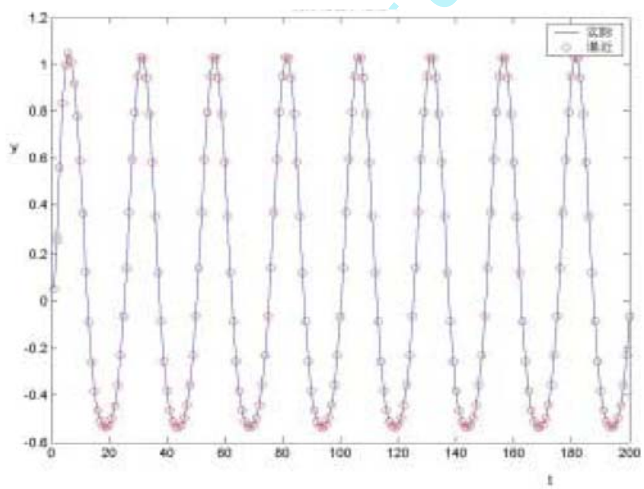

Figure 2. The track function $u(k) = \sin(2\pi k/25)$ of the fuzzy system

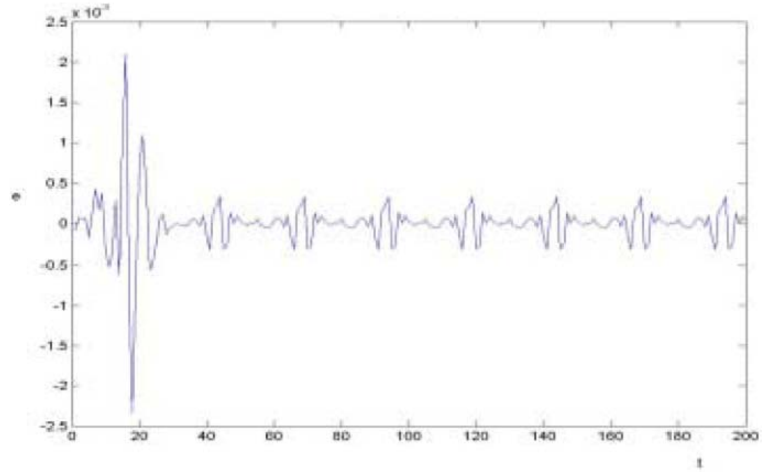

Figure 3. The tracking error of the fuzzy system

5. Conclusions

The "costae escarole" theory of niche has described the evolution process synthetically, and disclosed the competition among individual organisms and the inherent mechanism of the variety and development of organism diversity. The trend of variety and development of individual organism is the decisive factor of the extension of niche. Niche-GA is the selection mechanism using the extension of niche to improve the performance of GA, which reserves the individuals having a bigger influence on the environment by selecting the individuals with a bigger niche to be the members of sub generation based on the mechanics of natural selection, hence, it is a dynamic reform method and different from the past reform methods. The most significant advantage of this method is that it is not a static reform method, but a dynamic reform method. The simulation results show that Niche-GA works better for the numerical computation and the optimization of control parameters, and that the algorithm has a stronger stability and a better convergence.

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