An Augmented Bio-Inspired Algorithm (JA-ABC5a) to Design Optimal Digital IIR Filter

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Abstract: - Among swarm-intelligence based (SI) algorithms, artificial bee colony (ABC) algorithm that is inspired by the intelligent behavior of honeybees has recently captured much interest from optimization researchers. They have come out with the proposal of ABC variants with the aims to cater the limitations of ABC; slow convergence speed on unimodal functions and premature convergence tendency on multimodal functions. This research has recently become the main topic among optimization researchers. Nonetheless, the variants also have their limitations as they cannot solve the problem simultaneously. With the motivation from those inefficiencies, this work presents a new modified ABC variant, referred to as JA-ABC5a as a problem solver. JA-ABC5a is simulated on 27 commonly used benchmark functions prior to evaluating its optimization performance. Upon justifying its robustness, it is being applied to design an optimal digital IIR filter.

Key-Words: Artificial bee colony, Benchmark functions, Digital IIR filter, Swarm-intelligence algorithm.

1 Introduction

Recently, researchers have implemented bio-inspired computational intelligence algorithms such as evolutionary programming (EP), evolutionary strategies (ES), particle swarm optimization (PSO) algorithms and bacterial foraging optimization (BFO) with the attempt to efficiently solve complex problems. Those techniques have shown the ability to overcome the limitation of classic techniques by achieving solution closest to the global optimum as well the ability to solve discontinuous and non-convex objective functions [1, 2].

Among them, swarm intelligence-based (SI) algorithms such as firefly algorithm [3], artificial bee colony algorithm [4] and discrete particle swarm optimization [5] have attracted much attention from optimization researchers due to their ability to intelligently perform cooperation among the cooperative agents in their population. Moreover, they demonstrate unique attributes such as self-organized and decentralized control, making them a powerful tool to solve various optimization problems. However, the capabilities of bio-inspired computational intelligence algorithms are still doubted since they are found to be incapable of handling integer and discrete nature problems [1].

Among SI algorithms, the intelligent foraging behavior of honeybees through artificial bee colony (ABC) algorithm has captured much interest from researchers around the world due to its flexibility and simplicity [6]. It has shown better performance than other prominent optimization algorithms such as differential evolution (DE), genetic algorithm (GA), ant colony optimization (ACO) algorithm and particle swarm optimization (PSO) algorithm [6, 7]. Despite that, it faces the problem of slow convergence speed as well as tendency to converge prematurely which is basically due to its mutation equation. Its mutation is known to be good in exploration but poor at exploitation [8-10]. To overcome the problem, researchers have come out with the proposal of ABC variants. Unfortunately, most of the variants are incapable to counter those problems at once. Motivated from those flaws, this work proposes an augmented ABC variant named as JA-ABC5a as a vital solution.

Designing optimal digital Infinite impulse response (IIR) filters is known to be a complex task [11]. Nonetheless, they are required in digital signal processing to attenuate and eradicate undesired noise [12]. Besides, they require less computation and use a finite number of variables [13, 14]. They have also been successfully applied to solve various types of applications such as in wireless applications by Joshi, Madanayake [15], grid connected voltage source inverters by Gonzalez-Espin, Patrao [16], and temperature of power electronic device prediction by Davidson, Stone [17]. Due to that,
researchers have recently paid much attention to designing IIR filters [11].

There are two methods to design a digital IIR filter. One of them is parameter estimation in which an estimation of parameter settings of the filter; first and second-order coefficients, is required to produce a desired digital IIR filter. The estimation is subjected to meet the required condition while minimizing the magnitude response error. Various techniques have been applied by optimization researchers to optimally estimate the parameter settings of the desired filters including genetic algorithm [18], predator prey optimization method [19], particle swarm optimization algorithm [20], cat swarm optimization algorithm [13], teaching-learning based optimization algorithm [21] and two-stage ensemble memetic algorithm [11]. However, the algorithms have been found to require more computational time [13].

Thus, the proposed algorithm in this work, JA-ABC5a will be tested to optimally design a digital IIR filter prior to justifying its robustness.

2 Artificial Bee Colony (ABC) Algorithm

Artificial bee colony (ABC) algorithm is proposed by Karaboga in 2005. It simulates the intelligent foraging behavior of honeybees. It consists of five phases which are initialization, employed-bees, onlooker-bees, scout-bee and termination phases. ABC algorithm works from the interaction among the bees in three performance-deciding phases which are employed-bees, onlooker-bees and scout-bee phases. The other phases are just supporting phases. The flowchart of the standard ABC is illustrated in Fig. 1.

The algorithm starts with the random initialization of the food sources based on the population-size in the initialization phase. The food sources represent the possible solutions and the number of food sources (i.e. FoodNumber) is basically half of the population size. Next, those food sources are randomly assigned to the employed-bees around the hive. After that, the nectar amount that represents the fitness values of each of the food sources is calculated. In the employed-bees phase, the neighborhood of food sources associated with the employed-bees is explored using the following mutation equation [10]:

\[ z_{ij} = y_{ij} + \phi_{ij} (y_{ij} - y_{ji}) \]  

where: \( z_{ij} \) = New candidate solution of new food sources
\( y_{ij} \) = Food source to be updated
\( y_{ji} \) = Neighborhood food source
\( \phi_{ij} \) = Random numbers in the range [-1, 1]

The equation governs the interaction among the food sources and generates new food sources (i.e. candidate solutions). Then, greedy-selection mechanism is employed to select the best food sources between the candidate solution and the old food source \( y_{ij} \). The best food source among them (i.e. fitter fitness value) is called potential fitter food source. This potentially fitter food sources are then shared with onlooker-bees in the onlooker-bees phase.

In the onlooker-bees phase, the onlooker-bees do not update all potential food sources shared by employed-bees. They are further selected by the onlooker-bees to be updated using fitness-proportion selection scheme that is based on the probability value, \( P_i \) associated with the food source. Similar to employed-bees phase, greedy-selection is again applied to choose the best food source. Then, this best food source so far for that generation is memorized.

In the scout-bee phase, the food source that does not show improvement over a certain number of preset generations called limit is to be abandoned [22]. The employed-bees associated with the abandoned food source become scout-bee and will search the environment randomly for discovering a new food source to replace the abandoned food source. This is done in order to balance out the number of food sources in the population. Scout-bee searches the entire search space and picks the replacement using the following equation [10].

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**Fig. 1: The flowchart of the standard ABC algorithm**
\[ y'_i^j = y'_{\text{min}} + \text{rand}(0,1)(y'_{\text{max}} - y'_{\text{min}}) \]  
where:  
- \( y'_{\text{min}} \) = Lower limit of the search space  
- \( y'_{\text{max}} \) = Upper limit of the search space  
- \( \text{rand} (0,1) \) = Random numbers within [0,1]

In the termination phase, the algorithm checks for the termination criterion, maximum-generations. If the termination criterion is not met, then it repeats from step 2 until the numbers are reached. More details on the standard ABC algorithm can be found in [23] and [10].

3 Augmented ABC Variant (JA-ABC5A)

It has been previously mentioned that ABC has three performance-deciding phases. Thus, any modifications need to be implemented to these phases for effective improvement. Prior to enhance the performance of ABC and to cater the aroused problems, this research work extends the work by Sulaiman et al. [24] by modifying their proposed variant, JA-ABC5.

It is known that JA-ABC5 is developed by implementing few modifications to the standard ABC algorithm. JA-ABC5 is said to have balanced exploration and exploitation capabilities as it is able to enhance its exploration capability in the employed-bees phase and improve its exploitation capability in the onlooker-bees phase. However, further analysis has shown that JA-ABC5 still lacks in exploitation as the incorporated equation in the employed-bees phase and improve its exploitation to enhance its exploration capability in the exploration and exploitation capabilities as it is able to enhance the convergence rate of JA-ABC5a.

Thus, here comes the second term of the equation that uses the information of the randomly explored neighborhood food sources. As a result, this should improve the exploitation capability of the algorithm. Moreover, the equation from work [22] is known for its randomness. JA-ABC5a should now possess balanced exploration and exploitation processes and hence should be able to converge faster at achieving the global optimum.

4 Digital IIR Filter Design

The main task of designing optimal digital IIR filter is to estimate the settings of the first and second-order coefficients of the filters given by \( a_0, a_n, b_0, b_n, c_{11}, c_{1m}, c_{21}, c_{2m}, d_{11}, d_{1m} \) and \( d_{21}, d_{2m} \) that would give the minimum values of magnitude response errors on both pass-band and stop-band of the designed filters subjected to their constraints. The mathematical expression of the problem is given by [11]:

\[
\min f_i = \frac{1}{P_n} \sum_{i=1}^{P_n} H_p(\omega_i) + \frac{1}{S_n} \sum_{i=1}^{S_n} H_s(\omega_i)
\]

where \( H_p(\omega) = \begin{cases} 1 - \alpha_1 & \text{if } |H(e^{j\omega})| < 1 - \alpha_1 \\ 0 & \text{otherwise} \end{cases} \)

\[
H_s(\omega) = \begin{cases} 0 & \text{if } |H(e^{j\omega})| \geq 1 - \alpha_2 \\ 1 - \alpha_2 & \text{otherwise} \end{cases}
\]
\[
H(\omega) = \begin{cases} 
|H(e^{j\omega})| - \delta_z, & |H(e^{j\omega})| \geq \delta_z \\
0, & \text{otherwise}
\end{cases}
\]
\[
H(e^{j\omega}) = k \prod_{i=1}^{n+1} \left(1 + a_i (e^{j\omega})^{m_i} + b_i (e^{j\omega})^{2m_i} \right)
\]

where: \( P_n \) = Sampling frequency in the pass-band
\( S_n \) = Sampling frequency in the stop-band
\( H_p \) = Pass-band magnitude response error at \( \omega \)
\( H_s \) = Stop-band magnitude response error at \( \omega \)
\( K \) = Filter gain
\( a_i \) and \( b_i \) = First-order coefficients
\( c_{j1}, c_{j2}, d_{j1} \) and \( d_{j2} \) = Second-order coefficients

Based on the above mathematical expression, the optimal values of \( a_0, a_0, a_0, b_0 \ldots b_m, c_{j1} \ldots c_{j2m}, d_{j1} \ldots d_{j2m} \) that give the minimum values of magnitude response error of both pass-band and stop-band of the designed filters shall be determined, subjected to the limit of each of the parameters.

5 Experimental Settings

The performance of the proposed augmented ABC variant, JA-ABC5a is simulated and analyzed in two ways; its performance on benchmark functions and on the design of optimal digital IIR filters. The general parameters are population-size, maximum-generations and limit. They have been set to 50, 100 and \( \text{FoodNumber} \times D \), respectively. The \( \text{FoodNumber} \) represents the size of the possible solution by which indicating half of the population-size.

5.1 Benchmark Functions

The proposed JA-ABC5a has been simulated on 27 various commonly used benchmark functions found in the literature. They are ranged from unimodal to multimodal and from shifted to rotated functions and as listed in Table 1.

The performances of JA-ABC5a on the benchmark functions are compared with the standard ABC algorithm and existing variants found in the literature in order to validate its performances. The variants include improved ABC (IABC) [25], global best ABC (BABC1) [27], enhanced probability-selection ABC (EPS-ABC) [28] and two recently proposed variants; JA-ABC3 [29] and JA-ABC5 [24] algorithms.

| Function | Function Name | Initialisation Range |
|----------|---------------|----------------------|
| f1       | Griewank      | ±600                 |
| f2       | Rastrigin     | ±15                  |
| f3       | Rosenbrock    | ±15                  |
| f4       | RS Ackley     | ±32                  |
| f5       | Schwefel      | ±500                 |
| f6       | Himmelblau    | ±600                 |
| f7       | RS Sphere     | ±600                 |
| f8       | Step          | ±600                 |
| f9       | Binhachevsky2 | ±100                 |
| f10      | RS Schwefel 2.22 | ±100          |
| f11      | RS Schwefel Ridges | ±100          |
| f12      | RS Schwefel Ridges with Noise | ±15          |
| f13      | RS Elliptic   | ±100                 |
| f14      | Zekheliop     | ±15                  |
| f15      | Non-continuos Rastrigin | ±15          |
| f16      | Michalewicz   | 0-180                |
| f17      | First Expanded Function | ±15          |
| f18      | Second Expanded Function | ±15          |
| f19      | Third Expanded Function | ±15          |
| f20      | Fourth Expanded Function | ±500      |
| f21      | Fifth Expanded Function | ±100      |
| f22      | Sixth Expanded Function | ±100      |
| f23      | Seventh Expanded Function | ±15        |
| f24      | Eighth Expanded Function | ±100      |
| f25      | Rotated Griewank Function | [0, 600] |
| f26      | Rotated Ackley Function | ±32         |
| f27      | Rotated Rastrigin Function | ±5         |

5.2 Designing Optimal Digital IIR Filter

The digital IIR filter that will be designed in this work is band-stop (BS) filter. The settings of the filter follow the values from [11] for comparison purpose and are tabulated in Table 2.

| Parameters    | Settings |
|---------------|----------|
| Pass-band (\( \omega \)) | 0-0.3\( \pi \) U 0.7\( \pi \) |
| Stop-band (\( \omega \)) | 0.4\( \pi \)-0.6\( \pi \) |
| \( \delta 1 \) (dB) | 1          |
| \( \delta 2 \) (dB) | 90         |
| Order         | 14         |

The performance of JA-ABC5a is then compared with the same ABC variants as the previous section and other optimization algorithms that have been applied to solve optimal digital IIR filters design found in the work of [11]. They are ensemble
memetic algorithm (TSMA), modified differential evolution (MDE), self-adaptive differential evolution (SaDE) and local version of particle swarm optimization with constriction factor (PSO-cf).

6 Results & Discussion

6.1 Performance on Benchmark Functions

As mentioned beforehand, the proposed JA-ABC5a is simulated on 27 commonly used benchmark functions and its performances are then compared with the standard ABC and three existing ABC variants. Their performances are evaluated based on the minimum values obtained in 30 runs. The comparison is done on the basis of convergence speed and global optimum achievement. The obtained performances results are as illustrated in Fig. 3 to 7.

Fig. 4 to 7 show the efficiency of the proposed JA-ABC5a to reach the global optimum in less number of generations compared to the existing variants.

For instance, Fig. 4 illustrates that JA-ABC5a converges faster than the compared variants to reach the global optimum on the expanded function of Rosenbrock and Step functions. JA-ABC5a also seems to converge faster than JA-ABC5 which indicates that the enhancement done to JA-ABC5 in the form of JAABC5a is able to improve its performance. Similarly, Fig. 5 and Fig. 6 also portray the ability of JA-ABC5a to converge the fastest in achieving the global optimum on expanded function of Dixon-Price and Schwefel Ridge functions and rotated Griewank function.
Meanwhile, Fig. 7 demonstrates that not only JA-ABC5a is the fastest to converge but it is the only algorithm that is able to reach the global optimum on rotated Ackley function. In the meantime, the other compared variants are trapped in the local optima of the function.

On the other hand, Fig. 3 shows the inefficiency of JA-ABC5a to converge the fastest on Zekhelip function. It converges slower than one of the compared variant which is EPS-ABC [28]. Despite that, it basically converges faster than the other compared variants. More importantly, JA-ABC5a reaches the lowest minimum value i.e. global optimum of the function.

The excellent performances shown by JA-ABC5a on the tested benchmark functions vividly prove that the enhancement done to JA-ABC5 has been able to improve its optimization performance. The introduction of new mutation equation by hybridizing two mutation equations in employed-bees phase has balanced out both exploration and exploitation of the algorithm. The result is the ability of JA-ABC5a to be able to escape from local minima traps while rapidly converging. The incorporated modifications obviously show that balanced exploration and exploitation capabilities are essential and should be achieved by an optimization algorithm to exhibit robust optimization performance.

6.2 Designing Optimal Digital IIR Filter

Once the efficiency of JA-ABC5a as an optimization algorithm has been proven, it is now ready to be applied to design optimal digital IIR filter. It has been applied to estimate the optimal settings of a band-stop (BS) filter. Its performance is being compared with few optimization algorithms as mentioned in the previous section. The acquired results are depicted in Table 3, showing the magnitude response errors produced by the proposed JA-ABC5a algorithm, other ABC variants and other optimization algorithms.

The acquired results clearly demonstrate robust competency of JA-ABC5a to produce minimum value of magnitude response error in comparison to its counterparts. This is particularly due to the amendments made to the standard ABC algorithm to produce JA-ABC5a, a modified ABC variant. The proposed variant has been able to optimize the design of digital IIR filter, a complex real-world application. Additionally, the results in Table 3 show that the existing ABC variants, including the standard ABC perform better than the others when they manage to obtain smaller minimum magnitude response error compared to other types of algorithms. This vividly suggest the robustness of ABC and its variants at solving real-world optimization problems.

Table 3: Performance results of the optimization algorithms at optimizing BS filter

| Algorithms | Magnitude Response Error |
|------------|--------------------------|
| TSMA       | 3.28E+01                 |
| MDE        | 1.96E+03                 |
| SaDE       | 3.87E+01                 |
| PSO-cf     | 1.51E+02                 |
| ABC        | 2.35E+00                 |
| BABC1      | 2.31E+00                 |
| IABC       | 2.30E+00                 |
| EPS-ABC    | 2.34E+00                 |
| JA-ABC3    | 2.31E+00                 |
| JA-ABC5    | 2.30E+00                 |
| **JA-ABC5a** | **2.29E+00**             |

7 Conclusion

This paper proposes the development of an augmented ABC variant named as JA-ABC5a. It is formulated by modifying the recently proposed variant, JA-ABC5 prior to enhance and balance its exploration and exploitation capabilities. This is because a robust optimization algorithm should have balanced of those processes. The result is an augmented ABC variant in form of JA-ABC5a that has the fastest convergence rates in reaching the global optimum. This is portrayed by the graphical results. JA-ACB5a converges the fastest among all compared variants including the recently proposed variants (i.e. JA-ABC3 and JA-ABC5) on numbers of tested benchmark functions. There are few cases in which JA-ABC5a show slower convergence than EPS-ABC, but it actually converges faster than the others. Moreover, the most important thing to mention is JA-ABC5a is able to reach the global optimum when the other algorithms have been trapped in the functions’ local minima. The efficiency of JA-ABC5a is further demonstrated as it has successfully optimized the setting of BS filter by producing the least magnitude response error. The results vividly verify the robustness of JA-ABC5a as an optimization algorithm that is able to solve the complex real-world application.

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**Contribution of individual authors**

Noorazliza Sulaiman, implemented the algorithm, carried out the simulation and optimization, and prepared the manuscript.

Junita Mohamad-Saleh, responsible for mentorship to the team, research activity planning and execution, and manuscript’s review for content as well as English editing.

Abdul Ghani Abro, contributed ideas and original code.

Weng Hooi Tan, prepared the final paper into required template, and reviewed the manuscript.

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