

Particle swarm and ant colony algorithms hybridized for improved continuous optimization

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Abstract

This paper proposes PSACO (particle swarm ant colony optimization) algorithm for highly non-convex optimization problems. Both particle swarm optimization (PSO) and ant colony optimization (ACO) are co-operative, population-based global search swarm intelligence metaheuristics. PSO is inspired by social behavior of bird flocking or fish schooling, while ACO imitates foraging behavior of real life ants. In this study, we explore a simple pheromone-guided mechanism to improve the performance of PSO method for optimization of multimodal continuous functions. The proposed PSACO algorithm is tested on several benchmark functions from the usual literature. Numerical results comparisons with different metaheuristics demonstrate the effectiveness and efficiency of the proposed PSACO method.

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Keywords: Particle swarm optimization; Ant colony; Metaheuristics; Global optimization; Multimodal continuous functions

1. Introduction

Swarm intelligence metaheuristics, namely, particle swarm optimization (PSO) and ant colony optimization (ACO) are recently proved to be successful approaches to solve complex optimization problems. PSO algorithm, whose concept began as a simulation of a simplified social milieu, is a powerful optimization technique for solving multimodal continuous optimization problems [1–3]. While ACO approaches that imitate foraging behavior of real life ants, are known to be efficient and robust for solution of combinatorial optimization problems [4–7]. In this study, one of the ways of integrating the concepts of these two swarm intelligence metaheuristics for solution of multimodal continuous problems is explored.

Consider the following continuous global optimization problem as

$$(F) = \begin{cases} \min f(x) \\ \text{s.t. } S \subset \mathfrak{R}^n, \end{cases} \quad (1)$$

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where $f(x)$ is a highly non-convex function, which will in general have several local minima. In this study, we consider only minimization of problem (F), without loss of generality, for maximization, $\max f(x) = -\min[-f(x)]$. x is a real valued vector in a bounded space $S = \{x \in \mathfrak{R}^n, a_j \leq x_j \leq b_j; j = 1, \dots, n\} \subset \mathfrak{R}^n$. For solution of problem (F) in Eq. (1), until now there exist few hybrid implementations of PSO algorithm with other local search methods. The first hybrid algorithm is called, NM-PSO [8] (Nelder–Mead–particle swarm optimization), which comprises NM method at the top level, and PSO at the lower level. In NM-PSO method $3n + 1$ particles are initially randomly generated, where, n is the size of solution vector. ‘Best’ $n + 1$ solutions of total solutions are sent as initial points to NM method and remaining (worst) $2n$ solutions to PSO method to generate a total of $3n + 1$ new solutions. Global best particle is selected from $3n + 1$ particles and neighborhood best particles by evenly dividing the $2n$ particles into n neighborhoods according to objective function value and velocity update is applied on the $2n$ particles. CPSO [9] (chaotic particle swarm optimization) algorithm applies PSO to perform global exploration and chaotic local search to perform local search on the solutions produced in the global exploration process.

This paper proposes improved particle swarm optimization hybridized with an ant colony approach, called PSACO (particle swarm ant colony optimization), for optimization of multimodal continuous functions. The proposed method applies PSO for global optimization and the idea of ant colony approach to update positions of particles to attain rapidly the feasible solution space. The implementation of PSACO algorithm consists of two stages. In the first stage, it applies PSO, while ACO is implemented in the second stage. ACO works as a local search, wherein, ants apply pheromone-guided mechanism to update the positions found by the particles in the earlier stage. The implementation of ACO in the second stage of PSACO is based on the studies by Angeline [10] which showed that (1) PSO discovers reasonable quality solutions much faster than other evolutionary algorithms, and (2) if the swarm is going to be in equilibrium, the evolution process will be stagnated as time goes on. Thus, PSO does not possess the ability to improve upon the quality of the solutions as the number of generations is increased. The proposed PSACO method is tested on several widely used benchmark multimodal continuous functions. Numerical results are compared with the some other hybrid PSO methods and non-PSO methods available in the usual literature. The performance study demonstrates the effectiveness and efficiency of the proposed PSACO approach.

The remaining content of this paper is organized as follows: In Section 2, particle swarm optimization algorithm and the concept of ant colony method are briefly explained before delineating the proposed PSACO algorithm. The computational results are discussed in Section 3 and conclusions and directions of future work are given in Section 4. In Appendix A, several widely used test functions are given. They are applied in this paper to study the performance of the proposed PSACO method.

2. Improved particle swarm optimization

To make the paper self-explanatory, before actually proposing the improved particle swarm optimization using ant colony approach, the characteristics of particle swarm optimization algorithm and the principle of an ant colony approach are briefly explained in the following two sections as:

2.1. Particle swarm optimization (PSO)

PSO is a population-based, co-operative search metaheuristic introduced by Kennedy and Eberhart [11]. In PSO, candidate solutions of a population, called particles, coexist and evolve simultaneously based on knowledge sharing with neighboring particles. While flying through the problem search space, each particle generates a solution using directed velocity vector. Each particle modifies its velocity to find a better solution (position) by applying its own flying experience (i.e. memory having best position found in the earlier flights) and experience of neighboring particles (i.e. best-found solution of the population). Particles update their positions and velocities as shown below:

$$v_{t+1}^i = w_t v_t^i + c_1 r_1 (p_t^i - x_t^i) + c_2 r_2 (p_t^g - x_t^i), \quad (2)$$

$$x_{t+1}^i = x_t^i + v_{t+1}^i, \quad (3)$$

where x_t^i represents the current position of particle i in solution space and subscript t indicates an iteration count; p_t^i is the best-found position of particle i up to iteration count t and represents the cognitive contribution to the search velocity v_t^i . Each component of v_t^i can be clamped to the range $[-v_{\max}, v_{\max}]$ to control excessive roaming of particles outside the search space; p_t^g is the global best-found position among all particles in the swarm up to iteration count t and forms the social contribution to the velocity vector; r_1 and r_2 are random numbers uniformly distributed in the interval $(0, 1)$, while c_1 and c_2 are the cognitive and social scaling parameters, respectively; w_t is the particle inertia, which is reduced dynamically to decrease the search area in a gradual fashion [12]. The variable w_t is updated as

$$w_t = (w_{\max} - w_{\min}) * \frac{(t_{\max} - t)}{t_{\max}} + w_{\min}, \quad (4)$$

where, w_{\max} and w_{\min} denote the maximum and minimum of w_t respectively; t_{\max} is a given number of maximum iterations. Particle i flies toward a new position according to Eqs. (2) and (3). In this way, all particles P of the swarm find their new positions and apply these new positions to update their individual best p_t^i points and global best p_t^g of the swarm. This process is repeated until iteration count $t = t_{\max}$ (a user-defined stopping criterion is reached). The pseudo-code of PSO is given in Fig. 1, where, P denotes the number of particles in the population; $f(x_t^i)$ represents the objective function value of particle i at position x , while $f_t^{\text{best}}(x_t^{\text{best}})$ represents the best function value in the population of solutions P at iteration count t .

step 1. Initialize Optimization.

step 1.1 Initialize algorithm constants, t_{\max} , P .

step 1.2 Initialize randomly all particles positions x_t^i and velocities v_t^i .

step 1.3 Evaluate objective function value as $f(x_t^i)$ in equation (1).

step 1.4 Assign best positions $p_t^i = x_t^i$ with $f(p_t^i) = f(x_t^i)$, $i = 1, \dots, P$.

step 1.5 Find $f_t^{\text{best}}(p_t^{\text{best}}) = \min\{f(p_t^1), \dots, f(p_t^i), \dots, f(p_t^P)\}$ and initialize $p_t^g = p_t^{\text{best}}$ and $f(p_t^g) = f_t^{\text{best}}(p_t^{\text{best}})$.

step 2. Perform Optimization

while ($t \leq t_{\max}$)

step 2.1 Update particle velocity v_t^i and position x_t^i , according to equation (2) and equation (3) of all P particles.

step 2.2 Evaluate objective function value as $f(x_t^i)$ in equation (1).

step 2.3 Update particle best position if $f(p_t^i) > f(x_t^i)$ then $p_t^i = x_t^i$ with $f(p_t^i) = f(x_t^i)$.

step 2.4 Find $f_t^{\text{best}}(p_t^{\text{best}}) = \min\{f(p_t^1), \dots, f(p_t^i), \dots, f(p_t^P)\}$; if $f(p_t^g) > f_t^{\text{best}}(p_t^{\text{best}})$ then $p_t^g = p_t^{\text{best}}$ and $f(p_t^g) = f_t^{\text{best}}(p_t^{\text{best}})$.

step 2.5 Increment iteration count $t = t + 1$.

end while

step 3. Report best solution p^g of the swarm with objective function value $f(p^g)$.

Fig. 1. Pseudo-code for PSO algorithm.

2.2. Ant colony optimization (ACO)

ACO is a multiagent approach that simulates the foraging behavior of ants for solving difficult combinatorial optimization problems, such as, the traveling salesman problem and the quadratic assignment problem [5]. Ants are social insects whose behavior is directed more toward the survival of the colony as a whole than that of a single individual of the colony. An important and interesting behavior of an ant colony is its indirect co-operative foraging process. While walking from food sources to the nest and vice versa, ants deposit a substance, called pheromone on the ground and form a pheromone trail. Ants can smell pheromone, when choosing their way, they tend to choose, with high probability, paths marked by strong pheromone concentrations (shorter paths). Also, other ants can use pheromone to find the locations of food sources found by their nest mates. In fact, ACO simulates the optimization of ant foraging behavior. Recently, there are few adaptations of ACO for solution of continuous optimization problems [13,14]. In this work, a simple pheromone-guided search mechanism of ant colony is implemented which acts locally to synchronize positions of the particles of PSO to quickly attain the feasible domain of objective function.

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step 1. Initialize Optimization.

    step 1.1 Initialize constants for PSO and ACO processes,  $P, t_{\max}$ .

    step 1.2 Initialize randomly all particles positions  $x_t^i$  and velocities  $v_t^i$ .

    step 1.3 Evaluate objective function value as  $f(x_t^i)$  in equation (1).

    step 1.4 Assign best positions  $p_t^i = x_t^i$  with  $f(p_t^i) = f(x_t^i)$ ,  $i = 1, \dots, P$ .

    step 1.5 Find  $f_t^{best}(p_t^{best}) = \min\{f(p_t^1), \dots, f(p_t^i), \dots, f(p_t^P)\}$  and initialize  $p_t^g = p_t^{best}$ 
        and  $f(p_t^g) = f_t^{best}(p_t^{best})$ .

step 2. Perform Optimization

    while ( $t \leq t_{\max}$ )

        step 2.1 Update particle velocity  $v_t^i$  and position  $x_t^i$ , according to equation (2)
            and equation (3) of all  $P$  particles.

        step 2.2 Evaluate objective function value as  $f(x_t^i)$  in equation (1).

        step 2.3 Generate  $P$  solutions  $z_t^i$  using equation (5).

        step 2.4 Evaluate objective function value as  $f(z_t^i)$  in equation (1) and if
             $f(z_t^i) < f(x_t^i)$  then  $f(x_t^i) = f(z_t^i)$  and  $x_t^i = z_t^i$ .

        step 2.5 Update particle best position if  $f(p_t^i) > f(x_t^i)$  then  $f(p_t^i) = f(x_t^i)$  and
             $p_t^i = x_t^i$ .

        step 2.6 Find  $f_t^{best}(p_t^{best}) = \min\{f(p_t^1), \dots, f(p_t^i), \dots, f(p_t^P)\}$ ; if  $f(p_t^g) > f(p_t^{best})$  then
             $f(p_t^g) = f_t^{best}(p_t^{best})$  and  $p_t^g = p_t^{best}$ .

        step 2.7 Increment iteration count  $t = t + 1$ ;

    end while

step 3. Report best solution  $p^g$  of the swarm with objective function value  $f(p^g)$ .

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Fig. 2. Pseudo-code for PSACO algorithm.

2.3. Hybridization of particle swarm optimization with an ant colony approach

This section describes the implementation of proposed improvement in particle swarm optimization using an ant colony approach. The proposed method, called, PSACO (particle swarm ant colony optimization) is based on the common characteristics of both PSO and ACO algorithms, like, survival as a swarm (colony) by coexistence and cooperation, individual contribution to food searching by a particle (an ant) by sharing information locally and globally in the swarm (colony) between particles (ants), etc. The implementation of PSACO algorithm consists of two stages. In the first stage, it applies PSO, while ACO is implemented in the second stage. ACO works as a local search, wherein, ants apply pheromone-guided mechanism to refine the positions found by particles in the PSO stage. In PSACO, a simple pheromone-guided mechanism of ACO is proposed to apply as local search. The proposed ACO algorithm handles P ants equal to the number of particles in PSO. Each ant i generates a solution z_i^t around p_i^g the global best-found position among all particles in the swarm up to iteration count t as

$$z_i^t = \mathcal{N}(p_i^g, \sigma). \quad (5)$$

In Eq. (5), we generate components of solution vector z_i^t , which satisfy Gaussian distributions with mean p_i^g and standard deviation σ , where, initially at $t = 1$ value of $\sigma = 1$ and is updated at the end of each iteration as $\sigma = \sigma \times d$, where, d is a parameter in $(0.25, 0.997)$ and if $\sigma < \sigma_{\min}$ then $\sigma = \sigma_{\min}$, where, σ_{\min} is a parameter in $(10^{-2}, 10^{-4})$. Compute objective function value $f(z_i^t)$ using z_i^t and replace position x_i^t the current position of particle i in the swarm if $f(z_i^t) < f(x_i^t)$ as $x_i^t = z_i^t$ and $f(x_i^t) = f(z_i^t)$. This simple pheromone-guided mechanism considers, there is highest density of trails (single pheromone spot) at the global best solution p_i^g of the swarm at any iteration $t + 1$ in each stage of ACO implementation and all ants P search for better solutions in the neighborhood of the global best solution. In the beginning of the search process, ants explore larger search area in the neighborhood of p_i^g due to the high value of standard deviation σ and intensify the search around p_i^g as the algorithm progresses. Thus, ACO helps PSO process not only to efficiently perform global exploration for rapidly attaining the feasible solution space but also to effectively reach optimal or near optimal solution.

The pseudo-code of PSACO method is given in Fig. 2. The algorithm starts with initializing parameters of both PSO and ACO methods. The first stage consists of PSO, which generates P solutions using Eqs. (2) and (3). Objective function values are computed as $f(x_i^t)$. ACO is applied in the second stage to update the positions of particles in the swarm. This process is repeated until iteration count $t = t_{\max}$.

3. Results and discussion

The performance of the proposed PSACO algorithm for global optimization of continuous function is tested on several well-known benchmark multimodal problems. They are listed in Appendix A. All the test functions are multimodal in nature. Because of the characteristics, it is difficult to seek for the global minima. PSACO algorithm parameter settings used in all the simulations is given as: number of particles, $P = 10$; cognitive and social scaling parameters, $c_1 = 2$, $c_2 = 2$; maximum and minimum values of inertia weights, $w_{\max} = 0.7$, $w_{\min} = 0.4$; maximum number of iterations, $t_{\max} = 100 * n$, n is the size of solution vector. To gauge the performance of the proposed PSACO method with the performance of some other existing hybrid PSO methods and non-PSO methods, several sets of experiments are carried out and results are given in Tables 1–6. Table 7 lists different global optimization methods used for performance analysis. The details of experiments conducted are given below.

3.1. Results with fixed number of iterations

To compare the performance of PSACO with the performance of CPSO [9] (chaotic particle swarm optimization), Table 1 reports the results produced by PSACO after 2000 function evaluations in terms of mean value of objective function over 50 independent runs. The performance of CPSO, PSO and GA algorithms reported in [9] is also shown in Table 1. From Table 1, it can be observed that the results obtained by both

Table 1
Fixed iteration experiments results with PSACO algorithm

Function	Average objective function value			
	PSACO	CPSO	PSO	GA
<i>GP</i>	3.0000	3.0000	4.6202	3.1471
<i>BR</i>	0.3979	0.3979	0.4960	0.4021
<i>HR</i> _{3,4}	−3.8628	−3.8610	−3.8572	−3.8571
<i>HR</i> _{6,4}	−3.3198	−3.1953	−2.8943	−3.0212
<i>RA</i> ₂	−1.9999	−1.9940	−1.9702	−1.9645
<i>SH</i>	−186.7309	−186.7274	−180.3265	−182.1840

Table 2
Results of robustness analysis for PSACO algorithm

Function	PSACO		CPSO		PSO		GA	
	SR	AVEN	SR	AVEN	SR	AVEN	SR	AVEN
<i>GP</i>	100	157	100	192	98	1397	98	536
<i>BR</i>	100	156	100	154	94	743	92	1682
<i>HR</i> _{3,4}	100	159	90	119	96	183	16	112
<i>HR</i> _{6,4}	98	263	96	2551	26	3796	94	5727
<i>RA</i> ₂	100	112	98	653	100	1160	84	238
<i>SH</i>	100	307	100	360	98	1337	98	1516
Overall	99	192	97	672	85	1436	80	1635

Table 3
Performance of PSACO and NM-PSO on 17 test functions

Function	Required accuracy	% Success rate		Average number of function evaluations		Average error	
		PSACO	NM-PSO	PSACO	NM-PSO	PSACO	NM-PSO
<i>BR</i>	1e−3	100	100	209	151	2.6185e−13	0.00003
<i>ES</i>	1e−3	100	100	254	165	0.0000000	0.00004
<i>GP</i>	1e−3	100	100	240	217	0.0000000	0.00003
<i>B2</i>	1e−2	100	100	370	240	5.5511e−17	0.00003
<i>SH</i>	1e−2	100	100	534	400	1.0239e−09	0.00002
<i>RS</i> ₂	1e−3	100	100	327	339	1.7152e−10	0.00003
<i>ZA</i> ₂	1e−4	100	100	167	135	5.7061e−27	0.00003
<i>DJ</i>	1e−4	100	100	190	291	7.6900e−29	0.00005
<i>H</i> _{3,4}	1e−4	100	100	592	271	2.0755e−11	0.00024
<i>S</i> _{4,5}	1e−4	100	100	482	1177	5.8229e−11	0.00020
<i>S</i> _{4,7}	1e−4	100	100	483	1130	1.8134e−10	0.00017
<i>S</i> _{4,10}	1e−4	100	100	489	1179	3.0795e−10	0.00015
<i>RS</i> ₅	1e−2	100	100	517	3308	1.8538e−04	0.00560
<i>ZA</i> ₅	1e−4	100	100	516	1394	3.6352e−17	0.00026
<i>H</i> _{6,4}	1e−3	96	100	529	1541	4.4789e−11	0.00250
<i>GR</i> ₈	1e−3	87	100	1081	1354	6.2311e−22	0.00041
<i>GR</i> ₁₀	1e−3	86	100	1634	2024	1.2197e−15	0.00058

Table 4
Summary of results reported in Table 3

Dimension	% Success rate		Average number of function evaluations		Average error	
	PSACO	NM-PSO	PSACO	NM-PSO	PSACO	NM-PSO
$n < 4$	100	100	286	245	1.4946e−10	0.00006
$n \geq 4$	97	100	703	1638	2.0598e−05	0.00123
overall	99	100	495	901	1.0299e−05	0.00061

Table 5
Summary of results reported in Table 3

Function	Required accuracy	% Success rate			Average number of function evaluations			Average error		
		PSACO	CTSS	CHA	PSACO	CTSS	CHA	PSACO	CTSS	CHA
<i>BR</i>	1e−3	100	100	100	209	125	295	2.6185e−13	0.005	0.0001
<i>ES</i>	1e−3	100	100	100	254	325	952	0.0000000	0.005	0.001
<i>GP</i>	1e−3	100	100	100	240	119	259	0.0000000	0.001	0.001
<i>B2</i>	1e−2	100	100	100	370	98	132	5.5511e−17	5e−6	2e−7
<i>SH</i>	1e−2	100	100	100	534	283	345	1.0239e−09	0.001	0.005
<i>RS₂</i>	1e−3	100	100	100	327	369	459	1.7152e−10	0.004	0.004
<i>ZA₂</i>	1e−4	100	100	100	167	78	215	5.7061e−27	3e−7	3e−6
<i>DJ</i>	1e−4	100	100	100	190	155	371	7.6900e−29	0.0002	0.0002
<i>H_{3,4}</i>	1e−4	100	100	100	592	225	492	2.0755e−11	0.005	0.005
<i>S_{4,5}</i>	1e−4	100	75	85	482	538	598	5.8229e−11	0.007	0.007
<i>S_{4,7}</i>	1e−4	100	77	83	483	590	620	1.8134e−10	0.001	0.01
<i>S_{4,10}</i>	1e−4	100	74	81	489	555	635	3.0795e−10	0.001	0.015
Overall	2e−3	100	94	96	361	288	448	1.4700e−10	0.0025	0.004

PSACO and CPSO are much closer to the theoretical optima, and the proposed PSACO method is superior to all the methods in terms of the searching quality and derivation of results.

3.2. Robustness analysis of the proposed PSACO

Table 2 shows the robustness analysis results for the proposed PSACO. For comparison with CPSO [9], this paper has adopted two robustness measures, called, succeed ratio (SR) and average valid evaluation number (AVEN) given as follows:

$$SR = \frac{100N_s}{50}, \quad (6)$$

$$AVEN = \frac{\sum_{i=1}^{N_s} N_i}{N_s}, \quad (7)$$

where N_s is the total number of success runs from 50 independent runs. N_i is the function evaluation number of the i th success run. In case a solution obtained has the objective function value within 3.5% of its global optimum then it is called a success run and its function evaluation number is stored. Table 2 lists the SR and AVEN values produced by PSACO algorithm. For comparison purpose, Table 2 also shows the SR and AVEN values for CPSO, PSO and GA methods reported in [9]. From Table 2 it can be seen that PSACO can find global optima with very high probability for every function even with small function evaluation number. Besides, for those valid runs, it costs the least average function evaluation number. Thus, indirect co-operative search of ant colony approach has helped PSO to improve its effectiveness and reliability for complex numerical optimization.

3.3. Performance comparison of PSACO with NM-PSO

The results presented in Tables 3 and 4 are based on 100 independent runs of the proposed PSACO method on each of 17 test functions. All the test examples are multimodal functions and are given in Appendix A. In order to have comparable results, the accuracy was chosen based on the results of NM-PSO algorithm reported in [8]. Results reported in Table 3 are in terms of, the rate of successful minimizations, the average of the objective function evaluation numbers, and the average error. The average of the objective function evaluation numbers is evaluated in relation to only the ‘successful minimizations.’ The mean error is defined as the average of the difference between the best successful point found and the known global optimum, where only the ‘successful minimizations’ achieved by the algorithm are considered. The term ‘successful minimizations’ is the number of successful runs. In the successful runs the algorithm generates the best solution of

Table 6
Comparison of results of PSACO and non-PSO methods on 10–100 dimension functions

Function	Required accuracy	% Success rate					Average number of function evaluations					Average error				
		PSACO	NHGA	CHA	CGA	ECTS	PSACO	NHGA	CHA	CGA	ECTS	PSACO	NHGA	CHA	CGA	ECTS
RS_{10}	1e–2	95	100	83	80	85	1541	6257	14563	21563	15720	4e–04	3e–03	8e–3	0.02	0.02
RS_{50}	1e–2	88	100	79	78	75	10433	44706	55356	78356	63210	3e–03	4e–03	5e–3	0.05	0.02
RS_{100}	1e–2	86	100	72	66	75	24236	87582	124302	194302	162532	4e–03	4e–03	8e–3	0.07	0.05
ZA_{10}	1e–3	100	100	100	100	100	2299	10734	4291	6991	4630	2e–08	1e–6	1e–6	1e–6	2e–7
ZA_{50}	1e–3	100	100	100	100	100	47288	84327	75520	75201	63970	4e–06	1e–5	1e–5	1e–5	2e–7
ZA_{100}	1e–3	100	100	100	100	100	145648	141430	95246	195246	152030	4e–05	1e–3	1e–3	1e–3	1e–3

Table 7
Global optimization methods used for performance analysis

Method	Reference
Particle swarm ant colony optimization (PSACO)	This paper
Chaotic particle swarm optimization (CPSO)	[9]
Particle swarm optimization (PSO)	[9]
Genetic algorithm (GA)	[9]
Nelder–Mead–particle swarm optimization (NM-PSO)	[8]
Continuous hybrid algorithm (CHA)	[15]
Continuous tabu simplex search (CTSS)	[16]
Niche hybrid GA (NHGA)	[18]
Continuous GA (CGA)	[19]
Enhanced continuous tabu search (ECTS)	[20]

‘required accuracy’, where, ‘required accuracy’ is a given maximum value to consider that the algorithm has successfully found the solution. It is calculated as the absolute difference in the best solution found and the global optimum. The results obtained by NM-PSO method are also given in Table 3. Results reported in Table 3 show that NM-PSO method seems to converge more quickly in cases of lower dimensions ($n < 4$), and in cases of higher dimensions ($n \geq 4$) the proposed PSACO converges more effectively to the global optimum than the NM-PSO method. In order to gain a better knowledge of how PSACO algorithm performs under different problem sizes, a summary report of the three algorithms based on the results shown in Table 3 is tabulated in Table 4. The problems are further divided into two groups $n < 4$ and $n \geq 4$ based on their sizes. As shown in Table 4, for larger dimensions, PSACO algorithm presents better saving of function evaluations over NM-PSO algorithm. Regarding the average error, PSACO method finds solutions with higher accuracy than NM-PSO algorithm in both categories.

3.4. Additional comparison with non-PSO hybrid methods

The performance of PSACO algorithm has been further compared with two recently published hybrid algorithms, including, CHA [15] (continuous hybrid algorithm) and CTSS [16] (continuous tabu simplex search). The experimental results obtained for 12 test functions are given in Table 5, which reports the average number of function evaluations, the average of the objective function evaluation numbers, and the average error for 100 runs of each function. From Table 5, it can be observed that PSACO obtained solutions with highest average error accuracy of $2e-10$ with 100% performance on all examples. In view of the algorithm efficiency and effectiveness in term of this ‘smaller’ set of test functions, it can be anticipated that PSACO approach remains quite competitive as compared to the other existing methods.

3.5. Experiments to study the effect of high dimension

To investigate the effect of high dimension on searching quality of the proposed PSACO method, Ackley function is chosen for the test whose global minimum is $f(x) = 0$ at $x = 0$. This benchmark example has thousands of minima in the region and is very difficult to be optimized [17]. Liu et al. [9] also used this function to investigate the curse of dimensionality on the CPSO algorithm, which was run 10 times for Ackley function with different dimensions. A total number of function evaluations were set as 4×10^5 . Fig. 3 illustrates the varying curve of the mean objective value obtained by PSACO in 10 independent runs with respect to different dimensions. The PSACO was also run for a maximum of 4×10^5 function evaluations. From Fig. 3, it can be seen that the performance of PSACO algorithm is very good even for high dimension of problem. For comparison purpose, the average objective value reported by PSACO method is close to three units for Ackley function of dimension equal to 1000 while that reported by CPSO, PSO and GA methods in [9] is more than six units. The effect of dimension is also tested on two widely used difficult benchmark examples, viz., Rosenbrock and Zakharov with dimension of 10–100. Table 6 reports the average number of function evaluations, the average of the objective function evaluation numbers, and the average error for 100 runs of each function.

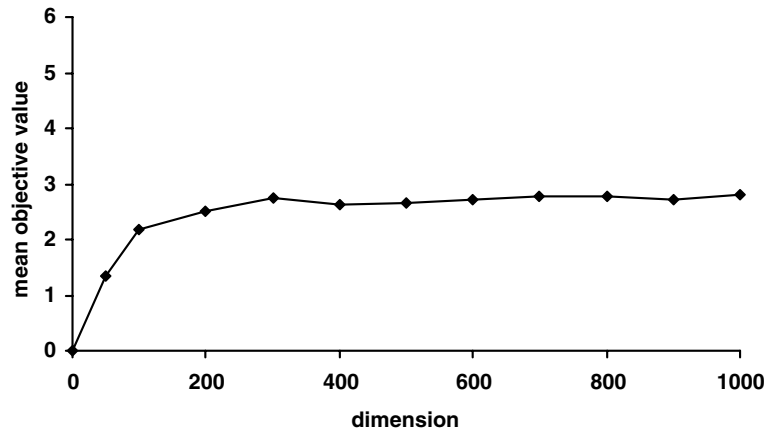


Fig. 3. Performance of PSACO in term of mean objective value for different dimension of Ackley function.

For comparison purpose, the results produced by other methods, CHA [15], NHGA [18] (Niche Hybrid GA), CGA [19] (continuous GA) and ECTS [20] (enhanced continuous tabu search) are also given in Table 6. The results show that PSACO method is a viable alternative to other metaheuristics to solve even moderate to high dimension multimodal functions.

4. Conclusions

This paper has proposed PSACO (particle swarm ant colony optimization) algorithm for solution of highly non-convex problems. A simple pheromone-guided local search is implemented to improve the performance of particle swarm optimization algorithm. The results show that ACO helps PSO process not only to efficiently perform global exploration for rapidly attaining the feasible solution space but also to effectively reach optimal or near optimal solution. The comparisons of numerical results with other hybrid PSO and non-PSO methods show that there is a scope of research in hybridizing swarm intelligence methods to solve difficult continuous optimization problems.

Appendix A

Goldstein–Price (GP) (2 variables)

$$GP(x_1, x_2) = (1 + (x_1 + x_2 + 1)^2(19 - 14(x_1 + x_2) + 3(x_1^2 + x_2^2) + 6x_1x_2)) \\ \times (30 + (2x_1 - 3x_2)^2(18 - 32x_1 + 12x_1^2 + 48x_2 - 36x_1x_2 + 27x_2^2)),$$

- search domain: $-2 \leq x_1, x_2 \leq 2$;
- four local minima;
- global minimum: $(x_1, x_2) = (0, -1)$, $GP(x_1, x_2) = 3$.

Branin (BR) (2 variables)

$$BR(x_1, x_2) = \left(x_2 - \frac{5.1}{4\pi^2}x_1^2 + \frac{5}{\pi}x_1 - 6\right)^2 + 10\left(1 - \frac{1}{8\pi}\right)\cos(x_1) + 10,$$

- search domain: $-5 \leq x_1 \leq 10$, $0 < x_2 < 15$;
- no local minimum;
- three global minima: $(-\pi, 12.275)$, $(\pi, 2.275)$, $(3\pi, 2.475)$;
- $BR(x_1, x_2) = 5/4\pi$.

Rastrigin (RA) (2 variables)

$$RA(x_1, x_2) = x_1^2 + x_2^2 - \cos(18x_1) - \cos(18x_2),$$

- search domain: $-1 \leq x_1, x_2 \leq 1$;
- 50 local minima;
- global minimum: $(x_1, x_2) = (0, 0)$, $RA(x_1, x_2) = -2$.

Shubert (SH) (2 variables)

$$SH(x_1, x_2) = \left(\sum_{i=1}^5 i \cos((i+1)x_1 + i) \right) \left(\sum_{i=1}^5 i \cos((i+1)x_2 + i) \right),$$

- search domain: $-10 \leq x_1, x_2 \leq 10$;
- 760 local minima;
- 18 global minima with $SH(x_1, x_2) = 0$.

Hartman (HR_{3,4}) (3 variables)

$$HR_{3,4} = \sum_{i=1}^4 c_i \exp \left[- \sum_{j=1}^n \alpha_{ij} (x_j - p_{ij})^2 \right],$$

- search domain: $0 \leq x_j \leq 1, j = 1, \dots, 3$;
- four local minima;
- one global minimum: $x = (0.11, 0.555, 0.855)$; $HR_{3,4}(x) = -3.86278$.

i	α_{i1}	α_{i2}	α_{i3}	c_i	p_{i1}	p_{i2}	p_{i3}
1	3	10	30	1	0.3689	0.1170	0.2673
2	0.1	10	35	1.2	0.4699	0.4387	0.7470
3	3	10	30	3	0.1091	0.8742	0.5547
4	0.1	10	35	3.2	0.03815	0.5743	0.8828

Hartman (HR_{6,4}) (6 variables)

$$HR_{3,4} = \sum_{i=1}^4 c_i \exp \left[- \sum_{j=1}^n \alpha_{ij} (x_j - p_{ij})^2 \right],$$

- search domain: $0 \leq x_j \leq 1, j = 1, \dots, 6$;
- four local minima;
- one global minimum: $x = (0.201, 0.150, 0.477, 0.275, 0.311, 0.657)$; $HR_{6,4}(x) = -3.32$.

i	α_{i1}	α_{i2}	α_{i3}	α_{i4}	α_{i5}	α_{i6}	c_i
1	10.0	3.0	17.0	3.5	1.7	8.0	1.0
2	0.05	10.0	17.0	0.1	8.0	14.0	1.2
3	3.0	3.5	1.7	10.0	17.0	8.0	3.0
4	17.0	8.0	0.05	10.0	0.1	14.0	3.2

i	p_{i1}	p_{i2}	p_{i3}	p_{i4}	p_{i5}	p_{i6}
1	0.1312	0.1696	0.5569	0.0124	0.8283	0.5886
2	0.2329	0.4135	0.8307	0.3736	0.1004	0.9991
3	0.2348	0.1451	0.3522	0.2883	0.3047	0.6650
4	0.4047	0.8828	0.8732	0.5743	0.1091	0.0381

De Jong (DJ) (3 variables)

$$DJ(x) = x_1^2 + x_2^2 + x_3^2,$$

- search domain: $-5.12 \leq x_j \leq 5.12, j = 1, \dots, n$;
- global minimum: $x = (0.0, 0.0, \dots, 0.0)$; $DJ(x) = 0.0$.

Ackley (AK_n) (n variables)

$$AK_n(x) = -20 \exp \left(-0.2 \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2} \right) - \exp \left(\frac{1}{n} \sum_{i=1}^n \cos(2\pi x_i) \right) + 20 + e,$$

- 11 functions were considered: $AK_{50}, AK_{100}, AK_{200}, \dots, ZA_{1000}$;
- search domain: $-32 \leq x_j \leq 32, j = 1, \dots, n$;
- several local minima (exact number of local minima unspecified in the usual literature);
- one global minimum: $x = (0, \dots, 0)$; $AK_n(x) = 0$.

Rosenbrock (RS_n) (n variables)

$$RS_n(x) = \sum_{j=1}^{n-1} [100(x_j^2 - x_{j+1})^2 + (x_j - 1)^2].$$

- Five functions were considered: $RS_2, RS_5, RS_{10}, RS_{50}$ and RS_{100} ;
- search domain: $-5 \leq x_j \leq 10, j = 1, \dots, n$;
- several local minima (exact number of local minima unspecified in the usual literature);
- one global minimum: $x = (1, \dots, 1)$; $RS_n(x) = 0$.

Zakharov (ZA_n) (n variables)

$$ZA_n(x) = \sum_{j=1}^n x_j^2 + \left(\sum_{j=1}^n 0.5 j x_j \right)^2 + \left(\sum_{j=1}^n 0.5 j x_j \right)^4.$$

- Five functions were considered: $ZA_2, ZA_5, ZA_{10}, ZA_{50}$ and ZA_{100} ;
- search domain: $-5 \leq x_j \leq 10, j = 1, \dots, n$;
- several local minima (exact number of local minima unspecified in the usual literature);
- one global minimum: $x = (0, \dots, 0)$; $ZA_n(x) = 0$.

Griewank (GR_n) (n variables)

$$GR_n(x) = \sum_{j=1}^n x_j^2 / 4000 - \prod_{i=1}^n \cos \left(\frac{x_i}{\sqrt{i}} \right) + 1,$$

- two functions were considered: GR_8, GR_{10} ;
- search domain: $-300 \leq x_j \leq 600, j = 1, \dots, n$;
- several local minima (exact number of local minima unspecified in the usual literature);
- one global minimum: $x = (0, \dots, 0)$; $GR_n(x) = 0$.

Shekel (S_4, n) (4 variables)

$$S_{4,n}(x) = - \sum_{i=1}^n [(x - a_i)^T (x - a_i) + c_i]^{-1},$$

$$x = (x_1, x_2, x_3, x_4); \quad a_i = (a_i^1, a_i^2, a_i^3, a_i^4)^T,$$

- three functions S_4, n were considered: $S_{4,5}, S_{4,7}, S_{4,10}$;
- search domain: $0 \leq x_j \leq 10, j = 1, \dots, n$;
- n local minima ($n = 5, 7$, or 10): $a_i^T = i$ th local minimum approximation:
- $S_{4,n}(a_i^T) \cong -1/c_i$;
- $S_{4,5}(n = 5)$ 5 minima with one global minimum: $S_{4,5}(x) = -10.1532$;
- $S_{4,7}(n = 7)$ 7 minima with one global minimum: $S_{4,7}(x) = -10.40294$;
- $S_{4,10}(n = 10)$ 10 minima with one global minimum: $S_{4,10}(x) = -10.53641$.

i	a_i^T				c_i
1	4.0	4.0	4.0	4.0	0.1
2	1.0	1.0	1.0	1.0	0.2
3	8.0	8.0	8.0	8.0	0.2
4	6.0	6.0	6.0	6.0	0.4
5	3.0	7.0	3.0	7.0	0.4
6	2.0	9.0	2.0	9.0	0.6
7	5.0	5.0	3.0	3.0	0.3
8	8.0	1.0	8.0	1.0	0.7
9	6.0	2.0	6.0	2.0	0.5
10	7.0	3.6	7.0	3.6	0.5

B2 (2 variables)

$$B2(x_1, x_2) = x_1^2 + 2x_2^2 - 0.3 \cos(3\pi x_1) - 0.4 \cos(4\pi x_2) + 0.7,$$

- search domain: $-100 \leq x_j \leq 100, j = 1, \dots, n$;
- several local minima (exact number of local minima unspecified in the usual literature);
- one global minimum: $(x_1, x_2) = (0, 0)$; $B2(x_1, x_2) = 0$.

Easom (ES) (2 variables)

$$ES(x_1, x_2) = -\cos(x_1) \cos(x_2) \exp(-[(x_1 - \pi)^2 + (x_2 - \pi)^2]),$$

- search domain: $-100 \leq x_j \leq 100, j = 1, \dots, n$;
- several local minima (exact number of local minima unspecified in the usual literature);
- one global minimum: $(x_1, x_2) = (\pi, \pi)$; $B2(x_1, x_2) = -1$.

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