KEPUTUSAN DEKAN FAKULTAS TEKNOLOGI INFORMASI
UNIVERSITAS BUDI LUHUR

NOMOR : K/UBL/FTI/000/001/09/21

TENTANG:
PENUGASAN KEGIATAN TRI DHARMA & PENUNJANG BAGI DOSEN
FAKULTAS TEKNOLOGI INFORMASI UNIVERSITAS BUDI LUHUR
SEMESTER GASAL TAHUN AKADEMIK 2021/2022

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NOMOR : K/UBL/FTI/000/001/09/21

TENTANG:
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FAKULTAS TEKNOLOGI INFORMASI UNIVERSITAS BUDI LUHUR
SEMESTER GASAL TAHUN AKADEMIK 2021/2022

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80.	0213068501	YUDI WIHARTO	TEKNIK INFORMATIKA
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85.	0322018502	AGNES ARYASANTI	SISTEM INFORMASI
86.	0315065602	AGUNG PRIHARTONO	SISTEM INFORMASI
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88.	0316108603	AGUS WALUYO	SISTEM INFORMASI
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90.	0316079202	ANUGRAH BAGUS SUSILO	SISTEM INFORMASI
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95.	0312049102	BAYU WIDIA SANTOSO	SISTEM INFORMASI
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99.	0328127303	DENI MAHDIANA	SISTEM INFORMASI
100.	0303129201	DEVIT SETIONO	SISTEM INFORMASI

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101.	0310128401	DEWI KUSUMANINGSIH	SISTEM INFORMASI
102.	0313049001	DHANY WICAKSONO	SISTEM INFORMASI
103.	0322018301	DIAN ANUBHAKTI	SISTEM INFORMASI
104.	0305036302	DJATI KUSDIARTO	SISTEM INFORMASI
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107.	0321117301	FX BIMA CAHYA PUTRA	SISTEM INFORMASI
108.	0306027701	GANDUNG TRIYONO	SISTEM INFORMASI
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110.	0325058101	HENDRI IRAWAN	SISTEM INFORMASI
111.	9903260690	HESTYA PATRIE	SISTEM INFORMASI
112.	0303048001	HUMISAR HASUGIAN	SISTEM INFORMASI
113.	0314049302	INDAH PUSPASARI HANDAYANI	SISTEM INFORMASI
114.	0303118201	ITA NOVITA	SISTEM INFORMASI
115.	0312069205	JEREMY JONATHAN	SISTEM INFORMASI
116.	0303067601	JOKO SUTRISNO	SISTEM INFORMASI
117.	0307079301	JULAIHA PROBO ANGGRAINI	SISTEM INFORMASI
118.	0319059103	KUKUH HARSANTO	SISTEM INFORMASI
119.	0317057603	LIHIN	SISTEM INFORMASI
120.	0311068701	LINDA MORA	SISTEM INFORMASI
121.	0330039301	LUTHFI SYAWALUDIN	SISTEM INFORMASI
122.	0422036901	MARDI HARDJIANTO	SISTEM INFORMASI
123.	0307038703	MARINI	SISTEM INFORMASI
124.	0328116903	MAYANTI	SISTEM INFORMASI
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126.	0324078202	MUHAMAD FITRA SYAWALL	SISTEM INFORMASI
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128.	0318077601	NIDYA KUSMAWARDHANY	SISTEM INFORMASI
129.	0315028502	NOFIYANI	SISTEM INFORMASI
130.	0305078002	NONI JULIASARI	SISTEM INFORMASI
131.	8812180018	NURALIA	SISTEM INFORMASI
132.	0315057803	NURWATI	SISTEM INFORMASI
133.	0302057901	PAINEM	SISTEM INFORMASI
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135.	0305128107	RATNA UJIAN DARI	SISTEM INFORMASI

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141.	0317098201	SAFITRI JUANITA	SISTEM INFORMASI
142.	0329098202	SAMSINAR	SISTEM INFORMASI
143.	0322049302	SITI EVA SYARIFAH	SISTEM INFORMASI
144.	0309097401	SRI MULYATI	SISTEM INFORMASI
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Weighted-Sum Extended Bat Algorithm Based PD Controller Design for Wheeled Mobile Robot



Nur Aisyah Syafinaz Suarin, Dwi Pebrianti, Nurnajmin Qasrina Ann, and Luhur Bayuaji

Abstract PID controller of WMR needs to be tuned as precise as possible in order to develop a good performance of WMR that is able to move from initial position to a desired position with the fast time response and minimum steady state error. Weighted-sum Extended Bat Algorithm (WS-EBA) is a multi-objective optimization method based on Extended Bat Algorithm. The weighted optimization approach is used to search the optimum value of Proportional-Integral-Derivative (PID) gains controller of Wheeled Mobile Robot (WMR) by referring to x and y position. Several experiments are conducted to test the effect of variables or parameters control to the value of PID gains and performance of WMR. Those parameters are the type of PID controller, number of agents in WS-EBA and the optimization functions used in the system to search the optimum value of PID gains. Results obtained from this research study indicates that PD controller, 30 number of searching agents and ITAE as the objective function gives the most suitable controller for WMR with result for X position is 11.00, 20.08 s and 0.00% for rise time, settling time and overshoot respectively. Additionally, for Y position, the results are 12.11, 22.08 s and 0.00% of rise time, settling time and overshoot respectively. The comparison of WS-EBA with Weighted-sum Particle Swarm Optimization (WS-PSO) and Weighted-sum Bat Algorithm (WS-BA) is also experimented in this research. WS-EBA outperformed the rest with the best result performance of WMR, consistency of solution, fastest convergence rate and the most balance of exploration and exploitation phase.

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Keywords Weighted-sum · Extended bat algorithm · Wheeled mobile robot · Proportional-Integral-Derivative (PID) controller

1 Introduction

Wheeled Mobile Robot has gained increasing popularity due to its ability and flexibility to freely move by using the wheels and potentiality to be applied on numerous applications such as to lift and moving heavy and static object. In order to achieve predefine goal or desired location that the WMR need to moves, it has to be equipped with a good controller. Fast response, minimum settling time and overshoot are the criteria which determine the performance of the controller on WMR. There are plenty of controllers available nowadays, e.g. Proportional-Integrated-Derivative (PID) controller, path planning, fuzzy logic controller and the simplest controller which is on-off controller [1–3]. The simple solution is preferable to be applied to the system to solve the problem rather than complex solution. However the simplest controller, on-off controller has an oscillating behaviour which limit its usage. The ultimate aim of the controller is to maintain zero error or minimum steady state error which is the difference between the process output and the desired output.

Proportional-Integrated-Derivative (PID) controller is well known with its simple structure and ability to produce a robust performance for the system. It has been applied to a lot of application such as to the system of machine [4], controller of flood and to control a mobile robot [5–7]. PID is a basic controller which consists of three unfixed gains variables. The gain that gives proportional output to the current error is known as P controller. When applied alone, P controller tends to produce steady state error and need to manual reset [8]. Integrated or I controller is the gain that counter-backs the limitation of P gain by eliminating the steady state error. However as the value of I gain increases, the speed is going to decrease. Last but not least is the Derivative or D controller. The D gain has the ability to become flexible and helps the system reacts when there is a change to the set point. Future can be predicted well by applying the D controller. The lag of system response due to the I gain can be fixed by applying D gain. However, the combination of each gain as a set of controller depends on the suitability and performance required by the system. The trade is between the accuracy, the speed and the robustness [9].

The gains of PID controller is not fixed and needs to be tuned to suit with the system and process. There are several well-known methods. The most basic method is trial and error method and manual tuning [9, 10]. It is the most simplest method but not a systematic method and time consuming. Next is Ziegler-Nichols method. There are two additional constants need to be tuned by using this method, which is constant for oscillation and period of oscillation [6]. The lengthy method and adding more constants make the controller become more complicated and hard to be tuned to the optimized value. Last but not least, the method that can be applied to tune the PID gains is by using mathematical optimization and metaheuristics

optimization method. Particle Swarm Optimization (PSO) was applied to tune PD controller [5, 11, 12], Simulated Annealing was applied to tune load frequency controller [13] and genetic algorithm (GA) was applied to solve unicycle type of mobile robot [7, 9]. Swarm intelligence is one of the group of metaheuristics algorithm method which is inspired by the swarm behaviour of living things. There are abundance of optimization methods available as according to No Free Lunch (NFL) theorem, there are no single solution of optimization is able to be applied to all problems. Thus the new optimization method is still rapidly growing.

Extended Bat Algorithm (EBA) is a hybrid optimization method developed from Bat Algorithm (BA) optimization and Spiral Dynamic Algorithm (SDA) optimization. It was created [14] and never been applied on the problem to optimize PID controller yet as recorded in published papers. The steps of the EBA optimization method which improve the searching method by search in spiral according to SDA and agents movement as in BA. This is to improves the result to avoid from trap in local minima and speed up the process to converge to find the best solution. PID controller needs to be tuned to the optimum value which give the best output with the minimum steady state error, minimum overshoot and fast response of the system. This is because WMR is the mobile robot which keeps moving to the desired position.

Weighted-sum is a multi-objective optimization method which used to optimize and find solution for multiple solutions in one system. Weighted-sum is the simplest solution to optimize multiple objective due to the linearize method applied in the approach. The linearize make the multiple objective functions become single objective function by applying weightage value for each objective function. Weighted-sum Extended Bat Algorithm (WS-EBA) is multiple-objective optimization which solve the optimization based on EBA approach. WS-EBA is chosen in this research study because there are two objective functions of WMR needs to minimize, i.e. error of x position and y position of WMR.

Apart from the ultimate aim which is to tune the gains of PID controller, there are several variables need to take into the consideration. These variables were recorded had gave impact and influenced the results of the controller when tuning by using metaheuristics optimization method. The variables are the number of agents used in the optimization method, the objective function and hyperparameters tuning of metaheuristics algorithm. Each algorithm has different type and number of hyperparameters. EBA consists of loudness, pulse rate, spiral radius and spiral angle while hyperparameter for particle swarm optimization (PSO) algorithm is the cognitive component, social component and inertia weight. The hyperparameter is important to determine the local and global searching by the agents and to control the exploration and exploitation phase for all the agents.

Thus in this paper, the most popular and simple yet can produce good performance of result, PID controller is being discussed and investigated to be applied to WMR. The paper is organized as follows. Section 2 presents the experimental design and methods while in Sect. 3, the simulation results and performance comparison in terms of are discussed. Lastly, conclusion is drawn in Sect. 4.

2 Methodology and Experimental Setup

2.1 Closed Loop System for WMR and PID Controller

Figure 1 shows the example of wheeled mobile robot used in this study which is the mBot wheeled mobile robot. The most important parameters of the mBot which adapted to the kinematic model are the length, L, the distance between the two wheels and radius, r, the radius of the wheel. The control system is fully developed from kinematic model and equation derived in Fig. 1 and Eqs. (1) to (8). This research study is a simulation-based study, thus converting a real mobile robot to control system that the performance can be measurable is a necessary. The input of the control system is the desired position (x and y position) where WMR needs to reach and the output is the current position of the WMR. A closed loop control system of the WMR is designed as in Fig. 2. The objective of this system is to minimize or eliminate the error which is the difference between desired position and current position.

$$\dot{x} = \frac{r}{2}(\omega_R + \omega_L)\cos\theta \tag{1}$$

$$\dot{y} = \frac{r}{2}(\omega_R + \omega_L)\sin\theta \tag{2}$$

$$\dot{\theta} = \frac{r}{L}(\omega_R - \omega_L) \tag{3}$$

r is the radius of the mBot's wheel, ω_R is the right wheel angular velocity, ω_L is the left wheel angular velocity and L is the distance between the mBot's wheels.

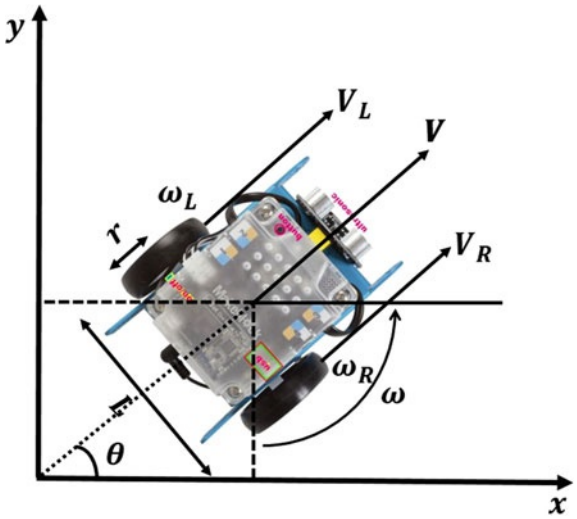

Fig. 1 Development of kinematic model of mBot (WMR)

In order to develop a kinematic model a single upright wheel on the plane is given as in Eqs. (4) and (6).

$$\dot{x} = v \cos\theta \tag{4}$$

$$\dot{y} = v \sin\theta \tag{5}$$

$$\dot{\theta} = \omega \tag{6}$$

By rearranging Eqs. (1) to (6), we get:

$$\omega_R = \frac{2v + \omega L}{2r} \tag{7}$$

$$\omega_L = \frac{2v - \omega L}{2r} \tag{8}$$

where ω_R is the angular velocity of right wheel of the mBot and ω_L is the angular velocity of the left wheel of the mBot. The output of ω_R and ω_L are formed from the inputs of v and ω. A constant number 0.113 m is used in the model. This constant number is the distance, L between two mBot's wheels and r refers to the radius of the mBot's wheel which is 0.03 m. The kinematic model has been verified by Dwi Pebrianti et al. by conducting an experiment to compare the developed kinematic model with the actual mBot robot performance [15]. The accuracy of the developed kinematic model is 85%.

Proportional-Integral-Derivative (PID) controller in the system is aiming to reduce the errors that feedback into the system. Weighted sum Extended Bat Algorithm (WS-EBA) is a multi-objective hybrid metaheuristic algorithm. It can be clearly seen in Fig. 2, there are two errors, the first error is for x position and second error is for y position. Thus, a single objective optimization technique is not able to minimise both of the errors by tuning the PID controller, multi objective optimization is needed to be

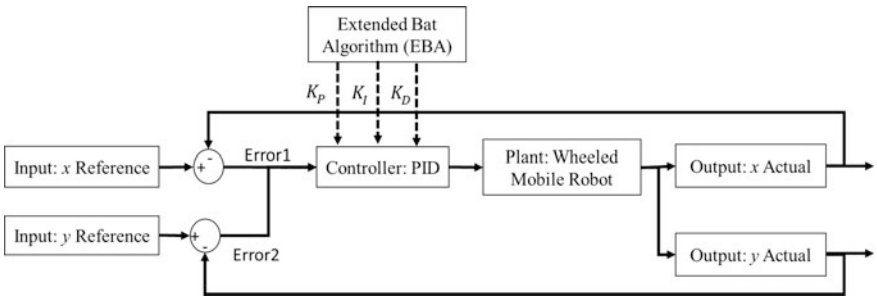

Fig. 2 Closed loop control system, controller (PID), plant (kinematic model of WMR), input (x and y desired position), output (x and y current position)

applied in the system. Weighted sum is the simplest multi-objective algorithm as it linearize into one function and the equation is stated in Eq. 9.

$$f_T = (W_1 \times f_1) + (W_2 \times f_2) \tag{9}$$

where f_T is total fitness function, W_1 is the weight for first fitness function, W_2 is the weight for second fitness function, f_1 is the first fitness from the first objective function and f_2 is the second fitness from the second objective function.

It is important to have a robust PID controller which can reduce and eliminate the errors in a short time and produce a stable performance of WMR. PID controller is a classical well-known controller due to its simple structure, convenient debugging, strong adaptability and most widely used in the systems. However, the challenging for this controller is to tune the gains to the optimized value so that the best performance of the system can be produced.

2.2 Weighted-Sum Extended Bat Algorithm

Extended Bat Algorithm (EBA) is a low level meta-heuristic hybridization algorithm of original Bat Algorithm (BA) and Spiral Dynamic Algorithm (SDA). The hybridization is known as low level because the hybrid is only involved in one part of Bat Algorithm which is the exploration part. Original Bat Algorithm is updating the position of the agent by using Eq. (10) while in SDA, updating the position is by using Eq. (11). However, in EBA, updating position is combination of BA and SDA as stated in Eq. (12).

$$x_i^t = x_i^{t-1} + v_i^t \tag{10}$$

$$x_i^{t+1} = rR(\theta)x_i^t - (r.R(\theta) - I_n)x^* \tag{11}$$

$$x_i^t = \left[rR(\theta)x_i^t - (r.R(\theta) - I_n)x^*\right] + v_i^t \tag{12}$$

where x is agent position, v is the velocity of the agent, r is the step rate between $x(t)$ and x^* *per t,* θ is the rotation rate $[-\pi, \pi]$, $R(\theta)$ is the composite rotation matrix, i is the number of agent, t is the number of iteration, I_n is the matrix identity and x^* is the position of best agent.

The combination of both algorithms is expected to perform well together and could improve the performance of the original BA. This is because, the performance of optimization method is depending on its ability to balance exploration and exploitation phases. By applying SDA searching method, the exploration phase of BA can be improved. The only part taken from SDA is for updating the x value, and the remaining algorithm is from BA. Figure 3 is the flowchart for WS-EBA tune PID controller of WMR.

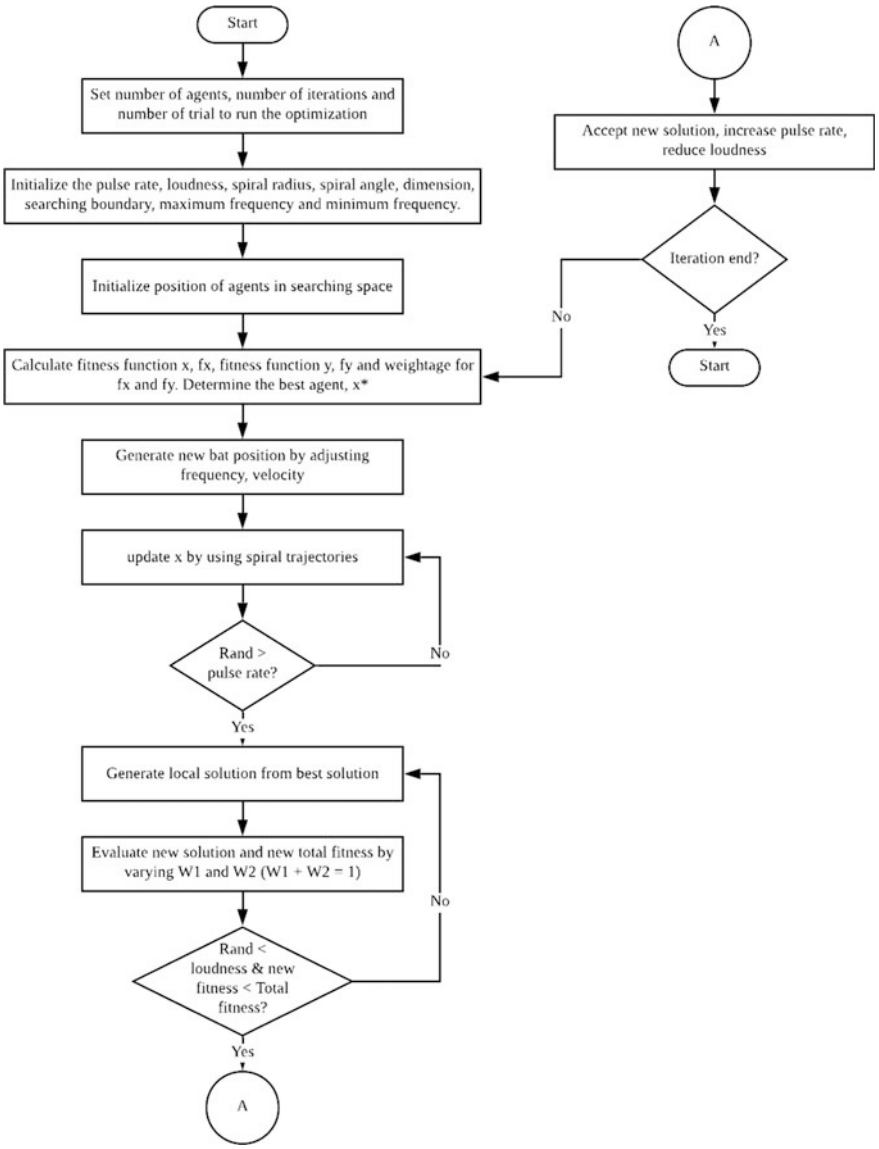

Fig. 3 Flowchart of Weighted-sum Extended Bat Algorithm (WS-EBA) to tune PID controller for WMR

Table 1 Parameters setup for WS-EBA, WS-PSO and WS-BA

Parameter	WS-EBA	WS-PSO	WS-BA
Number of searching agent	10/30	30	30
Number of iterations	100	100	100
Initial loudness, A	0.5	–	0.5
Initial pulse rate, p	0.5	–	0.5
Spiral radius, r	0.95	–	–
Spiral angle, θ	1	–	–
K_P boundary	[0 50]	[0 50]	[0 50]
K_I boundary	[0 100]	[0 100]	[0 100]
K_D boundary	[0 300]	[0 300]	[0 300]
Cognitive component, c1	–	0.9	–
Social component, c2	–	0.9	–
Inertia weight, w	–	0.5	–

Objective function (optimization index) is an important component in optimization method because the value need to be optimized (either minimized or maximize) is relied on the objective function. Objective functions which usually used to minimize the error in control system are Integral Square Error (*ISE*), Integral Absolute Error (*IAE*), Integral Time Squared Error (*ITSE*) and Integral Time Absolute Error (*ITAE*). Equations (13) to (16) are the equations of the objective functions, all the objective functions had been tested. The best objective function should be able to minimise the errors and give the optimum value of gain of PID controller for WMR.

$$ISE = \int_0^\infty \left(e_1^2(t) + e_2^2(t) + \ldots + e_n^2(t)\right)dt \tag{13}$$

$$\mathrm{IAE} = \int_0^\infty \left(|e_1(t)| + |e_2(t)| + \ldots + |e_n(t)|\right)dt \tag{14}$$

$$\mathrm{ITSE} = \int_0^\infty t \cdot \left(e_1^2(t) + e_2^2(t) + \ldots + e_n^2(t)\right)dt \tag{15}$$

$$\mathrm{ITAE} = \int_0^\infty t \cdot \left(|e_1(t)| + |e_2(t)| + \ldots + |e_n(t)|\right)dt \tag{16}$$

2.3 Experimental Setup

The parameter setup for WS-EBA is shown in Table 1. The experiment is conducted to determine the best PID based controller to be applied to the WMR, the

appropriate number of searching agents to be used to search the gains of PID controller in the algorithm and the best objective function to be used in the optimization process. All of the criteria mentioned are important in order to produce the robust performance of PID controller for WMR. In the table as well, the parameters setup for WS-PSO and WS-BA optimization are listed. Both of the optimizations are required in the comparison of controller tuned by proposed method with others swarm based optimization method. For PSO, the parameter setup is referring to the paper from [12] as recommended. For BA, the parameter setup is referring to our previous research paper [16].

3 Result and Discussion

3.1 PID Controller for WMR Tuned by WS-EBA

Proportional-Integral-Differential (PID) is a controller which consists of three gains those need to be tuned as precise as possible corresponding to the system. However, not each gains of the controller i.e. P-I-D, is compulsory to be applied in the system, it is depending on the suitability of the system to use those controller components. In order to develop the robust controller for wheeled mobile robot (WMR) of mobile robot, different PID based controllers are being tested and the best controller with outperformed performance is selected.

Table 2 PID gains value tuned by WS-EBA

Controller	No. of agents	Objective functions	K_P	K_I	K_D
PID	10	ISE	0.015	0.013	0.014
		IAE	0.004	0.004	2.901
		ITSE	0.000	0.004	477.447
		ITAE	0.000	0.003	145.828
	30	ISE	0.002	0.001	65.549
		IAE	0.015	0.013	0.013
		ITSE	0.008	0.006	152.931
		ITAE	0.000	0.002	236.19
PI	10	ISE	0.013	0.013	0.000
		IAE	0.009	0.012	0.000
		ITSE	0.014	0.012	0.000
		ITAE	0.009	0.011	0.000
	30	ISE	0.012	0.013	0.000
		IAE	0.011	0.013	0.000
		ITSE	0.012	0.012	0.000
		ITAE	0.013	0.012	0.000

(continued)

Table 2 (continued)

Controller	No. of agents	Objective functions	K_P	K_I	K_D
PD	10	ISE	0.105	0.000	0.093
		IAE	0.124	0.000	0.116
		ITSE	0.117	0.000	0.108
		ITAE	0.144	0.000	0.129
	30	ISE	0.221	0.000	0.207
		IAE	0.221	0.000	0.208
		ITSE	0.188	0.000	0.170
		ITAE	0.229	0.000	0.214
No PID	0	ISE	0.000	0.000	0.000
		IAE	0.000	0.000	0.000
		ITSE	0.000	0.000	0.000
		ITAE	0.000	0.000	0.000

Proposed method to tune PID controller is multiple-objective-optimisation method which is weighted sum Extended Bat Algorithm (EBA). The aim of this experiment is to recognize the most suitable PID controller for WMR of mBot. Table 2 shows the gain values of 3 types of PID controller tuned by WS-EBA. Additionally, the system without PID controller is included in this experiment as well to observe the difference between them. The agents in the algorithm are assigned to search for the optimal solution of the PID gains. For PI and PD controller, D gain and I gain has been neglected respectively. For no PID controller, all the gains have been neglected and the system is run without controller.

The solutions which is the value of gains for PID controller obtained by the WS-EBA for PID, PI and PD are different due to the different number of agents and objective function used in the system. The gains obtained by the PID and PI controller for 10 and 30 agents show only a small difference, in the other hand, PD controller obtained value with big difference with each other. The value obtained by 30 agents are higher than 10 agents. This is because the agents are searching based on the boundary of search area and the number of agents play important role to obtain the best solution, avoid to easily trap in local minima and to explore the area with the best solution.

Table 3 shows the performance of WMR when applying the gains in Table 2. The WMR system is as shown in Fig. 2. PD controller, with 30 number of agents and tuned by using ITAE objective function outperformed other controllers with the best value of rise time, settling time and percentage of overshoot. In the WMR system, short rise time is better than long time to rise to the desired position, short settling time is better than long time to stable and settle down and the low value of the overshoot percentage is better than has high overshoot percentage to determine the performance of WMR. Thus, PD controller recorded the best result based on the criteria above with the shortest rise time, settling time and the lowest value of percentage of overshoot.

PID and PI controller show the worst result by not reaching the reference position which is 1 m as stated by the result of settling time and percentage of the overshoot. The system is run for 60 s and during that time, the system still not reaches the settling time. The percentage of overshoot is too high which indicates that the system is not stable and unable to reach to the desired position. Performance of the robot without PID controller shows that it takes the longest settling time and rise time. The WMR needs to react fast as it is a moving robot that need to accomplish a task. Although the percentage of overshoot for the system without PID controller is among the lowest, PD controller perform the best in all aspects including for rise time and settling time.

PD controller consists of P and D gain values in the controller, without I gain value. I is integral gain which the function is to eliminate the steady state error. I gain limits the speed of the response and stability of the system. This gain can give integral windup effect to the system which accumulates a significant error during the rise, thus leads to continuous overshooting of the system performance. This situation can be avoided by recognizing the range of the gain. For the system that requires fast response, I components in the controller is not encourage to be implemented in the system.

For WMR system, the present of I gain value, such as in PID and PI controller make the error that is fed into the system accumulates and continue to increase the overshoot values. The superior controller for the system in this study is PD controller with the fastest rise time and the most accurate steady state value.

Karahan et al. [17] in their paper applied PD controller integrated with fuzzy controller for the wheeled mobile robot system, Baral et al. [13] applied PI controller in the load frequency controller system and Ye et al. [4] applied PID controller in the hydraulic system for position control. The PID controller is a well-known classical controller, easier to be implemented to the system compared with other controllers and can produce reliable result. However, to implement to the system, the suitability needs to be tested and recognized first. For this WMR system, PD controller is the best controller to be applied.

From the result, the similarities of all controller are the present of P gain value in the controller except for no controller. P is proportional gain which makes the feedback error in the system proportional to the system. The function is to help to stabilise the system at the same time remaining the steady state error, SS_E. The optimal value of P gain is important to control the oscillation of the robot. By referring to Table 2, table of PID gain values for each controller, P gain for PD controller is not the lowest or the highest, but the performance is the best among all in term of rise time, settling time and steady state error.

Searching agent is important element in optimization procedure where the agent is used to search the best result. The values of gain obtained by 10 number of agents is higher than by 30 number of agents. However, the high values of gain does not

indicate the best performance of WMR, the optimum value does. The searching area plays the important role as well in this process. The number of searching agent must be appropriate with the searching area, as too many searching agents in small area might lead to deadlock situation and too little number of searching agents might make the agents unable to explore the whole area and produce the bad result.

Table 3 Result analysis performance of WMR with different types of PID controller

Controller	No. of agents	Obj. func.	X position			Y position		
			T_r (s)	T_s (s)	O_s (%)	T_r (s)	T_s (s)	O_s (%)
PID	10	ISE	22.26	59.59	350.53	9.13	13.38	1.14
		IAE	20.61	49.96	1003.54	31.08	46.54	1.52
		ITSE	35.89	59.42	96.27	36.08	59.42	96.28
		ITAE	37.96	59.02	98.50	37.78	59.02	98.49
	30	ISE	37.94	59.35	1051.42	37.84	59.35	1.54
		IAE	22.45	59.58	97.07	8.95	13.10	97.07
		ITSE	38.05	59.39	98.50	38.03	59.39	98.50
		ITAE	36.16	59.40	93.32	36.09	59.40	93.32
PI	10	ISE	22.45	59.58	8557.86	0.33	5.67	1.45
		IAE	22.05	59.65	1035.47	9.44	14.01	1.53
		ITSE	21.97	59.64	887.99	9.47	13.84	1.42
		ITAE	22.04	59.65	8578.58	9.44	14.00	1.46
	30	ISE	22.43	59.58	1029.98	8.84	13.05	1.59
		IAE	22.47	59.58	1030.47	8.78	13.06	1.55
		ITSE	22.04	59.63	915.27	9.32	13.69	1.48
		ITAE	22.02	59.64	8848.02	9.33	13.85	1.53
PD	10	ISE	21.89	36.82	0.36	22.36	38.02	0.93
		IAE	18.99	32.99	0.79	19.63	34.70	0.43
		ITSE	20.47	36.72	0.06	21.16	38.45	0.08
		ITAE	**16.66**	**29.83**	**0.01**	**17.43**	**31.59**	**0.02**
	30	ISE	11.32	20.67	0.01	12.45	22.62	0.00
		IAE	11.31	20.57	0.00	12.43	22.55	0.01
		ITSE	12.83	23.48	0.00	13.91	25.82	0.00
		ITAE	**11.00**	**20.08**	**0.00**	**12.11**	**22.08**	**0.00**
No PID	0	–	41.28	58.97	257.09	2.31	59.94	0.01

In Table 3 as well shows the result performance for X position of mobile robot using PID, PI, PD controller and without PID controller tuned by EBA with different number of searching agents. PD controller with 30 number of searching agents produce better result with shorter rise time and settling time than 10 searching agents. The difference between these two comparison is quite significant as the difference is 30 searching agent is faster by 5.66 s than 10 searching agent for rise time and 8.75 faster for rise time.

For Y position, the result shows a big difference of performance for the comparison for PD controller for 10 and 30 searching agents. 30 searching agents produced better result for settling time by 12.11 s. The searching area of the PD controller which are set by the parameters of upper boundary and lower boundary for both gains are appropriate with the number of searching agents. Thus, the searching agents are able to search and obtain the result that gives good performance for the mobile robot. The number of searching agent is one of the important factor that can influence the performance of the system.

Sahib et al. [18], mentioned in his research that by using the most suitable objective function can highly improve the PID tuning optimization. The result of comparison between different objective functions are show in Table 3 as well. By referring Table 3, ITAE (Integral Time Absolute Error) is the best objective function to be applied in this system to tune PD controller. Rise time and settling time for ITAE is the shortest, 11.00 and 20.08 s respectively. IAE and ISE weight all error and independent of time which can result in a response with relatively small overshoot compared to ITAE and ITSE.

The result for Y position of mobile robot using PD controller tuned by minimizing four different objective functions shows the performance for ITAE is the best, same with X position. Overshoot produced by ISE and ITSE are higher than overshoot produced by IAE and ITAE by 50%. Rise time and settling time for IAE and ITAE are shorter than those produced by ITSE and ISE. These results indicate that by squaring the output will increase the error and make the system become unstable. Overshoot in the system plays an important role to measure the performance of the mobile robot.

3.2 Performance Comparison with WS-PSO and WS-BA

The comparison in this section only involves PD controller tuned by WS-EBA, WS-PSO and WS-BA. This is because only PD controller outperforms the other controller form previous experiment. The number of searching agents is set to 30 agents and the objective function used is ITAE due to the same reason as well. PSO algorithm has been chosen because the method was used [12] to tune PID controller for charger system and BA algorithm has been chosen due to the previous result of WMR tuned by BA [16]. Additionally, the originality of EBA is BA, thus it is appropriate to compare the performance.

Figure 4 shows the convergence curve of EBA, BA and PSO. All the algorithms have fully converged at the end of 100 iterations. Among the three algorithm, PSO does not converge and remains steady during the 100 iterations. The fitness value for PSO is the maximum. In the other hand, BA keeps trying to converge until 40 iterations and EBA stop to converge at 12 iterations. The fitness value for BA is the minimum. However, although the problem is to minimise the position error, but it is depending on the value of PD gains controller tuned by the mobile robot system.

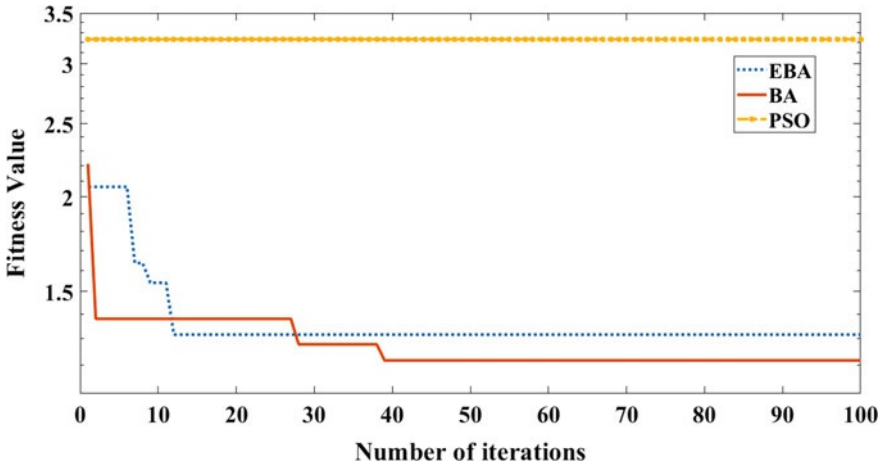

Fig. 4 Convergence curve fitness function for WS-EBA, WS-BA and WS-PSO

Table 4 Table weightage values for WS-EBA, WS-PSO and WS-BA

Algorithm	Total fitness (f_T)	Weightage 1 (W_1)	Fitness 1 (f_1)	Weightage 2 (W_2)	Fitness 2 (f_2)
WS-EBA	1.321	0.749	0.885	0.251	2.621
WS-PSO	3.224	0.453	1.587	0.547	4.580
WS-BA	0.742	0.642	1.032	0.358	0.222

Control parameters of each algorithm is different with each other. The good performance of the algorithm is depending on how well the algorithm is able to control and balance the exploration and the exploitation phase. Too much exploration will lead the searching agents diverge from the best solution while excessive exploitation phase will make the algorithm fall in deadlock and trapped in wrong solution. Thus, it is important to control the searching agents to search for the best solution.

Table 4 shows the value of total fitness, first and second weightage and fitness of ITAE function used for minimizing the first and second errors in the system. The summation of total weightage is equal to one. Total fitness obtained by WS-PSO is the maximum while total fitness obtained by WS-BA is the minimum. The values may indicate the convergence of the algorithm to search for the best solution. Being trapped in local minima will make the agents unable to explore more and give value higher than the solution. In the other hand, uncontrol exploration phase will make the agents missed the best solution by taking the solution from other low fitness value.

Table 5 shows the result of PD gains tuned by WS-EBA, WS-PSO and WS-BA. Each algorithm produced different results depend on the method of searching agents used to search in the algorithm. In this optimizations experiment, the best number of

Table 5 PD gains value for comparison with different algorithm

Optimization	K_P	K_D
WS-EBA	14.376	20.223
WS-PSO	16.562	63.962
WS-BA	14.875	40.452

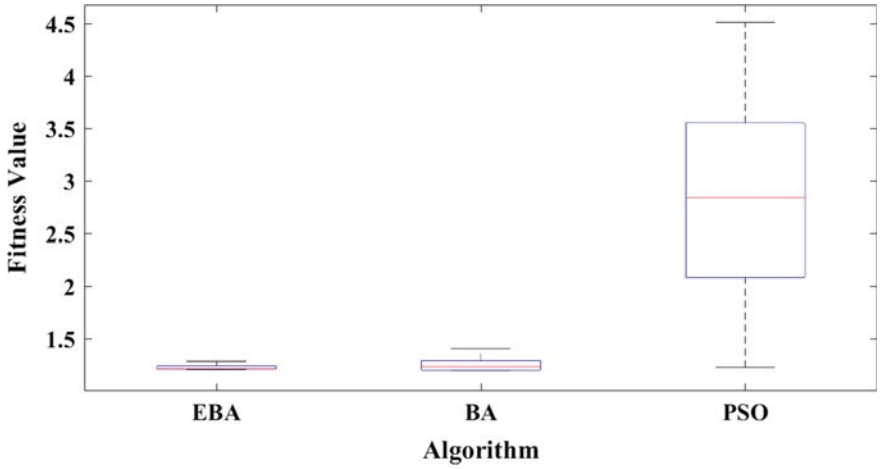

Fig. 5 Box plot of EBA, BA and PSO for result of fitness values for five times repeatability

searching agent used is 30 and the best objective function, ITAE is used in order to optimize the gain values of PD controller. The performance of the results can only be determined after implementing the controller in the kinematic model of the mBot and run the closed loop system.

Figure 5 shows the boxplot fitness value run for five times against algorithm and Table 8 shows the analysis of performance from the box plot. EBA produce the most consistent data as shown in the size of the box. The smaller the box, the more consistent the data with the median. Apparently, PSO has the highest median and the largest range by referring to the maximum point and minimum point of the box. This means that PSO is the worst in terms of consistency (Table 6).

Table 6 Information of box plot for EBA, BA and PSO by referring Fig. 5

Algorithm	Maximum point	Minimum point	Median	Number of point	Outliers
WS-EBA	1.284	1.204	1.216	5	No
WS-PSO	4.514	1.229	2.845	5	No
WS-BA	1.404	1.199	1.232	5	No

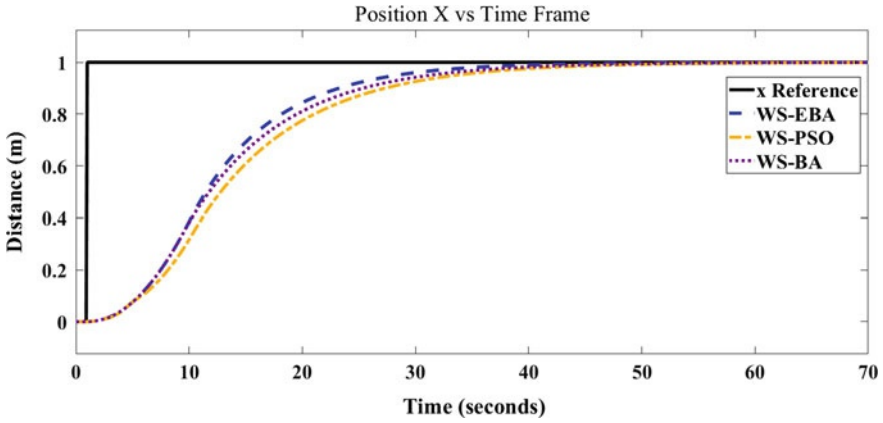

Fig. 6 Graph of X position for optimizing PD controller by using different algorithm

Table 7 Result of performance with different optimization algorithm approach, X position

Optimization	$T_r(s)$	$T_s(s)$	$O_s(s)$
WS-EBA	17.650	34.989	0
WS-PSO	21.454	41.440	0
WS-BA	19.753	38.776	0

Figure 6 and Table 7 display the results of PD controller tuned by different algorithm for X position. Performance of mobile robot when using PD controller tuned by WS-EBA is the best with the fastest rise time, 17.65 s and the fastest settling time, 34.98 s. The worst result is showed by WS-PSO. The result of PD controller tuned by BA acquired almost the same performance with WS-EBA because, WS-BA is the origin algorithm, and both use the same main method for searching the solution. WS-EBA is managed to obtain better result due to specific method it used, by applying spiral path to search the solution.

Figure 7 and Table 8 show the results of PD controller tuned by different algorithm for Y position. For this result, the performance of mobile robot is the same for using the PD controller which the gain values are tuned by WS-EBA and WS-BA. PD controller tuned by WS-PSO produced the worst performance by the longest time took to rise time, 1.49 s, settling time, 11.63 s and 62% of overshoot.

Although WS-BA gives the good performance in Y-position, WS-EBA produced the best performance for both position, X and Y position. This makes the controller tuned by WS-EBA is the best controller produced compared with other algorithms. Rise time, settling time and overshoot are the three main indicators to determine the performance of controller for the kinematic model of the system.

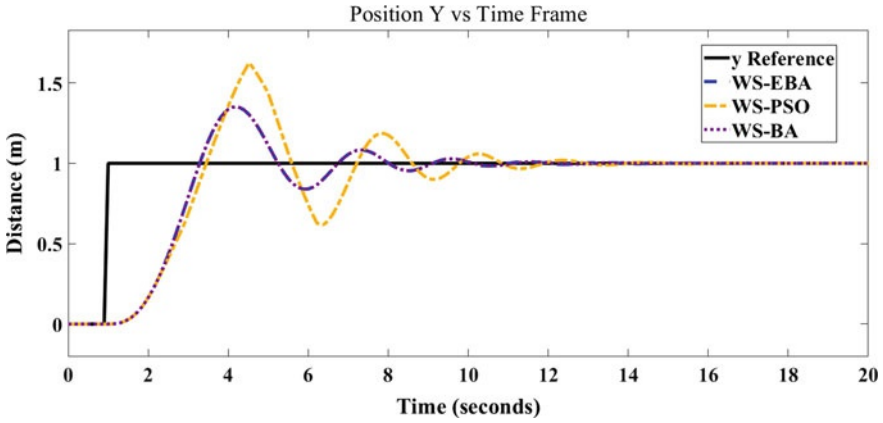

Fig. 7 Graph of Y position for optimizing PD controller by using different algorithm

Table 8 Result of performance with different optimization algorithm approach, Y position

Optimization	$T_r(s)$	$T_s(s)$	$O_s(s)$
WS-EBA	1.328	9.811	1.352
WS-PSO	1.488	11.626	1.626
WS-BA	1.328	9.821	1.352

4 Conclusion

Extended Bat Algorithm is one of the latest hybrid algorithms and has not yet been implemented to solve any controller optimization problem. By conducting this research study, the potentiality of EBA has been proven. Solving multi-objective optimization problem based on EBA is one of new challenge accepted by EBA. EBA produced the best result for optimizing and tuning the gains of PID controller. Based on the experiment conducted, PD controller, tuned by using 30 searching agents, using ITAE as the fitness function is the best controller compared with the PD controller tuned by WS- PSO and WS-BA. PD controller has been selected as the best among PID and PI controllers. PD controller with P gain 14.776 and D gain 20.223 has the best rising time, 17.65 s, settling time, 34.989 s and one of the controllers with the lowest overshoot which is 3.5%.

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Abstract

PID controller of WMR needs to be tuned as precise as possible in order to develop a good performance of WMR that is able to move from initial position to a desired position with the fast time response and minimum steady state error. Weighted-sum Extended Bat Algorithm (WS-EBA) is a multi-objective optimization method based on Extended Bat Algorithm. The weighted optimization approach is used to search the optimum value of Proportional-Integral-Derivative (PID) gains controller of Wheeled Mobile Robot (WMR) by referring to x and y position. Several experiments are conducted to test the effect of variables or parameters control to the value of PID gains and performance of WMR. Those parameters are the type of PID controller, number of agents in WS-EBA and the optimization functions used in the system to search the optimum value of PID gains. Results obtained from this research study indicates that PD controller, 30 number of searching agents and ITAE as the objective function gives the most suitable controller for WMR with result for X position is 11.00, 20.08 s and 0.00% for rise time, settling time and overshoot respectively. Additionally, for Y position, the results are 12.11, 22.08 s and 0.00% of rise time, settling time and overshoot respectively. The comparison of WS-EBA with Weighted-sum Particle Swarm Optimization (WS-PSO) and Weighted-sum Bat Algorithm (WS-BA) is also experimented in this research. WS-EBA outperformed the rest with the best result performance of WMR, consistency of solution, fastest convergence rate and the most balance of exploration and exploitation phase.

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