Optimal Design of Two-Degree-of-Freedom PIDA Controllers for Liquid-Level System by Bat-Inspired Algorithm

K. Lurang, C. Thammarat, S. Hlangnamthip and D. Puangdownreong

***Abstract*—**Regarding to control theory, the degree of freedom of a control system is defined by the number of control loops that can be adjusted independently. Traditionally, the one-degree-of-freedom (1DOF) control system has been widely conducted due to ease of use and simple realization. However, the design of control system depends on two main purposes, i.e. command-tracking and disturbance-rejecting. Two-degree-of-freedom (2DOF) control system has advantages over 1DOF for this scheme. In this paper, an optimal design of 2DOF-PIDA controllers for the liquid-level system by the bat-inspired algorithm (BA) is proposed. With BA-based, reponses of controlled system by the 2DOF-PIDA controllers are compared to those by the 1DOF-PIDA. As results, the 1DOF-PIDA and 2DOF-PIDA controllers can be optimally designed by the BA. Results show that, with 2DOF-PIDA control structure, the command-tracking and disturbance-regulating responses of the liquid-level system can be controlled effectively and independently.

***Keywords*—**Two-Degree-of-Freedom PIDA controller, Liquid-level system, Bat-inspired algorithm.

I. Introduction

IN control theory, the degree of freedom of a control system is defined by the number of control loops that can be adjusted independently [1],[2]. In other words, the degrees of freedom of the control system refers to how many of these closed-loop transfer functions are independent [3]. Traditionally, the one-degree-of-freedom (1DOF) control system has been widely employed due to ease of use and simple realization. However, the main purposes of the control design, i.e. command-tracking (or input-following) and disturbance-rejecting, have to be completely achieved. It can be determined as one of the multiobjective design problems based on modern optimization. Due to this, two-degree-of-freedom (2DOF) control system has advantages over 1DOF [1],[4-5]. By literatures, various 2DOF-PID control structures were proposed for industrial applications [6],[7]. Consequently, the results obtained by 2DOF-PID controllers were reported [8],[9]. Extended studies of 2DOF-PID were made about optimal analytical tuning [10-12], digital 2DOF-PID implementation with magnitude and slope limiters [13] and other 2DOF-PID topics in industrial applications [14]. For some years, control design paradigm has been changed from conventional analytical approach to new framework by using the metaheuristic optimization approach [15]. Metaheuristic optimization has become potential candidates and widely applied to various engineering problems. Such the metaheuristic optimization techniques have been increasingly applied to optimal tuning of the 2DOF-PI(D) controllers, such as immune algorithm (IA) for parallel distributed network [16], evolutionary computing (EC) for systems with time-delay [17], genetic algorithm (GA) for first order plus dead time (FOPDT) system [18], bacterial foraging (BF) for unstable systems [19], cuckoo search (CS) and firefly algorithm (FA) for automatic generation control [20], GA for discrete system [21] and 2DOF-PID controllers of BLDC motor speed control system by current search (CuS) [22].

Among metaheuristic optimization techniques, the bat-inspired algorithm (BA) is one of the most efficient population-based metaheuristics. The BA was firstly originated by Yang in 2010 [23]. Because the capability of echolocation of microbats is fascinating as these bats can find their prey and discriminate different types of insects even in complete darkness, the BA proposed by Yang is based on such the echolocation behavior. By literatures, the BA has been successfully applied to solve many engineering problems, for example, welded beam design [24], series-parallel power system optimization [25], economic load and emission dispatch [26], control systems [27] and so forth.

The proportional-integral-derivative-accelerated (PIDA) controller was firstly proposed by Jung and Dorf in 1996 [28]. The PIDA controller, possessing three arbitrary zeros and one pole at origin, can provide faster and smoother responses for the higher-order plants than the PID controller. In this paper, the BA is applied to control engineering application for designing optimal 2DOF-PIDA controllers for the liquid-level system to archived command-tracking and disturbance-rejecting purposes. Results obtained by the 2DOF-PIDA

K. Lurang is with the Doctor of Philosophy Program in Electrical Engineering, Graduate School, Southeast Asia University, Bangkok, Thailand, 10160. (e-mail: nongtritun@gmail.com).

C. Thammarat is with Department of Electrical Engineering, Faculty of Engineering, Southeast Asia University, Bangkok, Thailand, 10160. (e-mail: chaiyot@sau.ac.th).

S. Hlangnamthip is with Department of Electrical Engineering, Faculty of Engineering, Southeast Asia University, Bangkok, Thailand, 10160. (e-mail: sarotl@sau.ac.th).

D. Puangdownreong is with the Doctor of Philosophy Program in Electrical Engineering, Graduate School, Southeast Asia University, Bangkok, Thailand, 10160 (corresponding author phone: +66-2807-4500; fax: +66-2807-4528; e-mail: deachap@sau.ac.th).

controllers designed by the BA will be compared with those by the 1DOF-PIDA.

This paper consists of five sections. Once an introduction is presented in section I, the rest of the paper is summarized as follows. The problem formulation, consisting of the 2DOF structure, the liquid-level system and BA algorithm, are described in section II. The BA-based 2DOF-PIDA controller design for the liquid-level system is given in section III. Results and discussions are provided in section IV, while conclusions are followed in section V.

II. Problem Formulation

A. 2DOF Structure

Referring to the excellent control text book [3], the degrees of freedom of the control system refers to how many of these closed-loop transfer functions are independent. Consider the system shown in Fig. 1, where the system is subjected to the reference input $R(s)$, disturbance input $D(s)$ and noise input $N(s)$. $G_c(s)$ and $G_p(s)$ are the transfer functions of the controller and the plant, respectively. Also, $G_p(s)$ is assumed to be fixed and unalterable. From Fig. 1, three closed-loop transfer functions can be performed as stated in (1)-(3).

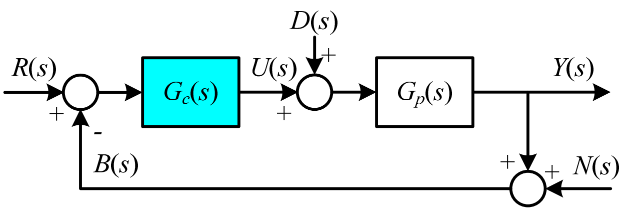

Fig. 1 1DOF control system

$$G_{yr}(s)=\frac{Y(s)}{R(s)}=\frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \tag{1}$$

$$G_{yd}(s)=\frac{Y(s)}{D(s)}=\frac{G_p(s)}{1+G_c(s)G_p(s)} \tag{2}$$

$$G_{yn}(s)=\frac{Y(s)}{N(s)}=-\frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \tag{3}$$

From (1)-(3), the expressions in (4)-(5) can be derived. Among three closed-loop transfer functions $G_{yr}(s)$, $G_{yn}(s)$ and $G_{yd}(s)$, if one of them is given, the remaining two are fixed. This means that the system shown in Fig. 1 is a 1DOF control system.

$$G_{yr}(s)=\frac{G_p(s)-G_{yd}(s)}{G_p(s)} \tag{4}$$

$$G_{yn}(s)=\frac{G_{yd}(s)-G_p(s)}{G_p(s)} \tag{5}$$

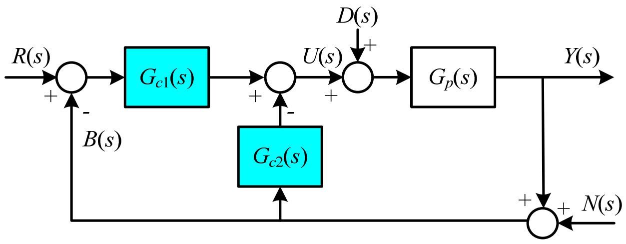

Fig. 2 2DOF control system

There are several control structures of the 2DOF-PID control systems [1-3]. Let's consider the system shown in Fig. 2. For this system, closed-loop transfer functions, $G_{yr}(s)$, $G_{yn}(s)$ and $G_{yd}(s)$, are given in (6), (7) and (8), respectively.

$$G_{yr}(s)=\frac{Y(s)}{R(s)}=\frac{G_{c1}(s)G_p(s)}{1+[G_{c1}(s)+G_{c2}(s)]G_p(s)} \tag{6}$$

$$G_{yd}(s)=\frac{Y(s)}{D(s)}=\frac{G_p(s)}{1+[G_{c1}(s)+G_{c2}(s)]G_p(s)} \tag{7}$$

$$G_{yn}(s)=\frac{Y(s)}{N(s)}=-\frac{[G_{c1}(s)+G_{c2}(s)]G_p(s)}{1+[G_{c1}(s)+G_{c2}(s)]G_p(s)} \tag{8}$$

From (6)-(8), the expressions in (9)-(10) can be performed. In this case, if $G_{yd}(s)$ is given, then $G_{yn}(s)$ is fixed, but $G_{yr}(s)$ is not fixed, because $G_{c1}(s)$ is independent of $G_{yd}(s)$. Thus, two closed-loop transfer functions among three closed-loop transfer functions $G_{yr}(s)$, $G_{yn}(s)$ and $G_{yd}(s)$ are independent. Hence, this system is a 2DOF control system.

$$G_{yr}(s)=G_{c1}(s)G_{yd}(s) \tag{9}$$

$$G_{yn}(s)=\frac{G_{yd}(s)-G_p(s)}{G_p(s)} \tag{10}$$

For 2DOF control system, both the closed-loop characteristics and the feedback characteristics can be adjusted independently to improve the system response performance [1-3]. In this work, the 2DOF control structure in Fig. 2 will be conducted.

B. Liquid-Level System

The three-tank liquid-level system can be represented in Fig. 3, where $q_i(t)$, $q_1(t)$ and $q_2(t)$ are liquid inflow rates into Tank-I, Tank-II and Tank-III, $q_o(t)$ is liquid outflow rate from Tank-III, $h_1(t)$, $h_2(t)$ and $h_3(t)$ are liquid levels of Tank-I, Tank-II and Tank-III, R_1, R_2 and R_3 are valve resistances of Tank-I, Tank-II and Tank-III, and A_1, A_2 and A_3 are areas of Tank-I, Tank-II and Tank-III, respectively. Such the system was previously modeled as $G_p(s)$ stated in (11) [29]. Once setting τ_1 = 1 sec., τ_2 = 1/2 sec. and τ_3 = 1/3 sec. as appeared in [29], the overall transfer function of the liquid-level system can be rewritten in (12). The model expressed in (12) will be used as a plant $G_p(s)$ in the control loop as shown in Fig. 2.

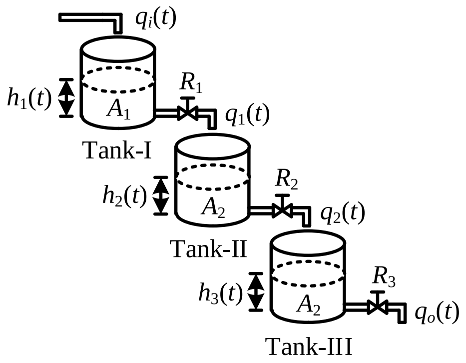

Fig. 3 three-tank liquid-level system

$$\left.\begin{aligned}\frac{Q_o(s)}{Q_i(s)} &= \frac{1}{(R_1A_1s+1)(R_2A_2s+1)(R_3A_3s+1)} \\ &= \frac{1}{(\tau_1 s+1)(\tau_2 s+1)(\tau_3 s+1)}\end{aligned}\right\} \tag{11}$$

$$G_p(s) = \frac{6}{(s+1)(s+2)(s+3)} \tag{12}$$

C. BA Algorithm

Proposed by Yang [23], the BA's algorithm is based on three following rules.

(1) All bats use echolocation to sense distance, and they also know the difference between food/prey and background barriers in some way.

(2) Bats fly randomly with velocity $\boldsymbol{v}_i$ at position $\boldsymbol{x}_i$ with a frequency $f_{\min}$, varying wavelength λ and loudness $\boldsymbol{A}_0$ to search for prey, and they can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission $r \in [0, 1]$, depending on the proximity of their target.

(3) Although the loudness can vary in many ways, it was assumed that the loudness varies from a large (positive) $\boldsymbol{A}_0$ to a minimum constant value $\boldsymbol{A}_{\min}$.

The BA's algorithm can be represented by the flow diagram as shown in Fig. 4. Each bat is associated with a velocity $\boldsymbol{v}_i$ and a location $\boldsymbol{x}_i$, at iteration t, in a d-dimensional search space. Among all the bats, there exists a current best solution $\boldsymbol{x}$*. Therefore, from above three rules, they can be translated into the updating equations for $\boldsymbol{x}_i$ and velocities $\boldsymbol{v}_i$ as stated in (13)-(15). When $\beta \in [0, 1]$ is a random vector drawn from a uniform distribution, each bat is randomly assigned a frequency which is drawn uniformly from $[f_{\min}, f_{\max}]$. During the iterations, the loudness $\boldsymbol{A}_i$ and the pulse rates r_i are adjusted as expressed in (16) to balance the exploration and exploitation. For $0 < \alpha < 1$ and $\gamma > 0$, it was found that $\boldsymbol{A}_i^t \to 0$, $r_i^t \to r_i^0$, as $t \to \infty$. Yang recommended that, in the simplest case, users can use $\alpha = \gamma \in [0.9, 0.98]$ [23-24],[30].

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \tag{13}$$

$$\boldsymbol{v}_i^t = \boldsymbol{v}_i^{t-1} + (\boldsymbol{x}_i^{t-1} - \boldsymbol{x}^*)f_i \tag{14}$$

$$\boldsymbol{x}_i^t = \boldsymbol{x}_i^{t-1} + \boldsymbol{v}_i^t \tag{15}$$

$$\boldsymbol{A}_i^{t+1} = \alpha \boldsymbol{A}_i^t, \quad r_i^{t+1} = r_i^0(1 - e^{-\gamma t}) \tag{16}$$

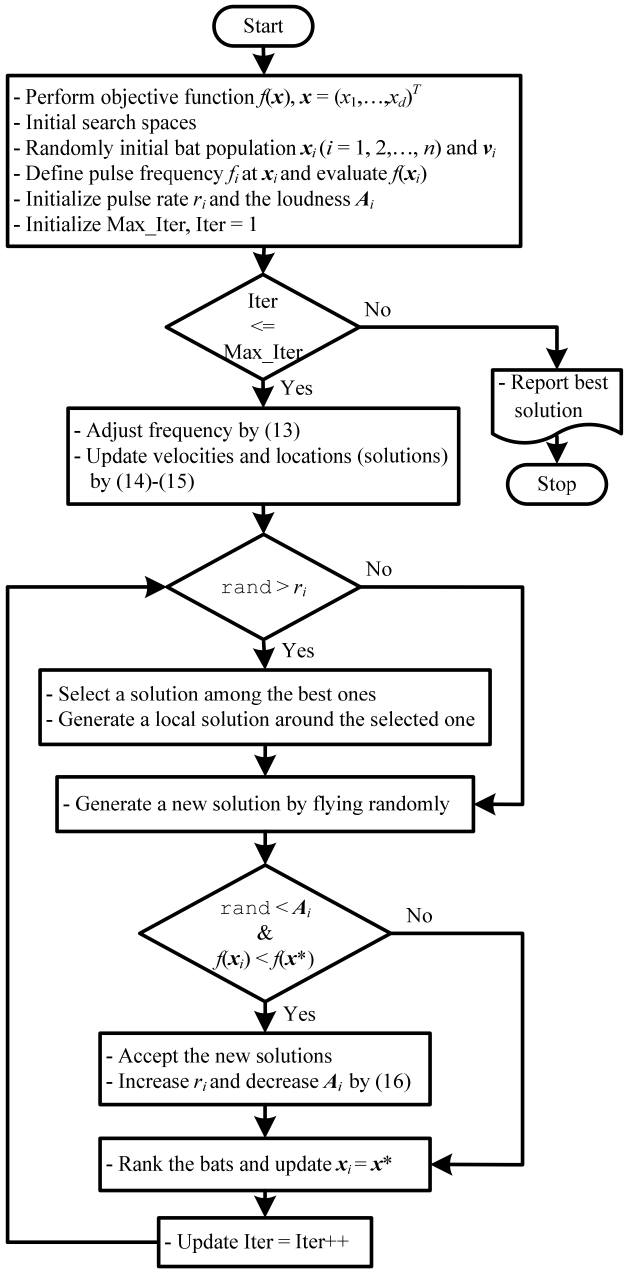

Fig. 4 flow diagram of BA algorithms

III. BA-Based 2DOF-PIDA Design

The BA-based 2DOF PIDA controller design for the liquid-level system is represented by the block diagram shown in Fig. 5. The controllers $G_{c1}(s)$ and $G_{c2}(s)$ are defined to be the PIDA controllers as expressed in (17) and (18) [28], where K_p

is proportional gain, K_i is integral gain, K_d is derivative gain and K_a is accelerated gain.

$$G_{c1}(s) = K_{p1} + \frac{K_{i1}}{s} + K_{d1}s + K_{a1}s^2 \quad (17)$$

$$G_{c2}(s) = K_{p2} + \frac{K_{i2}}{s} + K_{d2}s + K_{a2}s^2 \quad (18)$$

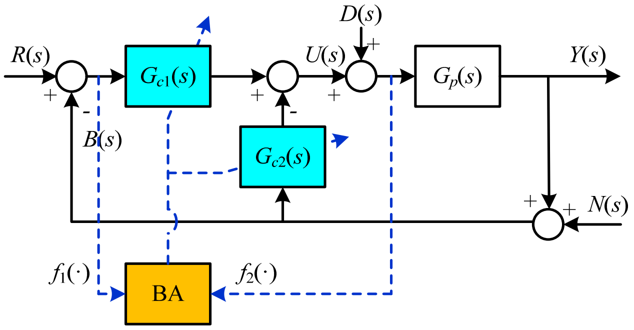

Fig. 5 BA-based 2DOF PIDA controller design

For the 2DOF-PIDA design framework, the command-tracking and disturbance-regulating responses are set as two particular objective functions, i.e. $f_1(\cdot)$ = command-tracking response and $f_2(\cdot)$ = disturbance-regulating response. In this work, both $f_1(\cdot)$ and $f_2(\cdot)$ are combined to be the main objective function $\boldsymbol{F}(\cdot)$ by using the penalty factors with normalization as stated in (19) where the penalty factors $\alpha_1 = \alpha_2 = 0.5$ are arbitrary set, while f_{1_Max} and f_{2_Max} are the maximum values of $f_1(\cdot)$ and $f_2(\cdot)$, respectively.

$$\textbf{Min} \quad \boldsymbol{F}(\cdot) = \alpha_1 \frac{f_1(\cdot)}{f_{1\_\mathrm{Max}}} + \alpha_2 \frac{f_2(\cdot)}{f_{2\_\mathrm{Max}}} \quad (19)$$

$\boldsymbol{F}(\cdot)$ including $f_1(\cdot)$ and $f_2(\cdot)$ will be fed to the BA as shown in Fig. 5 to be minimized by searching for optimal parameters of two PIDA controllers $G_{c1}(s)$ and $G_{c2}(s)$ corresponding to their constraints and search spaces defined in (20), where...

t_r	is rise time,
$t_{r\_\max}$	is maximum allowance of t_r,
M_p	is overshoot,
$M_{p\_\max}$	is maximum allowance of M_p,
t_s	is settling time,
$t_{s\_\max}$	is maximum allowance of t_s,
E_{ss}	is steady-state error,
$E_{ss\_\max}$	is maximum allowance of E_{ss},
M_{preg}	is overshoot from regulation,
$M_{preg\_\max}$	is maximum allowance of M_{preg},
t_{reg}	is regulation time,
$t_{reg\_\max}$	is maximum allowance of t_{reg},
$K_{p1\_\min}$	is lower bound of gain K_{p1},
$K_{p1\_\max}$	is upper bound of gain K_{p1},
$K_{i1\_\min}$	is lower bound of gain K_{i1},
$K_{i1\_\max}$	is upper bound of gain K_{i1},
$K_{d1\_\min}$	is lower bound of gain K_{d1},
$K_{d1\_\max}$	is upper bound of gain K_{d1},
$K_{a1\_\min}$	is lower bound of gain K_{a1},
$K_{a1\_\max}$	is upper bound of gain K_{a1},
$K_{p2\_\min}$	is lower bound of gain K_{p2},
$K_{p2\_\max}$	is upper bound of gain K_{p2},
$K_{i2\_\min}$	is lower bound of gain K_{i2},
$K_{i2\_\max}$	is upper bound of gain K_{i2},
$K_{d2\_\min}$	is lower bound of gain K_{d2},
$K_{d2\_\max}$	is upper bound of gain K_{d2},
$K_{a2\_\min}$	is lower bound of gain K_{a2} and
$K_{a2\_\max}$	is upper bound of gain K_{a2}.

$$\textit{Subject to} \quad \left. \begin{aligned} & t_r \le t_{r\_\max}, \\ & M_p \le M_{p\_\max}, \\ & t_s \le t_{s\_\max}, \\ & E_{ss} \le E_{ss\_\max}, \\ & M_{preg} \le M_{preg\_\max}, \\ & t_{reg} \le t_{reg\_\max}, \\ & K_{p1\_\min} \le K_{p1} \le K_{p1\_\max}, \\ & K_{i1\_\min} \le K_{i1} \le K_{i1\_\max}, \\ & K_{d1\_\min} \le K_{d1} \le K_{d1\_\max}, \\ & K_{a1\_\min} \le K_{a1} \le K_{a1\_\max}, \\ & K_{p2\_\min} \le K_{p2} \le K_{p2\_\max}, \\ & K_{i2\_\min} \le K_{i2} \le K_{i2\_\max}, \\ & K_{d2\_\min} \le K_{d2} \le K_{d2\_\max}, \\ & K_{a2\_\min} \le K_{a2} \le K_{a2\_\max} \end{aligned} \right\} \quad (20)$$

IV. Results and Discussions

To design an optimal 2DOF-PIDA controller for the liquid-level system, the BA's algorithm was coded by MATLAB version 2017b (License No.# 40637337) run on Intel(R) Core(TM) i5-3470 CPU@3.60GHz, 4.0GB-RAM. Parameters of the BA are set according to Yang's recommendations [23-24],[30], i.e. the numbers of bats n = 20, the frequencies $f_{\min}$= 0, $f_{\max}$ = 2, the initial loudness $\boldsymbol{A}_0$ = 0.5, the initial pulse rates r_0 = 0.5 and $\alpha = \gamma$ = 0.9. The maximum iteration Max_Iter = 100 is then set as the termination criteria (TC). 50 trials are conducted to find the best solutions (optimal PIDA controllers for the liquid-level system). Search spaces and their constraint functions are then performed as shown in (21). For comparison with the 1DOF-PIDA controller referred to Fig. 1, $G_{c2}(s)$ in Fig. 5 will be removed.

As results over 50 trials, the convergent rates of the objective function $\boldsymbol{F}(\cdot)$ in (19) proceeded by the BA are depicted in Fig. 6. With 50 trials run by the BA, the optimal 1DOF-PIDA and 2DOF-PIDA controllers for the liquid-level system are successfully obtained as stated in (22) and (23), respectively.

Command-tracking and disturbance-regulating responses of the liquid-level system with 1DOF-PIDA and 2DOF-PIDA controllers are depicted in Fig. 7 and Fig. 8.

$$\left.\begin{aligned} \textit{Subject to}\quad & t_r \le 2.0 \text{ sec.},\\ & M_p \le 2.0\%,\\ & t_s \le 3.0 \text{ sec.},\\ & E_{ss} \le 0.01\%,\\ & M_{preg} \le 25\%,\\ & t_{reg} \le 8.0 \text{ sec.},\\ & 0 \le K_{p1} \le 5.0, \quad 0 \le K_{i1} \le 10,\\ & 0 \le K_{d1} \le 2.0, \quad 0 \le K_{a1} \le 0.5,\\ & 0 \le K_{p2} \le 5.0, \quad 0 \le K_{i2} \le 0.1,\\ & 0 \le K_{d2} \le 2.0, \quad 0 \le K_{a2} \le 0.1 \end{aligned}\right\} \tag{21}$$

$$G_c(s)\big|_{\text{1DOF}} = 3.22 + \frac{1.93}{s} + 1.82s + 0.30s^2 \tag{22}$$

$$\left.\begin{aligned} G_{c1}(s)\big|_{\text{2DOF}} &= 4.98 + \frac{8.01}{s} + 1.50s + 0.22s^2\\ G_{c2}(s)\big|_{\text{2DOF}} &= 3.60 + \frac{0.0001}{s} + 1.60s + 0.06s^2 \end{aligned}\right\} \tag{23}$$

From Fig. 7, the command-tracking response of the liquid-level system without any controller provides t_r = 3.62 sec., M_p = 0%, t_s = 5.14 sec. and e_{ss} = 0%. Then, the command-tracking response of the liquid-level system with the 1DOF-PIDA controller gives t_r = 1.24 sec., M_p = 0.95%, t_s = 1.95 sec. and e_{ss} = 0%. Finally, the command-tracking response of the liquid-level system with the 2DOF-PIDA controller yields t_r = 1.16 sec., M_p = 0.62%, t_s = 1.64 sec. and e_{ss} = 0%.

From Fig. 8, the disturbance-regulating response of the liquid-level system with the 1DOF-PIDA controller gives M_{preg} = 20.56% and t_{reg} = 4.72 sec., whereas the disturbance-regulating response of the liquid-level system with the 2DOF-PIDA controller provides M_{preg} = 10.02% and t_{reg} = 2.12 sec.

As results in Fig. 7 and Fig. 8, the BA can provide both 1DOF-PIDA and 2DOF-PIDA controllers for the liquid-level system optimally and correspondingly to search spaces and their defined constraint functions. With 2DOF-PIDA control structure, command-tracking and disturbance-regulating responses of the liquid-level system can be control effectively and independently.

V. Conclusions

Application of the bat-inspired algorithm (BA) to design optimal two-degree-of-freedom PIDA (2DOF-PIDA) controllers for the liquid-level system has been proposed in this paper. As results compared with the one-degree-of-freedom PIDA (1DOF-PIDA) controller, it was found that the BA could provide optimal 1DOF-PIDA and 2DOF-PIDA controllers for the liquid-level system corresponding to search spaces and their defined constraint functions. With 2DOF-PIDA control structure, command-tracking (or input-following) and disturbance-regulating responses of the liquid-level system have been controlled effectively and independently. The 2DOF-PIDA control structure of the liquid-level system is more flexible than 1DOF-PIDA based on the control purposes.

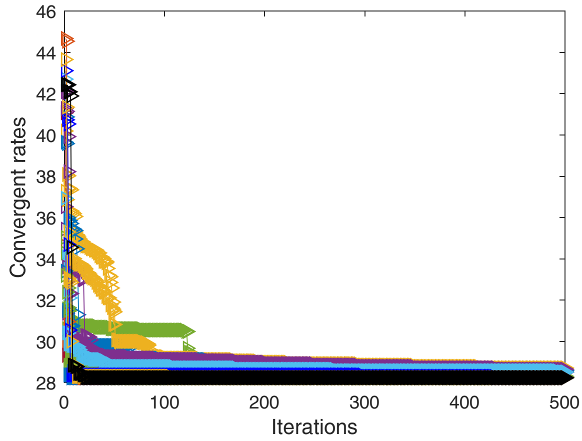

Fig. 6 convergent rates of BA over 50 trials

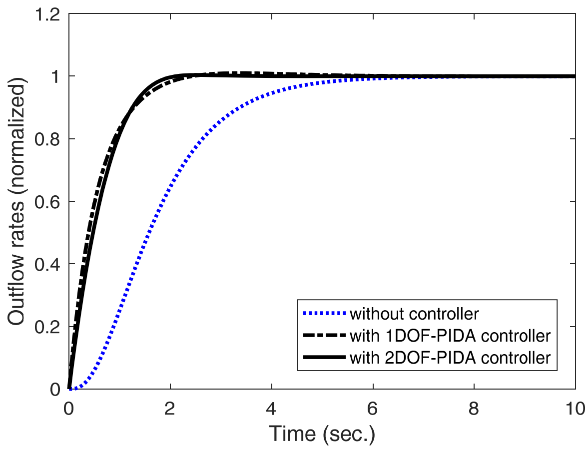

Fig. 7 command-tracking responses of liquid-level controlled system

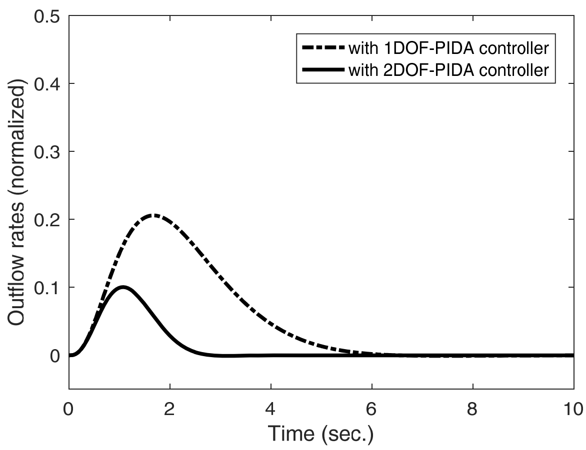

Fig. 8 disturbance-regulating response of liquid-level controlled system

REFERENCES

[1] I. M. Horowitz, *Synthesis of Feedback Systems*, Academic Press, 1963.

[2] K. J. Åström and T. Hägglund, *Advanced PID Control*, ISA Press, 2006.

[3] K. Ogata, *Modern Control Engineering*, 5th-edition, Pearson Prentice Hall, 2010.

[4] M. Araki and H. Taguchi, "Two-degree-of-freedom PID controllers," *Systems, Control and Information*, vol. 42, pp. 18–25, 1998.

[5] M. Araki and H. Taguchi, "Two-degree-of-freedom PID controllers," *International Journal of Control, Automation, and Systems*, vol. 1, no. 4, pp. 401–411, 2003.

[6] M. Araki, "On two-degree-of-freedom PID control systems," *SICE Research Committee on Modeling and Control Design of Real Systems*, 1984.

[7] M. Araki, "Two-degree-of-freedom control system: part I," *Systems and Control*, vol. 29, pp. 649–656, 1985.

[8] K. Hiroi, "Two-degree-of-freedom PID control system and its application," *Instrumentation*, vol. 29, pp. 39–43, 1986.

[9] M. Namie, T. Ueda, T. Tsukabe and H. Taguchi, "Two-degree-of-freedom PID controller used for temperature control: Simultaneity reference response and disturbance response," *OMRON Technics*, vol. 28, pp. 285–291, 1988.

[10] H. Taguchi, M. Doi and M. Araki, "Optimal parameters of two-degree-of-freedom PID control systems," *Trans. SICE*, vol. 23, pp. 889–895, 1987.

[11] H. Taguchi and M. Araki, "On tuning of two-degree-of-freedom PID controllers with consideration on location of disturbance input," *Trans. SICE*, vol. 38, pp. 441–446, 2002.

[12] P. Bagheri and H. Nemati, "Novel tuning strategy for two-degree-of-freedom PI controllers," in *Proc. 18th IFAC World Congress*, pp. 6757–6762, 2011.

[13] K. Hiroi and K. Nagakawa, "Improvement of a digital PID algorithm with rate limitation on MV change," in *Proc. 28th SICE Annual Conference*, pp. 243–244, 1989.

[14] M. Kanda and K. Hiroi, "Super two-degree-of-freedom PID algorithm," in *Proc. 30th SICE Annual Conference*, pp. 465–466, 1991.

[15] V. Zakian, *Control Systems Design: A New Framework*, Springer-Verlag, 2005.

[16] D. H. Kim, "Tuning of 2-DOF PID controller by immune algorithm," in *Proc. CEC'02 Congress on Evolutionary Computational*, pp. 675–680, 2002.

[17] T. Kawabe, "Robust 2DOF PID controller design of time-delay systems based on evolutionary computation," in *Proc. 4th WSEAS International Conference on Electronics, Control and Signal Processing*, pp. 144–149, 2005.

[18] H. Nemati and P. Bagheri, "A new approach to tune two degree of freedom (2DOF) PI controller," in *Proc. IEEE Multi-conference on Systems and Control*, pp. 1819–1824, 2010.

[19] K. Latha and V. Rajinikanth, "2DOF PID controller tuning for unstable systems using bacterial foraging algorithm," in *Proc. 3rd International Conference on Swarm, Evolutionary, and Memetic Computing*, pp. 519–527, 2012.

[20] P. Dash, L. C. Saikia and N. Sinha, "Comparison of performances of several cuckoo search algorithm based 2DOF controllers in AGC of multi-area thermal system," *Electrical Power and Energy Systems*, vol. 55, pp. 429–436, 2014.

[21] R. F. Hassan, "Design and implementation of two degree of freedom proportional integral derivative controller," in *Proc. 7th International Conference on Information Technology*, pp. 75–80, 2015.

[22] D. Puangdownreong, D. Kumpanya, C. Kiree and S. Tunyasrirut, "Optimal tuning of 2DOF-PID controllers of BLDC motor speed control system by intensified current search," in *Proc. 2015 Global Engineering & Applied Science Conference*, pp. 107–115, 2015.

[23] X. S. Yang, "A new netaheuristic bat-inspired aAlgorithm," *Nature Inspired Cooperative Strategies for Optimization (NISCO 2010) (Eds. J. R. Gonzalez et al.), Studies in Computational Intelligence*, Springer Berlin, 284, Springer, pp. 65–74, 2010.

[24] X. S. Yang, "Bat algorithm for multiobjective optimization," *Int. J. Bio-Inspired Computation*, vol. 3, no.5, pp.267–274, 2011.

[25] A. Benaissa, A. Zeblah, A. Belafdal and A. Chaker, "An efficient bat algoritm for series-parallel power system optimization," *J. Electr Electron Syst*, vol. 5, pp. 189, 2016.

[26] B. Ramesh, V. C. J. Mohan and V. C. V., Reddy, "Application of bat algorithm for combined economic load and emission dispatch," *Int. J. of Electricl Engineering and Telecommunications*, vol. 2, no.1, pp. 1–9, 2013.

[27] C. Thammarat, K. Lurang, D. Puangdownreong, S. Suwammarongsri, S. Hlangnamthip and A. Nawikavatan, "Application of bat-inspired algorithm to optimal PIDA controller design for liquid-level system," in *Proc. the iEECON2018 International Conference*, pp. 556–559, 2018.

[28] S. Jung and R. C. Dorf, "Analytic PIDA controller design technique for a third order system," in *Proc. 35th IEEE Conference on Decision and Control*, pp. 2513–2518, 1996.

[29] P. Srinivas, K. V. Lakshmi and V. N. Kumar, "A comparison of PID controller tuning methods for three tank level process," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 3, no. 1, pp. 6810–6820, 2014.

[30] X. S. Yang, "Bat algorithm: literature review and applications," *Int. J. Bio-Inspired Computation*, vol. 5, no. 3, pp. 141–149, 2013.

Kittisak Lurang was born in Chaiyaphum, Thailand, in 1979. He received the B.Eng. degree in electrical engineering from Niwattana University (NU), Kanchanaburi, Thailand, in 2002, and in M.Eng. degree in electrical engineering from King Mongkut University of Technology Thonburi (KMITT) Bangkok, Thailand, in 2007.

Since 2004, he has been as a teacher at Department of Electrical Engineering, Faculty of Engineering, Western University (WTU), Kanchanaburi, Thailand. Now, he is a Ph.D. candidate of Doctor of Philosophy Program in Electrical Engineering, Graduate School, Southeast Asia University (SAU), Bangkok, Thailand. His research interests include intelligent control system and metaheuristics applications.

Chaiyo Thammarat was born in Chonburi, Thailand, in 1953. He received the B.Eng. degree in electrical engineering from King Mongkut Institute of Technology Thonburi (KMITT), Bangkok, Thailand, in 1976, and in M.Eng. degree in electrical engineering from Lamar University, Beuamont, Texas,U.S.A, in 1986. From 1979 to 1998, he worked with Royal Thai Navy, Thailand.

Since 1998, he has been with Department of Electrical Engineering, Faculty of Engineering, Southeast Asia University (SAU), Bangkok, Thailand, where he is an assistant professor of electrical engineering. His research interests include intelligent control system and novel metaheuristics as well as their applications.

Sarot Hlangnamthip was born in Samutprakan, Thailand, in 1965. He received the B.Ind.Tech. degree in electrical engineering and M.Eng. degree in engineering management from Southeast Asia University (SAU), Bangkok, Thailand, in 1995 and 2005, respectively.

Since 1993, he has been with Department of Electrical Engineering, Faculty of Engineering, SAU, Bangkok, Thailand, where he is an assistant professor of electrical engineering. His research interests include electrical machine design, intelligent control system and applications of metaheuristics

Deacha Puangdownreong was born in Phra Nakhon Si Ayutthaya, Thailand, in 1970. He received the B.Eng. degree in electrical engineering from Southeast Asia University (SAU), Bangkok, Thailand, in 1993, the M.Eng. degree in control engineering from King Mongkut's Institute of Technology Ladkrabang (KMITL), Bangkok, Thailand, in 1996, and the Ph.D. degree in electrical engineering from Suranaree University of Technology (SUT), Nakhon Ratchasima, Thailand, in 2005, respectively.

Since 1994, he has been with the Department of Electrical Engineering, Faculty of Engineering and Graduate School, Southeast Asia University, where he is currently an associated professor of electrical engineering. His research interests include control synthesis and identification, novel metaheuristics as well as their applications.