



Three-Channel Cost Function Based Artificial Bee Colony Algorithm for PID Tuning *

Recep Kaya¹, Murat Furat²

¹ İskenderun Technical University, Institute of Engineering and Sciences, Electrical Electronic Engineering, Hatay, Turkey (ORCID: 0000-0002-0336-1800)

² İskenderun Technical University, Institute of Engineering and Sciences, Electrical Electronic Engineering, Hatay, Turkey (ORCID: 0000-0003-3179-5099)

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Abstract

Recently, interest in swarm intelligence optimization techniques (Particle Swarm Optimization, Genetic Algorithm, Tabu Research Algorithm, etc.) has increased and this issue has become the focus of attention especially for scientists. Optimum controller parameters can be found with less experience in a short time by using optimization algorithms. PID is a type of controller which is widely used in the industry. The characteristic of the PID controller has effected the controller coefficients and optimum parameters must be tuned for good control. The speed control of a DC motor that is commonly used in practice is one of the important problems in engineering. DC motors are economical as well as important electrical machines of both industrial applications and our daily life due to their ease of control and optimum moment-speed characteristics. The best values of K_p , K_i and K_d with classical methods are a time consuming problem. The use of meta-heuristic methods gives both speed and accuracy in finding optimum values. In this study, optimum parameters are determined for a PID controller using Artificial Bee Colony Algorithm (ABC). The PID controller is designed as a speed controller for DC motor and simulated. In the literature, generally, the optimization was carried out with a single cost function or a combination of different functions with appropriate gains. This type of approach does not fit for the PID controller optimization since the effect of each parameter is different on the output of the system. Because of this reason, the optimum value of each parameter has been searched separately by using the three-channel cost function. The proposed algorithm in the present study gives more successful results than the traditional ABC algorithm having a single cost function.

Keywords: Three-Channel Cost Function, Artificial Bee Colony Algorithm, Swarm Intelligence, PID, DC Motor.

PID Ayarlama İçin Üç Kanallı Amaç Fonksiyonu Tabanlı Yapay Arı Kolonisi Algoritması

Öz

Son zamanlarda, sürü zekası optimizasyonu tekniklerine (Parçacık Sürüsü Optimizasyonu, Genetik Algoritma, Tabu Araştırma Algoritması, Yapay Arı Koloni Algoritması, vb.) ilgi artmıştır ve bu konu özellikle bilim adamları için ilgi odağı haline gelmiştir. Optimizasyon algoritmaları kullanılarak optimum kontrolör parametreleri kısa sürede daha az deneyim ile bulunabilir. PID, endüstride yaygın olarak kullanılan bir kontrolcü türüdür. PID kontrolcünün karakteristiği kontrolcü parametrelerine bağlıdır ve iyi bir kontrol için parametrelerin optimum değerlerde ayarlanması gerekir. Pratikte yaygın olarak kullanılan bir DC motorun hız kontrolü, mühendislikte önemli sorunlardan biridir. DC motorlar, kontrol kolaylığı ve optimum moment-hız özellikleri nedeniyle hem endüstriyel uygulamaların hem de günlük yaşamımızın ekonomik ve önemli elektrikli makineleridir. K_p , K_i ve K_d 'nin klasik yöntemlerle en iyi değerleri zaman alıcı bir sorundur. Meta-sezgisel yöntemlerin kullanılması, optimum değerlerin bulunmasında hem hız hem de doğruluk sağlar. Bu çalışmada, Yapay Arı Koloni Algoritması (ABC) kullanılarak bir PID kontrolörü için optimum

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parametreler belirlenmiştir. PID kontrol DC motorun için hızını kontrol etmek amacıyla tasarlanmıştır ve benzetim çalışması yapılmıştır. Literatürde genellikle optimizasyon, tek bir amaç fonksiyonu veya farklı amaç fonksiyonlarının uygun kazançlarla bir kombinasyonu ile gerçekleştirilmiştir. Bu yaklaşım yaklaşımı, PID denetleyicisi optimizasyonu için uygun değildir çünkü her parametrenin etkisi sistemin çıktısı üzerinde farklıdır. Bu nedenle her bir parametrenin optimum değeri üç kanallı amaç fonksiyonu kullanılarak ayrı ayrı araştırılmıştır. Bu çalışmada önerilen algoritma, tek amaç fonksiyonuna sahip geleneksel ABC algoritmasından daha başarılı sonuçlar vermektedir.

Anahtar Kelimeler: Üç-Kanallı Amaç Fonksiyonu, Yapay Arı Kolonisi, Sürü Zekâsı, PID, DA Motoru

1. Introduction

The ease of controls of DC motors and their economical low cost solutions with their optimum moment-speed characteristics make these engines home appliances, industrial, robotic, etc. has given it the opportunity to practice in many areas The speed control of the DC motors was carried out by Ward Leonard for the first time in 1891 with voltage adjustment [1]. Although there are studies on speed control of a wide range of alternating current (AC) motors, which are widely used in the industry, this feature, which is inherent in the nature of DC motors, has not yet been achieved in AC motors. For this reason, traditional DC motors maintain their indispensable position in various industrial application areas and these engines will remain competitive in the future. Proportional-Integral-Derivative (PID) controller is one of the most common controllers used in industry for many years for process control applications. There are a variety of control techniques for speed control of DC motors.

There are several traditional and numerical controller types, such as proportional integral (PI), Fuzzy PID (FLC) or optimization. Each controller type has its own advantages and disadvantages [2]. In a recent study, it was stated that most of the inspection bodies in industrial applications are of the PI / PID type [3]. The correct setting of PID parameters has an important place in terms of the performance of the system under control. These parameters, which depend on the system model, were determined by the Ziegler-Nichols (Z-N) method for many years by analyzing the unit step response of the system. In practice, operator assistance is required for this process. The operator decides what the PID parameters should be by using various tests on the system. Although this process is difficult, it is also a long process in terms of time. Moreover, the optimum parameters to be obtained at the end of the process can't be guaranteed. Recently, many meta-heuristic algorithms have been used to obtain an optimal PID controller which achieve different levels of performance success. Thus, the task of the operator is transferred to algorithms, and many controller parameters are evaluated according to a particularly systematic and the best or best in the potential solution area [4]. Moreover, this process is completed in a shorter time. Successful application of ABC to numerical problems, traveler vendor problems, power system controller design, fuzzy data clustering and route planning problem encourages selection of the algorithm for this study. ABC algorithm was proposed by Karaboğa in 2005 and examined the behavior of bees living in the colony and turned it into a model [5].

The organization of the study is as follows:

Following the Introduction, in Chapter 2, preliminary information about swarm intelligence and artificial bee colony algorithm is given. In Chapter 3, the proposed method with the changes made on the artificial bee colony algorithm is explained and simulation results are given as graphically. The conclusion section is given in the last chapter.

2. Material and Method

2.1. Swarm Intelligence (SI)

SI is an important optimization method. SI is the total behavior shown by decentralized, natural or artificial self-organizing systems. The swarm intelligence algorithm was first implemented in a computer by using a simulation software [6].

Different from evolutionary algorithms, SI algorithms are an artificial intelligence discipline that deals with the investigation of the behaviors that have emerged as a result of the interaction of living individuals with each other and their habitats and transforming them into a model. The term SI was first introduced in [7].

In order for the swarm's behaviors interacting with each other and their environment to be evaluated within the scope of herd intelligence, it must have the following characteristics:

- The number of individuals should be sufficient.
- Individuals are generally the same type.

It should have an indirect coordination mechanism between factors and actions. So, one action's leave in the environment is a stimulating effect for the other action to take place [8].

- Division of Labour: When the behavioral model of bees evaluated within the scope of swarm intelligence, some of the bees search for food randomly according to their abilities, some of them concentrate on the food source and some of them give information about the food sources [5].

2.2. Artificial Bee Colony Algorithm

In ABC, the bee's research behavior is modeled so that numerical problems are optimized. It is a meta-intuitive algorithm based on herd intelligence. This algorithm is based on the model which was created especially on the bees' foraging behavior of honey bees. The model has three different parts: employed and unemployed foraging bees and food sources. Although the number of bees living together is high, there is no hitch or turmoil in the hive, thanks to the excellent division of work and self-organizing capabilities [5]. In the algorithm, bees are identified by positions in the search space. The matrix size of the food sources search area determines the parameters' number to be optimized in the problem. In the algorithm, bees are identified by positions in the search space. The size of the search space determines the number of parameters to be optimized in the problem. Each of the bees works towards a food source in the search space. Bees' positions, so food sources, are also possible solutions to that problem. The best food source is evaluated by calculating the suitability value using a cost function. Bees change their new positions according to their previous positions and positions of other best food sources. In the search area, the position of the best food source found by bees is assigned as the solution to the problem. Artificial bee colony consists of three different groups of bees. These; EBs finding food sources are OBs watching the dance of EBs to choose the best food sources and SBs searching random food. Half of the population is made up of EBs and the other half is OBs. First, in the algorithm, EBs find new food sources and measure the nectar amount with the cost function to determine the suitability of the food sources they find. Then they start searching for a new food source that is more suitable for their neighborhood. When an EB finds a more suitable new food source, they leave the previous food source to the OBs and memorize this new food source. The EB, who cannot find a new food source that is more suitable as the number of iterations, turns into a SB and starts searching randomly in the search area after releasing the food source.

There are three types of bees in artificial bee colony:

- Employed bees (EBs)
- Onlooker bees (OBs)
- Scout Bees (SBs)

EBs searching for specific food sources, OBs watching the dances of EBs to choose a food source from bees in the hive, and SBs looking for random food sources. Employed and SBs are also unemployed bees. Initially, all food source locations are randomly selected by scout bees. Later, food sources nectar is collected by EBs and SBs, and this causes the nectar to be depleted as a result of constantly collecting food sources. Then the EB that uses the exhausted food source becomes the scout bee to find new food sources. So, the bee that has consumed its food source becomes a scout bee. In ABC, the locations of food sources correspond to a possible solution to the problem, and the nectar ratio of a food source corresponds to the quality (cost) of this solution. The number of EBs in the hive is equal to the number of food sources (solutions) since each bee used is associated with only one food source.

Conventional ABC algorithm consists of 5 steps as follows:

- Initialization Step,
- Employed Bees Step,
- Onlooker Bees Step,
- Scout Bees Step,
- Loop Until Termination.

2.2.1. Initialization Step

All positions of the population of food sources, \vec{x}_i are initiated by SBs ($i=1 \dots SN$, SN : population size) and allows adjustment of control parameters. Since every food source \vec{x}_m is a solution value to the optimization problem, each \vec{x}_i vector holds the n variable ($\vec{x}_i, i = 1, \dots, n$) to be optimized by minimizing the cost function.

The following expression can be used for algorithm purposes [8], [9]:

$$x_{ij} = lb_i + rand(0,1) * (ub_i - lb_i) \tag{1}$$

where lb_i and ub_i are bounds of the parameter x_{ij} , respectively.

2.2.2. Employed Bees Step

While determining appropriate solution values in the search area, EBs randomly determine one of the food sources and calculate the suitability of this food source, that is, the solution value. EBs store the solution value obtained. Then, as EBs turn to food sources, the information in the memory determines a better food source according to the purpose of the problem and these solutions are updated and kept in memory. Here, it is worth noting that as long as the value of each good solution improves, the values will be stored in memory as follows [10]:

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}) \tag{2}$$

where \vec{x}_{ij} , is the solution value of a randomly selected food, j is the index number of the randomly selected parameter, and ϕ_{ij} is a randomly generated number in the range $[-a, a]$. After the new food source \vec{v}_i is produced, its suitability is calculated and if it is better than the previous solution \vec{x}_i , the greedy choice is applied between \vec{v}_i and \vec{x}_i .

The cost value of the solution, $f_i(\vec{x}_i)$, can be calculated for problems minimizing the cost value using the formula as [11]:

$$f_i(\vec{x}_i) = \begin{cases} \frac{1}{1+f_i(\vec{x}_i)} & \text{if } f_i(\vec{x}_i) \geq 0 \\ 1 + \text{abs}(f_i(\vec{x}_i)) & \text{if } f_i(\vec{x}_i) < 0 \end{cases} \quad (3)$$

where $f_i(\vec{x}_i)$ is the cost function value of solution \vec{x}_i .

2.2.3. Onlooker Bees Step

There are two different bee groups for unemployed bees: OBs and scouts. The EBs transfer the position information of the food source to the OBs waiting in the hive by dancing, and then the OBs select the food sources within the appropriate probability values according to this information.

In the ABC algorithm, OBs choose a better food source based on probability values calculated with the suitability value of the solution determined by EBs. Therefore, a cost-based selection technique, such as a roulette wheel selection method, can be used. [9].

The probability value p_i of \vec{x}_i selected by an onlooker bee can be calculated using the expression given in the formula [10], [11].

$$p_i = \frac{f_i(\vec{x}_i)}{\sum_{m=1}^{SN} f_i(\vec{x}_i)} \quad (4)$$

After the \vec{x}_i selection, which is the probability value of a food source for an onlooker bee, the neighboring new food source is determined using the \vec{v}_i Eq.(2) and the cost value is calculated. As in the employed bee stage, a greedy choice is applied between \vec{v}_i and \vec{x}_i , whichever is better. Therefore, more viewers are sent to richer food sources and positive feedback behavior arises.

2.2.4. Scout Bees Step

As explained above, after the stages of sending EBs and OBs to food sources are completed, if the counter limit value has passed, that is, if the cost value of the solution cannot be improved anymore, the explorer bee phase begins.

In the life of real bees, this can be explained as follows:

If there is no nectar left in a food source, the EB responsible for collecting the nectar becomes an SB responsible for finding new food sources. In other words, for the solution value that cannot be improved at a certain limit value in ABC, just like the real bees' foraging behavior, EBs turn into SBs and a new food source is created by these SB and the solution value of the food source is calculated. The conformity value of the new food source created is compared with the conformity value of the previous solution and if the obtained solution value is better than the previous one, it is stored. If it is not better, the first solution remains in memory.

2.2.5. Loop Until Termination

All these steps are carried out as much as the number of iterations determined previously, and when the stop criterion is fulfilled, the algorithm is terminated and the loop is exited.

2.2.6. Summary of the ABC Algorithm

- The solution matrix is created as much as the number of random variables. The fitness values of the solution set created are found by the applied cost function.
- Improvement formula is applied to all solution matrices in order. If improvement is achieved in the solution matrix, the new solution matrix is replaced with the previous solution matrix.
- In solution matrices, the probability value of those with high suitability values is calculated to be high. Thus, the improvement formula is applied to the solution matrix chosen randomly according to the high probability, as in the previous stage.
- If there is a solution matrix that is not improved further up to the specified limit value, they are deleted from memory and a random solution matrix is created instead.
- Return to the second step until you reach the maximum number of iterations [10].
- In the literature, ABC algorithm is an easy, flexible and strong algorithm [9].

Each algorithm that shows an intuitive approach has global and local search features. In order to produce successful solutions, a global search and local search should be conducted in a balanced way in the solution space. When more attention is given to local search in the solution space, the solutions are very close to each other and early convergence problems, when global search is emphasized in the solution space, it causes the problems to move away from each other and not to find good solutions. In ABC algorithm, EB and SB perform the global search feature and the OBs perform the local search feature. Also, it is another factor that ensures local and global search equilibrium by the watchful bees to select good sources with probability.

In this study, new features have been integrated into ABC algorithm to reveal a stronger algorithm. Firstly, it is envisaged to make changes in all positions instead of the changes made in one position. The fact that EBs can find new sources in vector is provided by Eq. (5) instead of equation (2).

$$v_i = x_i + \theta_i(x_i - x_{ks}) \tag{5}$$

where θ_i is a vector consisting of random numbers between 0 and 1 and an accelerator coefficient.

The s index in x_{ks} assigns a random position up to $s = 1, \dots, PN$, and provides improvement by using the value at that position, PN: Population Number.

Secondly, it was ensured that OBs turned to the best source and searched around it.

The tendency of OBs to conduct research around good resources has been made more effective by integrating Eq. (6) instead of Eq. (2) around neighboring resource research mechanism around the best global solution;

$$v_i = x_i + \theta_i.(x_i - x_{kj}) \tag{6}$$

Here θ_i is a vector consisting of random numbers between 0 and 1 and an accelerator coefficient.

The j index in x_{kj} assigns a random position up to $j=1, \dots, OBN$, and provides improvement by using the value at that position, OBN: Onlooker Bee Number.

The main purpose of the global best solution is that it can be realized only by the OBs and not the EBs, and the main purpose of the algorithm is to protect the global research feature. Also, considering that OBs are better suited to search for good solutions in the basic ABC algorithm, it is a correct decision to give the best solution to only OBs. ABC model developed with the proposed modification differs from other global solution-based ABC algorithms in the literature with this feature.

2.3. Optimum Speed Control of DC Motor

There are many methods in classical PID controller designs. Such as Ziegler-Nichols, Cohen Coon method etc. Since PID control is simple and easy to implement, it is still the preferred controller today. Although it has a wide range of applications, there is still no standard definition for PID. Conventional PID control consists of three independent parameters.

In the present study, a DC motor model is used as a plant to be optimized with PID controller. DC motor model used in the present study is shown in Fig. 1. In order to be more realistic with respect to real DC motor, band limited noise is added to the output of the model. 10V which correspondence to 1000rpm shaft speed is applied to the input of the system according to the open loop control and the output shaft speed is measured. In Fig. 2, The steady-state output produced is measured as 6V, which corresponds to the output shaft speed of 600rpm. The system is modeled as second order system as (7) [14]:

$$G(s) \cong \frac{Ke^{-t_d s}}{\tau_\rho s + 1} \cong \frac{K}{(\tau_\rho s + 1)(t_d s + 1)} \tag{7}$$

where K is the gain, t_d is the time delay and τ_ρ is the time constant. Using the input-output plot of the system, the plant coefficients are found to be $t_d=0.2260$, $\tau_\rho=0.2479$, $K=0.6$. Then, band-limited noise is applied to the output of the model as shown in Fig. 1.

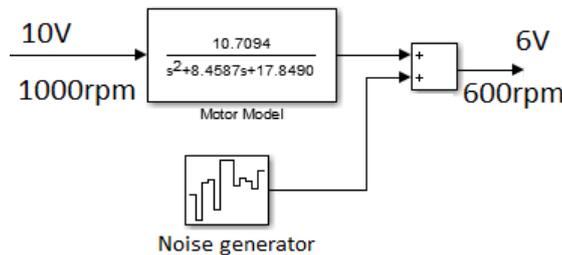


Fig. 1 The DC Motor Model with Noise

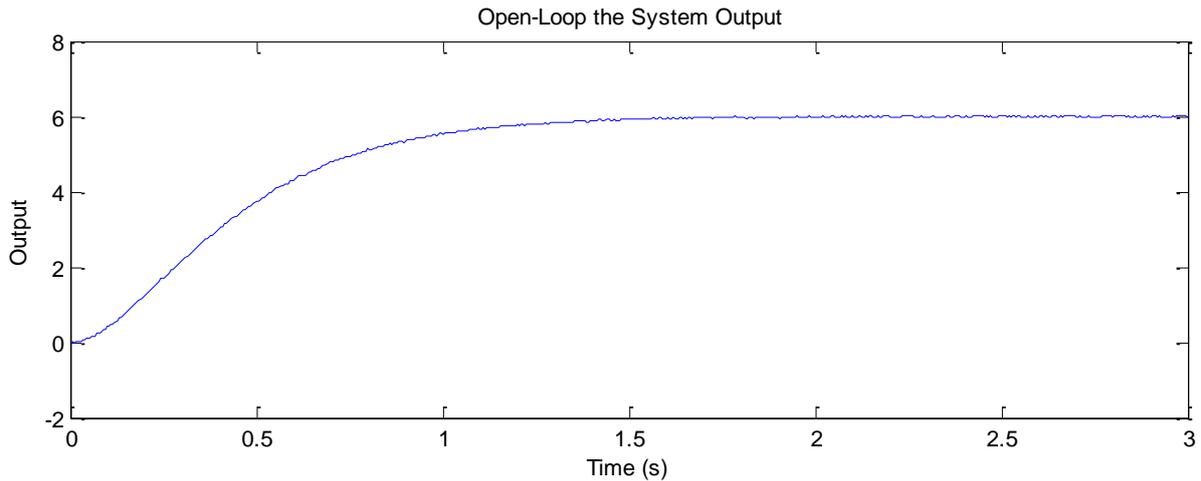


Fig. 2 Open-Loop the System Output

The general expression of the PID controller is as follows:

$$u(t) = K_p * e(t) + \frac{1}{T_i} \int e(t)dt + T_d * \frac{d(e(t))}{dt} \tag{8}$$

Transfer function of PID in Laplace form:

$$PID(s) = K_p + \frac{K_i}{s} + K_d s \tag{9}$$

where K_p : Proportional gain

T_i : Integral time constant

T_d : Derivative time constant

$e(t)$: It is expressed as the difference between the given input value and the output.

When we run the classical artificial bee colony algorithm for the first time, K_p , K_i and K_d parameters determined randomly within specified bounds were first operated with the traditional ABC algorithm prepared for the PID. The cost function for all parameters of the PID is selected as:

$$ISE = \int_0^t e(t)^2 dt \tag{10}$$

For the K_p , K_i and K_d parameters, the cost value of (10) is minimized and the K_p , K_i and K_d parameters, which correspond to the best cost value, are assigned as the control parameters of the DC motor. The structure of optimizing PID with ABC algorithm is in Fig. 3.

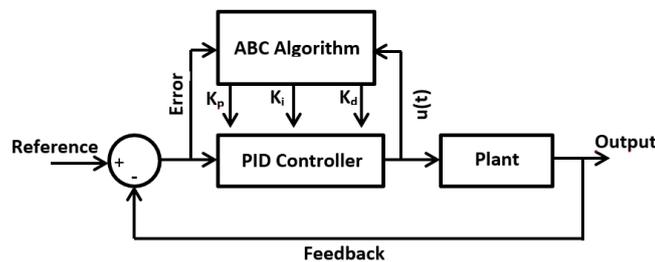


Fig. 3 Block diagram of PID optimization with ABC algorithm

2.4. Proposed Three-Channel Cost Function Based ABC

Traditional optimization algorithms inspired from nature are generally used with single cost function. In the PID controller, there are three parameters. The effect of each parameter on the output of the controlled system is different each other. If the value of proportional gain is small, steady-state error is observed at the output. On the other hand, large proportional gain produces overshoot at the output. In order to eliminate the steady-state error, integral gain is adjusted. Although, derivative term increases the dynamic response of the system, large derivative gain results in high frequency fluctuations in control input which is undesirable for real systems. Because of these reasons, it is not suitable to use single cost function to find optimum values of each PID parameter.

Remark: Since the effect of each parameter of PID at the output of the control system is different each other, appropriate cost functions should be defined to find optimum values of each PID parameter.

ISE, is the criterion that measures the performance of a system created by integrating the square of the system's error within a defined time interval; this performance measure criterion is often used in linear optimal control and probability theory [12]. One of the cost functions to be minimized in the classical PID algorithm is the ITAE performance criterion [13]. It is used to find optimum integral gain in the proposed ABC algorithm. Both ISE and ITAE is error-based functions that suitable characterize the corresponding PID parameters. Except those, the standard deviation is selected for optimizing derivative gain because small values of derivative gain are desired for real systems. Large values of derivative gain results in high frequency fluctuations having large magnitude which is highly undesirable for real systems.

In the present study, separate cost function is selected for each parameter of PID as follows:

$$\text{for } K_p, \text{ ISE} = \int_0^t e(t)^2 dt$$

$$\text{for } K_i, \text{ ITAE} = \int_0^t t|e(t)|dt \tag{11}$$

$$\text{for } K_d, \text{ Standard deviation of control input, } u(t) \tag{12}$$

The general flow chart of the proposed algorithm is given in Fig. 6. All of the cost values are calculated at the same time for the corresponding PID parameters.

3. Results and Discussion

Simulations are performed on a second order model of the system having noise at the output given in Fig. 1. Duration of the simulation is selected as 5s and the reference is given as 10V. 50 iterations are adjusted with 10 foods. In Fig. 4 the reduction of cost function selected for traditional ABC algorithm is illustrated. At the end of simulation, the output of the system is obtained as in Fig. 5. It is observed that the best parameters are obtained at 17th iteration with traditional ABC having single const function of (10).

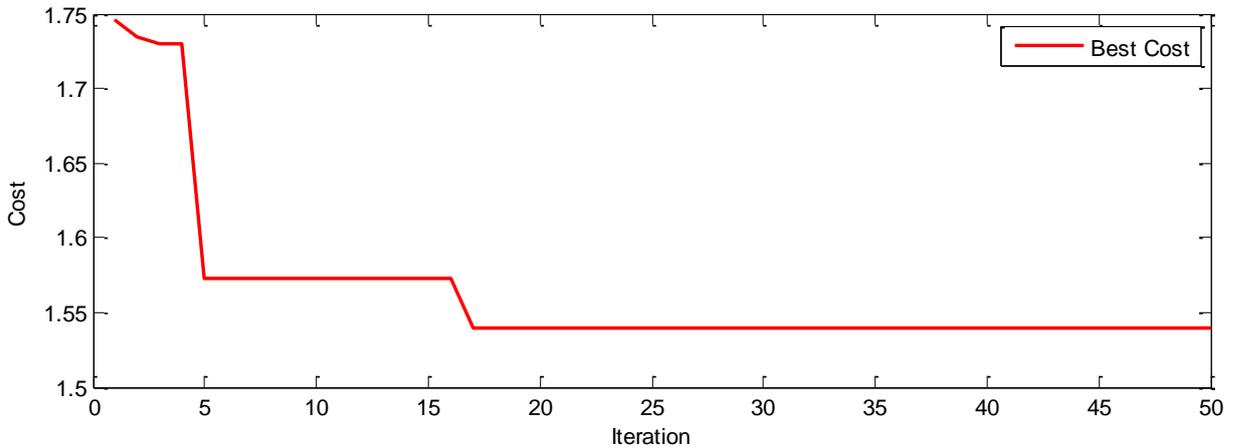


Fig. 4 Cost function change of traditional ABC algorithm

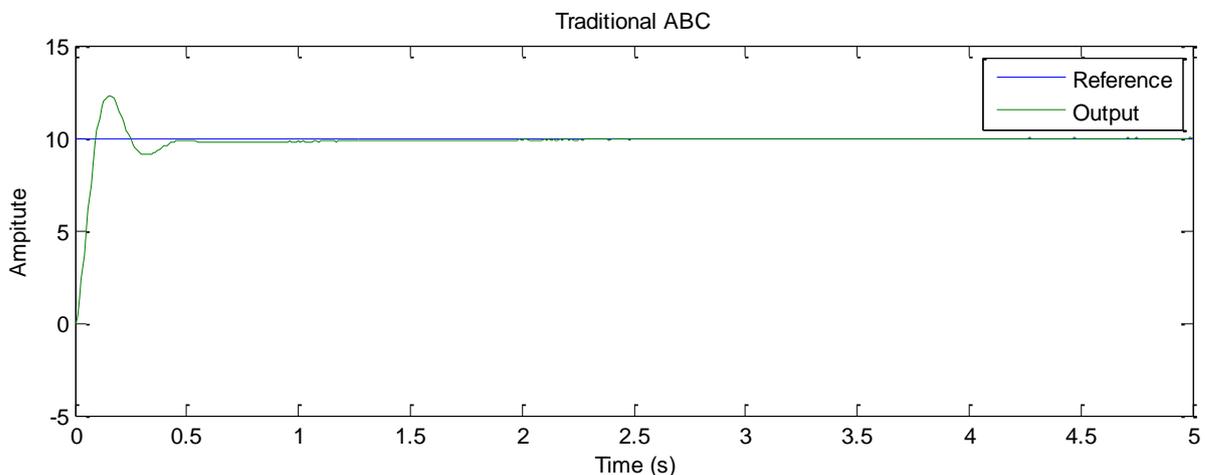


Fig. 5 Output of the system with optimized parameters of traditional ABC algorithm

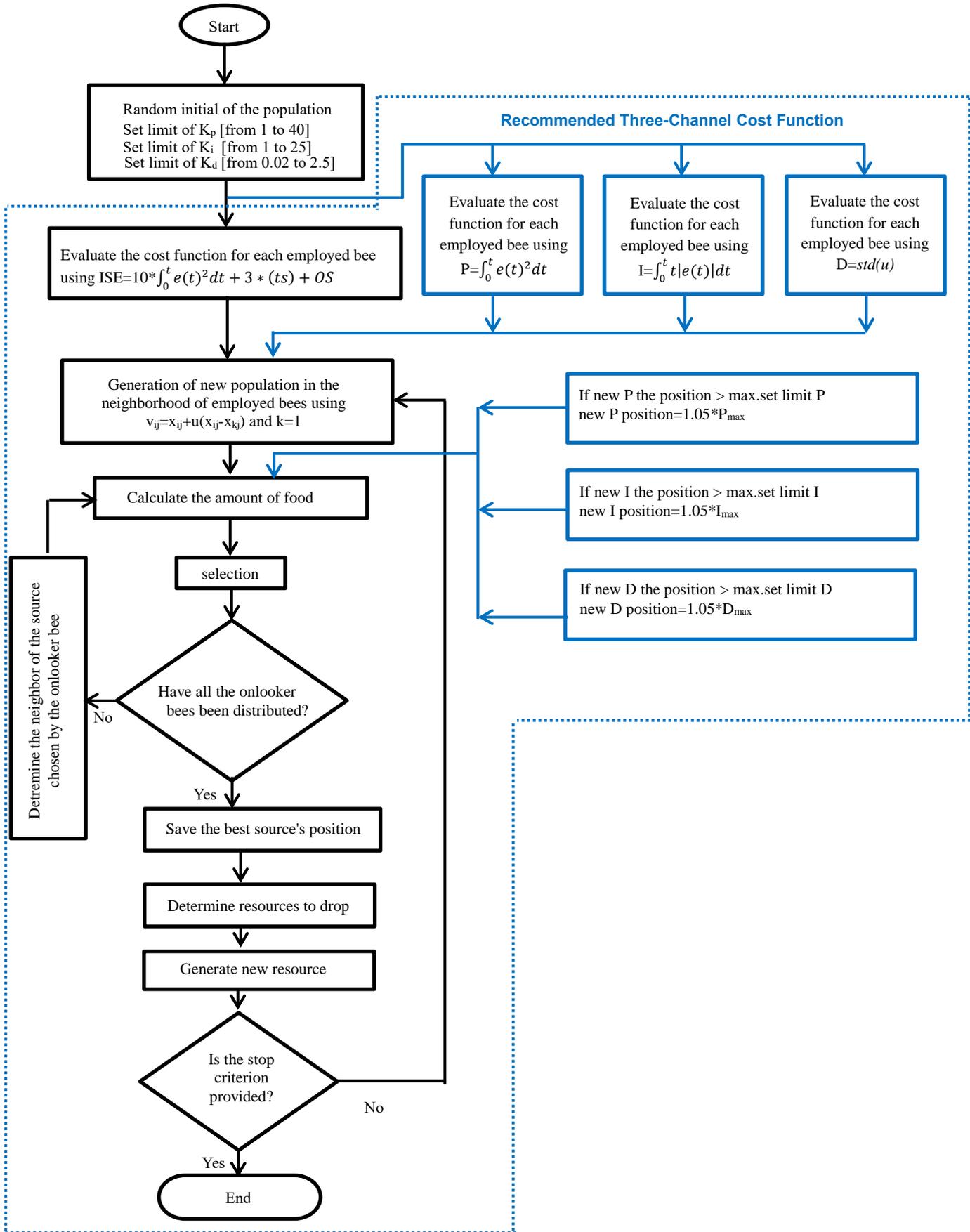


Fig. 6 Flowchart of proposed three-channel cost function based ABC algorithm

In the proposed ABC algorithm, instead of using single const function for all parameters of the PID controller, three-channel cost function is introduced for each parameter of PID controller. The simulation results with 50 iterations and 10 foods are shown in Figs. 7 - 10. The cost function performance of the proposed method is better than the traditional single cost function-based ABC algorithm.

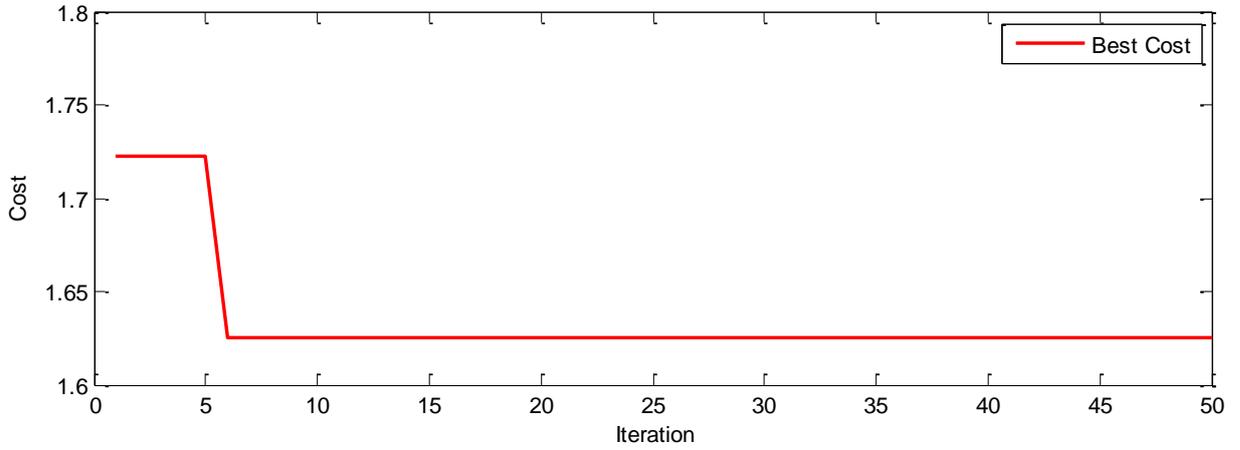


Fig. 7 Cost function change of proportional gain

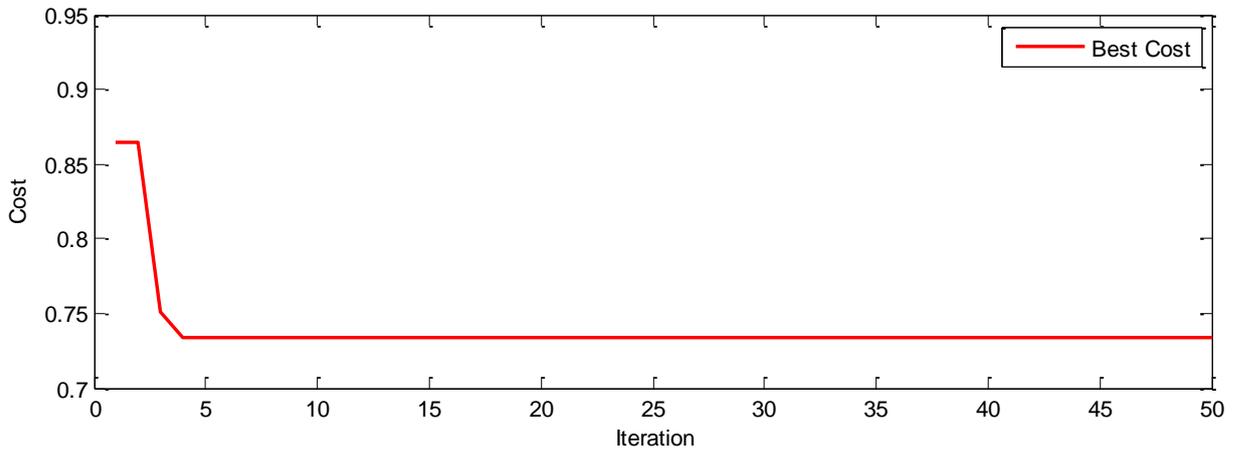


Fig. 8 Cost function change of integral gain

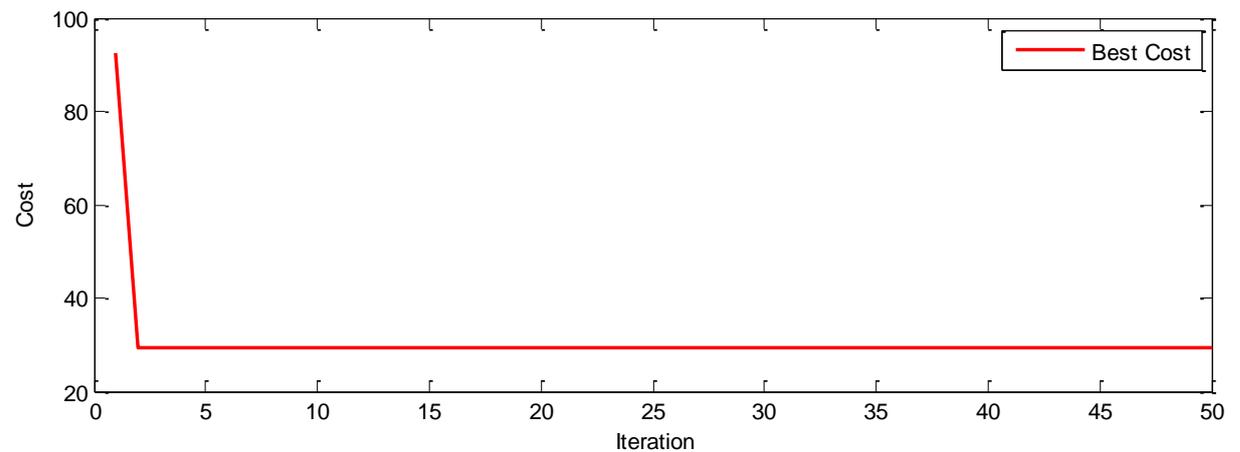


Fig. 9 Cost function change of derivative gain

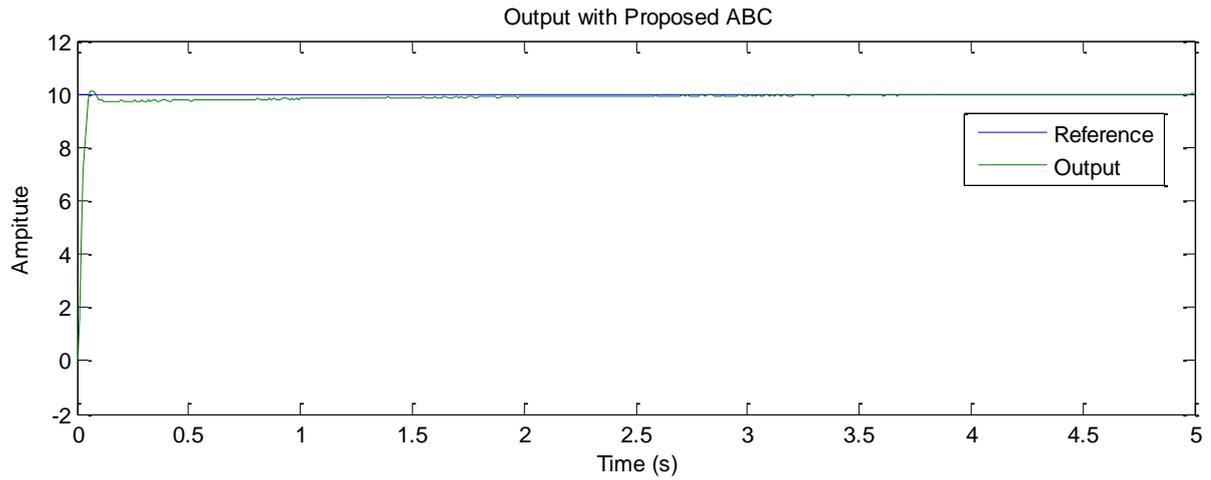


Fig. 10 Output of the system with optimized parameters of proposed ABC algorithm

The optimum PID parameters and corresponding performance values are in Table 1. The final values of ISE and ITAE show that, the performance of the proposed algorithm is better than the traditional one. In addition, there is no overshoot at the output of the system when the proposed algorithm is used. The produced control input is smoother when the proposed algorithm is used.

Table 1 Simulation results

Quantity	Traditional ABC	Proposed ABC
K_p	41.2058	27.4532
K_i	6.8154	15.4821
K_d	2.6144	2.3753
ISE	4.2014	1.6250
ITAE	0.8150	0.7373
Standard Deviation of $u(t)$	32.6335	22.8579

4. Conclusion

PID controller has three independent parameters but it is the most preferred controller because of well known characteristics of its parameters to the controlled system. On the other hand, it also important to reduce the optimizing cost of PID while using it for real systems. Since the effect of each parameter at the output of controlled system is different each other, three-channel cost function is introduced for optimization. The introduced three-channel cost function is used in ABC algorithm for PID control of a second order system having noise at the output. The simulation results are shown that the proposed cost functions give better output with less iteration. Consequently, it is better to use such types of cost functions for the controllers used in the optimization of real systems.

Future studies can be performed with different cost functions that characterize the PID parameters better than proposed functions in order to enhance the optimization algorithm.

References

- [1] Bingöl, O., Pacaci, S., (2012) "A virtual laboratory for neural network controlled DC motors based on a DC-DC buck converter", *Int J Eng Educ*, 28(3), 713 – 723.
- [2] Singh, V., Garg, V. K., (2014) "Tuning of PID controller for speed control of DC motor using soft computing techniques – A Review", *International Journal of Applied Engineering Research*, Vol. 9(9), pp. 1141 – 1148.
- [3] Tepljakov, A., Gonzalez, E. A., Petlenkov, E., Belikov, J., Monje, C. A. and Petráš, I., (2016) "Incorporation of fractional-order dynamics into an existing PI/PID DC motor control loop", *ISA Trans*, vol. 60, pp. 262 – 273.
- [4] Çelik, E., Öztürk, N., (July 2017) "Doğru Akım Motor Sürücülerini için PI Parametrelerinin Simbiyotik Organizmalar Arama Algoritması ile Optimal Ayarı", *Bilişim Teknolojileri Dergisi*, Vol.10(3).
- [5] Öztürk, C., Hançer, E., Karaboğa, D., (2014) "Küresel En İyi Yapay Arı Koloni Algoritması İle Otomatik Kümeleme", *Gazi Üniv. Müh. Mim. Fak. Der.*, Vol. 29(4), pp. 677-687.
- [6] Mavrovouniotisa, M., Lib, C. and Yangc, S., (January 12,2017) "A survey of swarm intelligence for dynamic optimization: Algorithms and applications", Preprint submitted to *Journal of Swarm and Evolutionary Computation*.
- [7] Reynolds, C. W., (1987) "Flocks, herds and schools: A distributed behavioral model". *Computer Graphics*. 21 (4), s. 25–34. doi:10.1145/37401.37406. ISBN 0-89791-227-6.
- [8] Dorigo, M. and Birattari, M., (2007) "Swarm intelligence" *Scholarpedia*, 2(9):1462, Access 11 March 2020, http://www.scholarpedia.org/article/Swarm_intelligence
- [9] Karaboga, D. (2010) "Artificial bee colony algorithm" *Scholarpedia*, vol. 5(3), Access 11 March 2020, http://www.scholarpedia.org/article/Artificial_bee_colony_algorithm

- [10] Özdemir, M., (2013) “Zaman Kısıtı Altında Takım Oryantiring Problemlerinin Yapay Arı Kolonisi Yaklaşımı ile Çözümü,” *Yüksek Lisans Tezi*, İstanbul Üniversitesi, Sosyal Bilimler Enstitüsü.
- [11] Karaboga, D, (2005) “An idea based on honey bee swarm for numerical optimization.” *Technical Report* TR06, Erciyes University, Engineering Faculty, Computer Engineering Department.
- [12] Integral Square Error. (n.d.) *McGraw-Hill Dictionary of Scientific & Technical Terms*, 6E. (2003). Access 11 March 2020, <https://encyclopedia2.thefreedictionary.com/integral+square+error>
- [13] Maiti, D., Acharya, A., Chakraborty, M., Konar, A., and Janarthanan, R., (2008) “Tuning PID and PI/ λ D δ controllers using the integral time absolute error criterion.” In 2008 4th *International Conference on Information and Automation for Sustainability*, pp. 457-462. IEEE.
- [14] Furat, M., Eker, İ., (June 2012) “Experimental Evaluation of Sliding-Mode Control Techniques”, *Çukurova University Journal of the Faculty of Engineering and Architecture*, 27(1), pp. 23-37.