Artificial Bee Colony Optimization Algorithm with Flexible Manipulator System

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Abstract – *This paper presents the Artificial Bee Colony (ABC) optimization algorithm with application to flexible manipulator system (FMS). The aim of the algorithm is to find the best possible tuning parameter that can provide accurate angle trajectory of FMS. Five performance criteria have been used as an objective function of this problem where several conditions with different ABC parameters setting are set to determine which performance criteria is most suitable in tuning the PID controller in order to obtain the best FMS performance. The results show that the ABC with Root Mean Square Error (RMSE) as performance criteria outperforms the ABC with other performance criteria and it able to tune the PID controller of FMS to the desired hub angle trajectory.*

Keywords: *ABC optimization algorithm, PID, FMS, Performance criteria*

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I. Introduction

Artificial Bee Colony (ABC) algorithm is a swarm based meta-heuristic algorithm developed by Dervis Karaboga in 2005 [1], [2]. ABC algorithm is motivated by the intelligent foraging behavior of honeybees [3]. The aim of these honeybees is to discover the food source position with high amount of nectar. Beside the scout bees who will discover the food source randomly, the employed bees and onlooker bees will also communicate with each other to share the information about the quality of food sources found. The onlooker bees will determine the quality of food sources that employed bees have found by observing the wagging dance performed by the employed bees [4]. Fig. 1 shows the food source searching process performed by honeybees. In ABC algorithm, random parameter is used to obtain the global best solution, which the artificial bee will fly around in a multidimensional search space. This random search movement method makes ABC algorithm to have a faster convergence rate to the global optimal with high accuracy [5].

In food source initialization stage, the population size is denoted as *SN*, whereby *SN* indicates the number of employed bees. By referring to the following equation (1),

$$x_{i,j} = x_{min,j} + rand(0,1)(x_{max,j} - x_{min,j}) \quad (1)$$

where $x_{i,j}$ denotes the i th food source within the population, where $i = 1,2,3, \ldots, SN$ and $j = 1,2,3, \ldots, D$ represents the search space dimension, while the $x_{max,j}$ and $x_{min,j}$ represents the upper and lower boundaries for dimension, j respectively. Each of the food source is randomly assigned to *SN* number of the employed bees, then the employed bees will evaluate the quality of the food source.

After the employed bees have explored one food source, the employed bees will adjust themselves to another food source randomly to improve the quality of the food sources by exploiting them. During this step, a new food source position, $v_{i,j}$ on the basis of the current food source position, $x_{i,j}$ is calculated by using the following equation (2).

$$v_{i,j} = x_{i,j} + \phi(x_{i,j} - x_{k,j}) \quad (2)$$

Where $k = 1,2,3, \ldots, SN$, the terms k and j are random chosen index and k must be different from i. ϕ denotes a random number from -1 to 1.

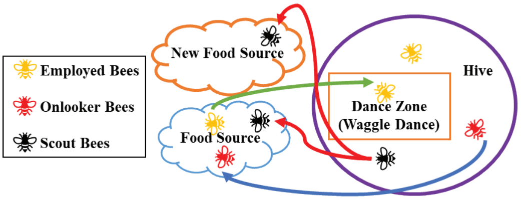


Fig. 1. The food source searching process perform by honeybees.

When any dimension of i th food source exceeds the boundaries of space which has been defined in equation (1), the food source must be positioned in the edge points of space as represented by equation (3).

$$v_{i,j} = \begin{cases} x_{max,j}\ ,\ v_{i,j} > x_{max,j} \\ x_{min,j}\ ,\ v_{i,j} < x_{min,j} \\ v_{i,j}\ ,\ x_{min,j} \leq v_{i,j} \leq x_{max,j} \end{cases} \tag{3}$$

Employed bees will compare the quality of the food source after exploring it. If the new source, $v_{i,j}$ has better quality, a greedy selection mechanism is applied. Therefore, $x_{i,j}$ will be replaced by this new food source, $v_{i,j}$. The fitness value for the new food source, $v_{i,j}$ is calculated by using the following equation (4).

$$fit_i = \begin{cases} \dfrac{1}{1+f(v_{i,j})}\ , & f(v_{i,j}) \geq 0 \\ 1+\ \left|f(v_{i,j})\right|, & f(v_{i,j}) \leq 0 \end{cases} \tag{4}$$

$f(v_{i,j})$ indicates the objective value of $v_{i,j}$.

After all the employed bees complete their search, the information about the quality of food source that they exploited is shared with onlooker bees by performing the wagging dance. The higher the quality of the food source, the better the quality of the wagging dance. The quality of wagging dance is evaluated by the following equation (5),

$$P_i = \frac{fit_i}{\sum_{i=1}^{SN} fit_i} \tag{5}$$

where the probability value, P_i denotes the quality of the wagging dance. By using the probability value, P_i which is obtained from equation (5), the onlooker bees will select a random food source which has the probability value P_i. Following this, it continues to make alterations related to its selected food source, where this activity is similar to the stage of the employed bees. Thus, a roulette wheel selection mechanism is employed in this ABC algorithm.

When the food source cannot be further improved during a specified time frame which is a threshold value (limit) which is defined before running the algorithm, the food source will be abandoned and the employed bees will become a scout bees which are responsible to search a new food source randomly to replace with those as indicated in equation (2) [6]. Fig. 2 shows the process of ABC algorithm.

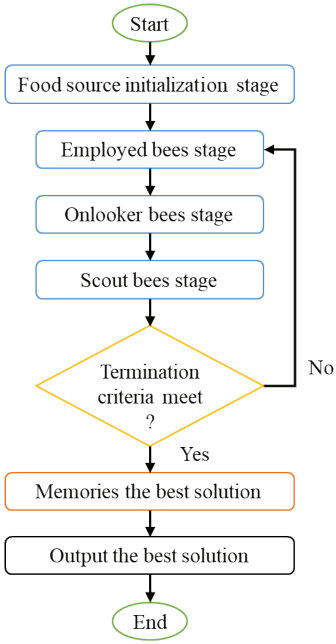


Fig. 2. The process of ABC algorithm.

Flexible manipulator system (FMS) is one of the newly introduced features used in production process in order to cope with various customer demands in the modern manufacturing industry [7]. Fig. 3 shows the flexible manipulator system consists of direct current (DC) motor, reduction gear, accelerometer, strain gauge, shaft encoder and tachometer [8]. The manipulator arm of the FMS is slew by the DC motor with reduction gear. The accelerometer and strain gauge function to observe the vibration behavior around the end-point and the root of FMS respectively, while the shaft encoders and tachometers is used to obtain the hub angle and hub velocity respectively [9].

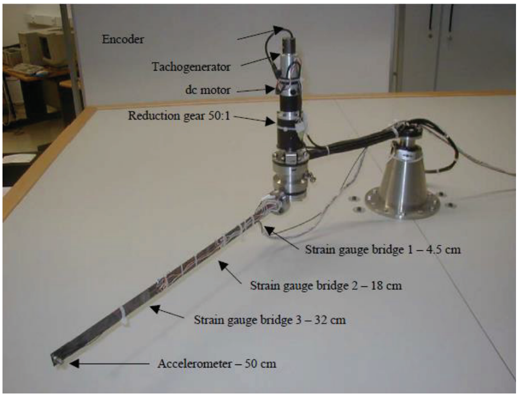


Fig. 3. The flexible manipulator system.

FMS exhibits several advantages over its rigid counterpart, for example FMS is lighter in weight, uses smaller actuator, consumes less power, has higher payload to robot weight ratio, safer to operate, less expensive, requires less material, better mobility, and operates cost-efficiently [8][10]. However, there is an extremely important problem that arise in FMS which is to maintain accurate positioning, where this problem becomes severe especially when FMS carries a load and the flexibility of the system which leads to vibration [11]. In order to overcome these problems, the ABC algorithm is used in this project to tune the proportional-integral-derivative (PID) controller that controls the hub angle of FMS in order to stabilize the system.

As the time goes with the development of technology, the research for the flexible manipulator system has been widely discovered due to the high dependency on this technology for many applications such as robotic arm, weaving mechanism, space craft antenna, magnetic tape drivers, printers, telescopic members etc. The flexible manipulator system also has been evolved from single link flexible manipulator system to two link and multi-link flexible manipulators which contain two or more joints that can make it able to move in all direction, bend in 360 degree and has multipurpose of movement [12].

In closed-loop feedback system, controller such as Proportional (P) controller, Proportional-Derivative (PD) controller, Proportional-Integral (PI) controller, and Proportional-Integral-Derivative (PID) controller can be used to control the transient respond and steady state of the system.

Proportional controller can stabilize the unstable first order process which is the process with only one energy storage by increasing the proportional gain factor K_p. This is because when K_p increases, the steady state error of the system will decrease. When the steady state error is decreased to a certain value, P controller can also decrease the rise time of the system. However, increasing K_p will lead to overshoot in the system response.

Proportional-Derivative controller is the combination of proportional and derivative controllers to improve the stability of the system in terms of reducing the overshoot and settling time without affecting the steady state error. While Proportional-Integral controller can also eliminate the steady state error due to the combination of controllers which contains of P controller, the PI controller has a negative impact in terms of the speed of the response and overall stability of the system.

In order to eliminate the problem arises in PI controller, a controller with derivative mode can be introduced into the PI controller to become a Proportional-Integral-Derivative controller. PID controller are widely used in the process industry, where more than 95% of controllers are PID controller as it combines the advantages of proportional, derivative, and integral controllers mentioned above [14]. PID controller can stabilize the unstable system in higher order processes that contain more energy storage by reducing the steady-state error by using the integral control, decreases the rise time by using the proportional control, and reduces the overshoot by using the derivative control [13].

In this paper, ABC algorithm is used to tune the gain factors of K_p, K_i, and K_d in PID controller to optimize the performance of the hub angle of the flexible manipulator system. Fig. 4 show the block diagram of the control system in FMS.

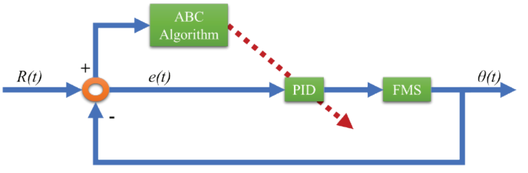


Fig. 4. The block diagram of control system FMS.

In engineering, the performance of system, machines or simulation are always be measured to observe their accuracy and effectiveness toward the effect of different input and any other aspects which have possibility to affect the output or results.

In this paper, the performance of hub angle of the flexible manipulator system can be measured in term of the rise time (Tr), settling time (Ts), steady state error (ess), and overshoot (OS). The performance is measured with different performance criteria such as Integral Squared Error (ISE), Mean Square Error (MSE), Root Mean Square Error (RMSE), Integral Absolute Error (IAE), and Integral Time-weighted of Absolute Error (ITAE) [14]. When different performance criteria are used in the simulation, ABC algorithm will generate different values in gain factors of K_p, K_i and K_d for the PID controller, where the different values in gain factors lead to different performance of the hub angle of the FMS. Therefore, the most suitable performance criteria for ABC algorithm in the FMS tuning process can be determined after comparing the performance of the hub angle.

II. Methodology

The methodology to reach main results consists of ABC algorithm is used for tuning the variables in PID controller of the flexible manipulator system with suitable performance criteria (error).

In order to evaluate the suitability of ABC algorithm in FMS for tuning the variables in the PID controller that determines the step response characteristic, an objective function and a Simulink model of the FMS must be created.

The ABC algorithm is run in 10 independent runs by using the objective function and the parameter is varied after each 10 independent runs. The data is collected for each 10 independent runs and the results are tabulated according to the categories of parameters that varied.

The K_p, K_i and K_d with the best objective value are selected and used in the simulation for the hub angle of the FMS. The step response characteristic is referred to the rise time, settling time, steady state error and overshoot.

Thus, the step response characteristic can be evaluated after the simulation is done. Beside this, the best performance of the hub angle can be concluded by set conditions to analyze the performance criteria. Fig. 5 shows the flow chart of the PID controller tuning method for the FMS by using the ABC algorithm with suitable performance criteria (error).

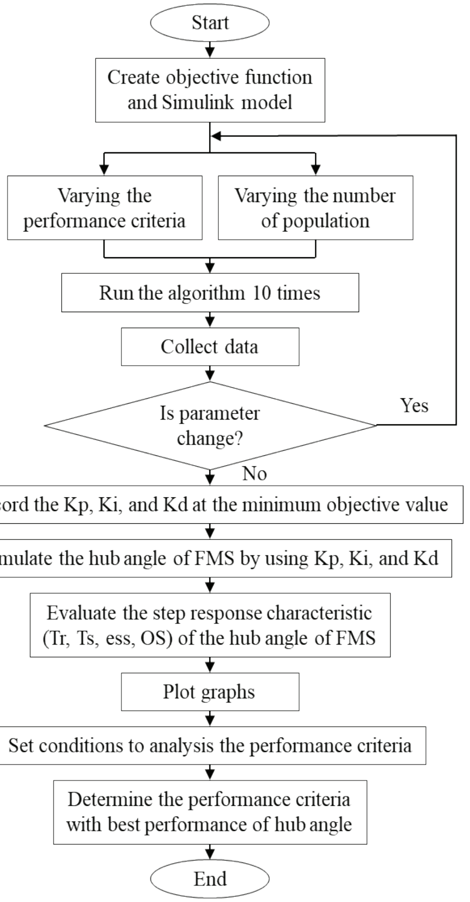


Fig. 5. Flow chart for tuning the PID controller of FMS by using ABC algorithm with suitable performance criteria (error).

III. Results

In this section, PID controller of the FMS is tuned by using the ABC algorithm. The most suitable performance criteria for the ABC algorithm in the FMS tuning process are determined.

Table I shows the optimized PID controller parameters that were obtained with different number of foods for each performance criteria after 10 independent runs of ABC algorithm. These optimized PID controller parameters are substituted into the PID controller to evaluate the optimal performance of the FMS.

TABLE I
THE OPTIMIZED PID CONTROLLER PARAMETERS WITH DIFFERENT NUMBER OF FOODS FOR EACH PERFORMANCE CRITERIA

Parameter		Proportion gain, K_p	Integral gain, K_i	Derivative gain, K_d
ISE	NP = 10	9.1125	0.2149	1.7291
	NP = 20	9.1103	0.2150	1.7290
	NP = 30	9.1115	0.2125	1.7290
MSE	NP = 10	5.3332	4.9622	1.5121
	NP = 20	3.9384	4.2520	0.8632
	NP = 30	4.7927	7.9526	1.0307
RMSE	NP = 10	3.9121	4.4397	0.7800
	NP = 20	3.9307	0.0000	1.1328
	NP = 30	4.9057	5.7510	0.9873
IAE	NP = 10	5.0911	0.0000	1.1240
	NP = 20	4.3382	0.0000	0.9465
	NP = 30	4.8658	0.0000	1.0674
ITAE	NP = 10	4.1846	0.0000	0.9238
	NP = 20	3.6475	0.0000	0.8545
	NP = 30	3.6661	0.0000	0.8534

The optimal performance of the FMS is evaluated by the step response characteristic of the hub angle of the FMS. The step response characteristic consists of the rise time, settling time, steady state error and overshoot. Table II shows the step response characteristic of the hub angle of the FMS with different number of foods for each performance criteria.

TABLE II
THE STEP RESPONSE CHARACTERISTIC OF THE HUB ANGLE OF FMS WITH DIFFERENT NUMBER OF FOODS FOR EACH PERFORMANCE CRITERIA

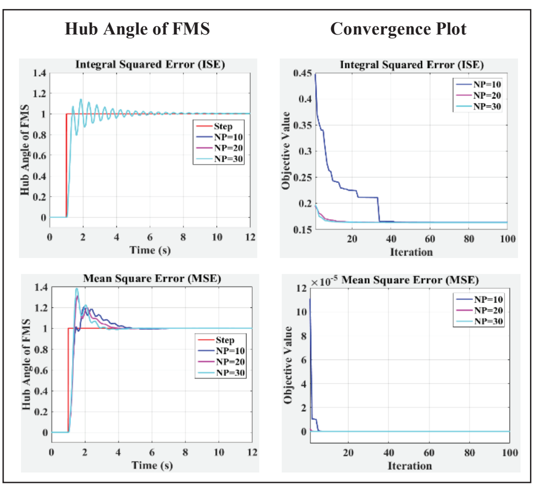
Parameter		Rise Time T_r (s)	Settling Time T_s (s)	Steady State Error, e_{ss} (%)	Overshoot OS (%)
ISE	NP = 10	0.211	5.589	0.400	14.368
	NP = 20	0.211	5.589	0.400	14.368
	NP = 30	0.211	5.589	0.400	14.368
MSE	NP = 10	0.270	4.253	0	21.341
	NP = 20	0.239	3.430	0	30.921
	NP = 30	0.218	2.792	0	38.194
RMSE	NP = 10	0.230	3.346	0	40.141
	NP = 20	0.708	2.354	0	0.505
	NP = 30	0.220	3.315	0	34.459
IAE	NP = 10	0.260	2.549	0	4.737
	NP = 20	0.263	2.363	0	6.989
	NP = 30	0.259	2.541	0	13.440
ITAE	NP = 10	0.268	2.179	0	5.851
	NP = 20	0.291	2.154	0	3.646
	NP = 30	0.286	2.159	0	4.737

The results in Table II shows that the step response characteristic for the ISE is same for different number of foods evaluated in the system. It means that the ABC algorithm converged to the same optimal solution that generated the same results in optimized PID controller parameters and step response characteristic. ISE has the shortest rise time among all the performance criteria that evaluated in the system, which means that for the application that requires faster starting time taken from 10% to reach 90% of the final value, can use ISE with 10, 20, or 30 number of foods.

However, the settling time and steady state error for ISE is the worst among all the performance criteria evaluated in the FMS. The longest settling time in the ISE causes the time taken for the system to reach the steady state and stays within 2% of steady state become slower, thus for the application that requires high stability, it is not suitable to use ISE as the performance criteria. Among all the performance criteria that were evaluated in the FMS, only ISE has steady state error, which means there were difference between the input and output although the PID controller parameters were optimized by using the ABC algorithm. The steady state error for other performance criteria is zero.

The overshoot in this project is the hub angle of the FMS that exceed the steady state. For RMSE with 20 number of foods, the overshoot and rise time is the lowest and highest respectively among all the performance criteria that were evaluated. In opposite, the highest overshoot is recorded in the RMSE with 10 number of foods, while the lowest settling time among all the performance criteria is recorded in the ITAE with 20 number of foods.

The graphs of the hub angle and the convergence plots of the FMS with difference number of foods for each performance criteria are shown in Fig. 6. The convergence plots of the FMS show that the higher the number of foods, the faster the rate of convergence to the optimal point.



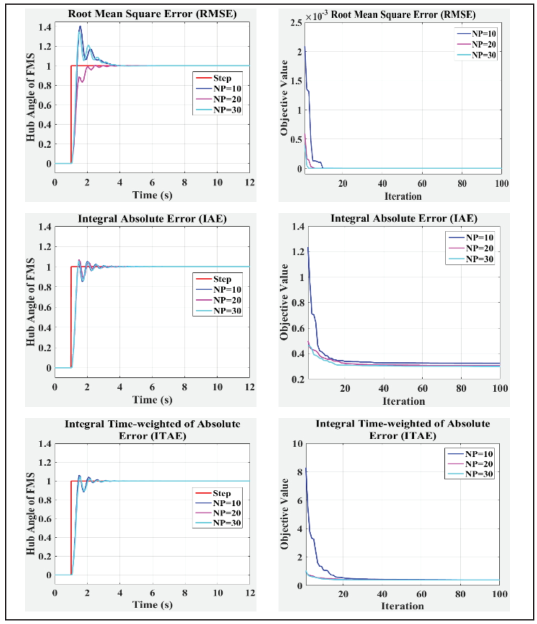


Fig. 6. The graphs of hub angle and the convergence plot of FMS with difference number of foods for each performance criteria.

Table III shows the processing time and objective value for each performance criteria and the graphs are shown in Fig. 7. The graphs in Fig. 7 show that when the number of foods is increased, the processing time of the ABC algorithm increases, and the objective value decreases. This is because when the number of foods is increased, the solutions of the optimization problem increases. Therefore, the processing time that is required to obtain the best solution is longer. The greater the number of foods, the better objective value that close to zero can be obtained.

TABLE III
THE PROCESSING TIME AND OBJECTIVE VALUE FOR EACH PERFORMANCE CRITERIA

Parameter		Processing Time, t (s)	Objective Value (Error)
ISE	P = 10	2660	1.629E-01
	P = 20	6258	1.629E-01
	P = 30	9384	1.629E-01
MSE	P = 10	2681	1.037E-20
	P = 20	6228	6.231E-22
	P = 30	9999	3.619E-24
RMSE	P = 10	3140	4.753E-12
	P = 20	6115	1.630E-12
	P = 30	10833	2.220E-13
IAE	P = 10	2794	2.987E-01
	P = 20	6915	2.984E-01
	P = 30	8987	2.984E-01
ITAE	P = 10	3130	3.822E-01
	P = 20	7021	3.811E-01
	P = 30	9666	3.809E-01

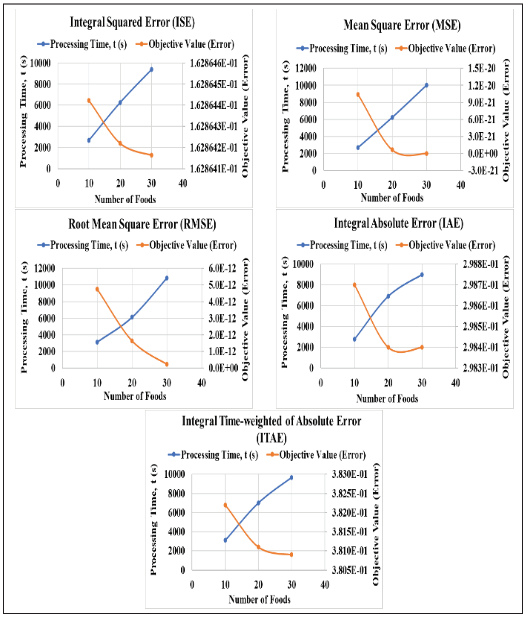


Fig. 7. The graph of processing time and objective value versus number of foods for each performance criteria.

Next, there are several conditions to analyze which performance criteria is more suitable to tune the PID controller for achieving the best FMS performance. Equation (6) is used in this analysis.

$$\theta_{per} = \beta_1 T_r + \beta_2 T_s + \beta_3 e_{ss} + \beta_4 OS \quad (6)$$

where:

θ_{per} = Performance of hub angle
$\beta 1$ = Coefficient of rise time
Tr = Rise time
$\beta 2$ = Coefficient of settling time
Ts = Settling time
$\beta 3$ = Coefficient of steady state error
ess = Steady state error
$\beta 4$ = Coefficient of overshoot
OS = Overshoot

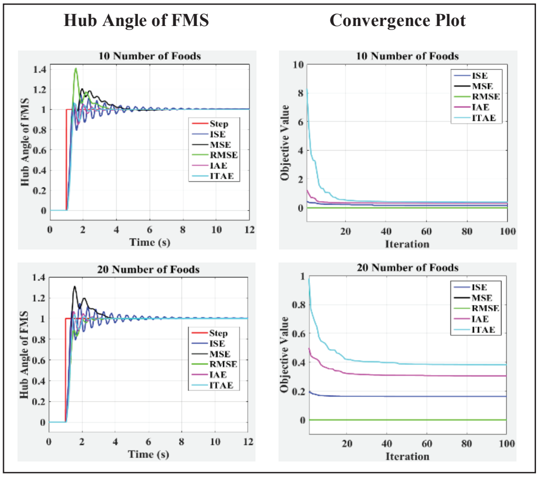
The coefficient for the transient response and steady state condition is set equally important in Condition 1, the coefficient of the rise time is set more important in Condition 2 and the coefficient of the overshoot is set more important in Condition 3. Table IV shows the equation for several conditions of the analysis. The lower the value of θ_{per}, the better the performance of hub angle.

TABLE IV
EQUATION FOR SEVERAL CONDITIONS TO ANALYSIS THE SUITABLE PERFORMANCE CRITERIA TO TUNE THE PID CONTROLLER FOR OBTAIN THE BEST FMS PERFORMANCE

	The more important coefficient	**Equation**
Condition 1	Equally important	$\beta_1 = \beta_2 = \beta_3 = \beta_4 = 0.25$ $0.25T_r + 0.25T_s + 0.25e_{ss} + 0.25OS = \theta_{per}$
Condition 2	Rise time	$\beta_1 = 0.4, \beta_2 = \beta_3 = \beta_4 = 0.2$ $0.4T_r + 0.2T_s + 0.2e_{ss} + 0.2OS = \theta_{per}$
Condition 3	Overshoot	$\beta_4 = 0.4, \beta_1 = \beta_2 = \beta_3 = 0.2$ $0.2T_r + 0.2T_s + 0.2e_{ss} + 0.4OS = \theta_{per}$

The results are calculated based on Condition 1, Condition 2, and Condition 3 . Throughout the calculation, these 3 conditions show that the lowest value of θ_{per} is RMSE with 20 number of foods. This is because of the lowest value of its overshoot compared with the others. By comparing the same overall results, the highest value of θ_{per} is RMSE with 10 number of foods since it has the highest overshoot compared with the others.

Fig. 8 shows that the objective value for RMSE is the lowest among all difference performance criteria and the rate of convergence for RMSE is also the fastest compared to the others in the convergence plot. While the ITAE has the highest objective value and slowest rate of convergence, where its characteristic in convergence plot is opposite with the RMSE. The graph of the hub angle of the FMS shows that RMSE has the lowest overshoot for 20 number of foods, but RMSE also has the highest overshoot for 10 number of foods as shown in Fig. 8.



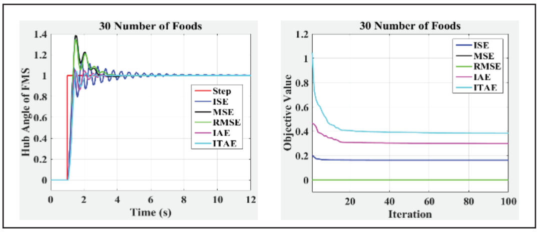


Fig. 8. The graphs of hub angle and the convergence plot of FMS with difference performance criteria for each number of foods.

IV. Conclusion

In this paper, after optimizing the PID controller parameters for the FMS by using the ABC algorithm, the performance criteria RMSE with 20 number of foods recorded the best performance of the hub angle in 3 conditions that was evaluated in this experiment due to its lowest overshoot.

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