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Autonomous Human Body Control, Part X: Blood pCO2 Control using I-first Order, 1 / 2 Orders Compensators and PD-PI controller compared with a PID Controller

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Abstract:

This paper is the tenth in a series of research papers presenting the control of an autonomous human body. It handles the control of the pCO2 level in the human blood using an I-first order, 1/ 2 orders compensators and a PD-PI controller all from the second generation of control compensators and PID controllers. Some tuning techniques for the proposed compensators/controllers are proposed based on zero/pole cancellation, fulfilling some time-based characteristics for the closed-loop control system, trial and error and MATLAB optimization. The step time response of the control system using the investigated compensators/controller is presented and compared with that of a conventional PID controller from the first generation of PID controllers tuned in this work using the MATLAB optimization toolbox and the time-based characteristics are extracted and compared. The comparison reveals the best compensator/controller among the four ones presented depending on a graphical and quantitative comparison study for reference input tracking.

Keywords — Autonomous human body control, blood pCO2 control, I-first order compensator, 1/ 2 orders compensator, PD-PI controller, PID controller, compensators/controllers tuning.

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I. INTRODUCTION

The partial pressure of carbon dioxide (pCO2) is a measure of the carbon dioxide within the arterial or venous blood with normal level range from 35 to 45 mmHg [1]. '*Hypercapnia*' describes high CO2 levels in the blood above 45 mmHg. If a patient is living with '*Hypercapnia*', he may be suffering from some symptoms including: dizziness, flushing, headache, inability to concentrate, rapid breathing, shortness of breath, acute confusion, coma, widening of blood vessels in the skin, panic attack, respiratory failure, seizure and swelling of the optic nerve [2]. These serious symptoms clarify the need to accurate and efficient control strategy to force purify the blood from excessive CO2. '*Hypercapnia*' is regulated through the use of oxygenator machines in an open-loop control manner with some limited trials with closed-loop control manner [3]. We start by presenting a literature review about pCO2 modeling and control since 1997:

Rees, Andreassen, Hovorka and Carson (1997) described a model of carbon dioxide transport on the blood. They used the model equations to represent the flow of CO2 between tissues blood and lung alveoli and used the model to represent th effects of hypo and hyper-ventilation on CO2 concentration [4]. Hexamer and Weiner (2003) described a process model for the gas transfer (O2, N2, CO2) in an oxygenator (artificial lung) for use as a design tool and a process model for the automation of the blood gas management during cardiopulmonary bypass. They showed that the

process gain vary markedly with the blood flow and presented a step time response for O2 and CO2 gases [5]. Manap, AbdulWahab and Zuki (2017) simulated the CO2 blood gas exchange in a membrane oxygenator. The objective was to evaluate the effect of sweep gas flow rate on CO2 partial pressure (pCO2) and to determine the response of pCO2 to the step change of the sweep gas flow rate. They generated simulated open-loop time response for pCO2 with three sweep gas flow rates of 1, 2 and 4 L/min [6]. Manap, AbdulWahab and Zuki (2020) evaluated the performance of Ziegler-Nichols continuous cycling and particle swarm optimization methods in tuning the gains of a PID controller applied to control the CO2 elimination from a membrane oxygenator during extracorporeal blood purification process. They used the sweep gas flow rate as a control variable and the pCO2 as a controlled variable and examined the robustness of the tuning methods for set point tracking and disturbance rejection [7].

Elenkov et al. (2022) presented a performance comparison for reference input tracking of pCO2 using three control algorithms: PI controller, nonlinear model predictive controller and deep reinforcement learning controller. They used an improved model of a membrane oxygenator. They concluded that the PI controller had the fastest time response with 2.24 settling time [8]. Suriyaprakash and Dhinakaran (2024) examined the control of pCO2 in a blood perfusion system where the pCO2 was measured and fed to an automated gas flow controller based on deep neural network internal model controller through a switch. They tested the performance of the proposed controller for various pCO2 values with output recording [9].

II. THE CONTROLLED BLOOD PCO2 AS A PROCESS

- Manap et al [6] investigated the simulation of blood CO2 exchange in membrane oxygenator for specific values of blood flow rate and sweep gas flow rate. They presented the step flow rate of pCO2 for three levels of sweep gas to blood flow rates without presentation of any mathematical model for this time-change. I have considered one of those time responses at blood flow rate of 2 L/min and sweeping gas flow rate of 1 L/min (0.0166667 L/s). This resulted in change of pCO2 from 25 to 35.64 mmHg and time span from 0 to 40 s. Using this time response, the step input was 0.016667 L/s (A) and the steady-state response change was 10.636 mmHg (c_{ss}) producing a process gain K_p of 638.03239 mmHg/(L/s) (c_{ss}/A). The time response of pCO2 had a maximum overshoot at a time of 3.75 s indicating that it cannot be represented by a first order model. From the experience of the author in system dynamics it was decided to consider this time response as a step time response of a 1 / 2 orders process without time delay giving a process transfer function $G_p(s)$ as:

$$G_p(s) = K_p(1+T_{z0}s)/(T_{p0}s+1)^2 \quad (1)$$

Where the process gain, K_p is given by:

$$K_p = 638.03239 \text{ mmHg/(L/s)} \quad (2)$$

- The zero time constant Tz0 and double pole time constant Tp0 is identified using an ITAE performance index [10] and the MATLAB optimization toolbox [11] with the help of chat GPT [12]. The identified parameters using the simulated time response of Manap et al. [6] as a pCO2 process data are as follows with a correlation coefficient of 0.9959:

$$T_{z0} = 6.75 \text{ s}, \quad T_{p0} = 2.40 \text{ s} \quad (3)$$

- The unit step time response of the pCO2 process defined by Eqs.1, 2 and 3 is shown in Fig.1 as generated by the step command of MATLAB [13].

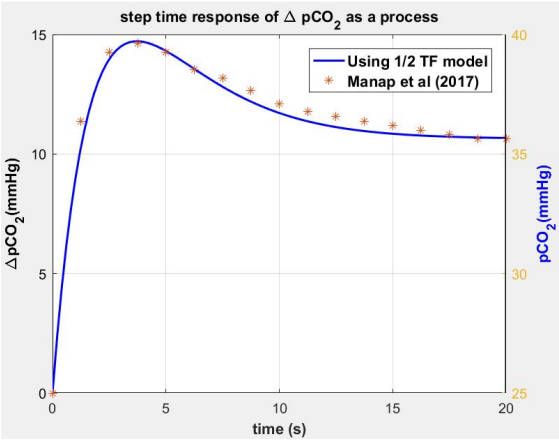

Fig.1 Step time response of the blood pCO2 change as a process.

The blood pCO2 process defined by Eq.1 has the following time-based characteristics associated with a step input of 0.016667 L/s sweeping gas:

- Steady-state response: 10.636 mmHg
- Maximum percentage overshoot: 37.6 %
- Settling time to ± 2 % tolerance: 14.96 s

III. CONTROLLING THE BLOOD PCO2 USING A PID CONTROLLER

- The conventional PID controller is one of the controllers of the first generation of PID controllers. Manap et al. applied a PID controller to control CO2 elimination in a membrane oxygenator with two different tuning techniques [7]. I could not compare with their work because they didn't provide the CO2 model as a process and pushed me to start with using a PID controller to control the pCO2 in the membrane oxygenator and tune it my self.
- I tuned the PID controller gain parameters for the optimal control of the pCO2 process defined by the transfer function in Eqs.1, 2 and 3 minimizing an ITAE performance index [10] using the MATLAB optimization toolbox [11] providing the following PID gain parameters:
  $K_{pc1} = 0.01991$; $K_{i1} = 0.01174$;
  $K_{d1} = 0.019485$ (4)
- The closed-loop transfer function of the control system structure with a single control loop incorporating the PID controller and the pCO2 process defined by Eq.1 is derived and used to plot the step time response of the pCO2 control system using the controller gain parameters in Eq.4 and MATLAB step and plot commands [13] providing the step time response shown in Fig.2 for a desired pCO2 change of 15 mmHg (corresponding to 40 mmHg absolute value). The lower and upper limits of 35 and 45 mmHg (absolute values) [1] are shown in the plot.

COMMENTS:

- Maximum overshoot: zero
- Settling time to ± 2 % tolerance: 2.512 s
- Steady-state error: zero

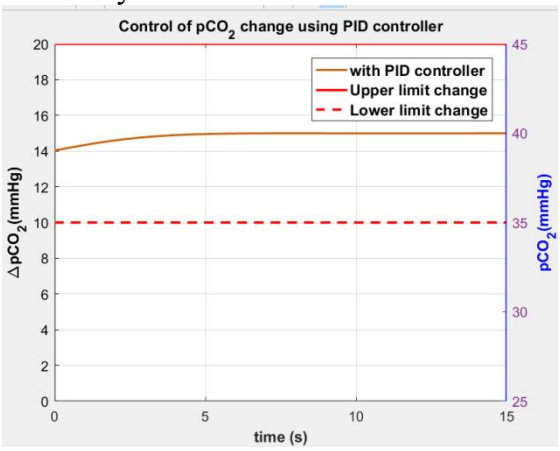

Fig.2 Step time response of a PID controlled blood pCO2.

IV. CONTROLLING THE BLOOD PH USING AN I-FIRST ORDER COMPENSATOR

- The I-First order compensator is one of the second generation of control compensators introduced by the author since 2014. The author used the I-first order compensator in September 2024 to control an autonomous car longitudinal velocity [14]. It has the transfer function $G_{I1st}(s)$ given by:

$$G_{I1st}(s) = (K_{i2}/s)[(T_{z2z}s+1)/(T_{p2}s+1)] \quad (5)$$

Where:

K_{i2} = integral gain of the compensator
T_{z2} = time constant of the compensator zero
T_{p2} = time constant of the compensator pole

- The I-first order compensator is set in a single-loop control system block diagram just before the process and after the error detector receiving the error signal and as input.
- The three parameters of the I-first order compensator are tuned as follows:
  - The zero/pole cancellation technique [15] is applied to the open-loop transfer function of the block diagram loop for the blood pCO2 control. The compensator zero (in Eq.5) is chosen to cancel the simple pole ($T_{p0}s+1$) of the pCO2 process (in Eq.1) providing the value of the compensator zero as:
    $T_{z2} = 2.40$ s (6)

- The compensator pole (in Eq.5) is chosen to cancel the simple zero ($T_{z0}s+1$) of the pCO2 process (in Eq.1) providing the value of the compensator pole as:
  $T_{p2} = 6.75$ s (7)
- The transfer function of the closed-loop control system, $M_2(s)$ is deduced using Eqs.1 and 5 in a unit feedback single loop control system. It is given by:
  $M_2(s) = \omega_{n2}^2 / (s^2+2\zeta_2\omega_{n2}s+ \omega_{n2}^2)$ (8)

Where:

$\omega_{n2}^2 = K_pK_{i2}/T_{p0}$, $2\zeta_2\omega_{n2} = 1/T_{p0}$ (9)

- It is known from the dynamics of second-order control systems that critical damping provides dynamics without any maximum overshoot. Therefore, for a critical damping design ($\zeta_2 = 1$).
- The settling time of a second order control system is related to $\zeta_2\omega_{n2}$ through the relationship [16]:
  $T_s = 4/(\zeta_2\omega_{n2})$ (10)
- For a desired settling time of (say), Eq.10 provides the control system natural frequency, ω_{n2} for critical damping condition as:
  $\omega_{n2} = 4$ rad/s (11)

- Now, Eq.9 gives the value of the compensator gain K_{i2} for a critical damping dynamic second-order control system. That is:
  $K_{i2} = 0.060186$ (12)
- The step time response for reference input tracking using the compensator transfer function in Eq.8 is obtained using the command 'step' of MATLAB [13] as shown in Fig.3 for a desired pCO2 of 15 mmHg.

COMMENTS:

- Maximum overshoot: zero
- Settling time to ± 2 % tolerance: 1.459 s
- Settling time to pCO2 limits: 0.573 s
- Steady-state error: zero

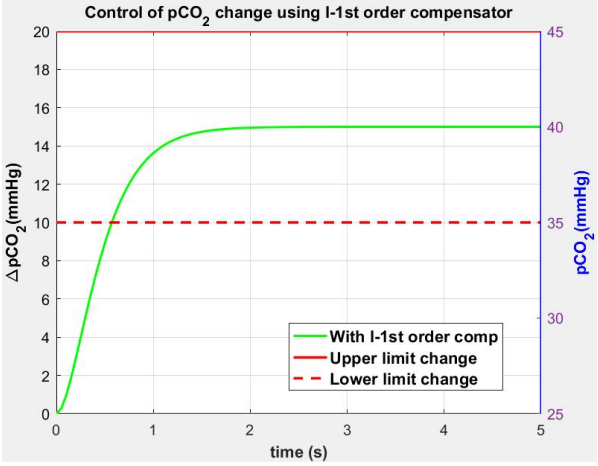

Fig.3 Step time response of a I-first order compensator controlled blood pCO2.

V. CONTROLLING THE BLOOD PH USING A 1 / 2 ORDERS COMPENSATOR

- The 1 / 2 orders compensator is one of the second generation of control compensators introduced by the author since 2014. The author used the 1 / 2 orders compensator in May 2025 to control the hemoglobin level of a human being [17]. It has the transfer function $G_{1by2}(s)$ given by:

$G_{1by2}(s) = K_{c3}(T_{z3}s+1)/[(T_{p3}s+1)(T_{p4}s+1)]$ (13)

Where:

K_{c3} = compensator gain

T_{z3} = time constant of the compensator zero

T_{p3}, T_{p4} = time constants of the compensator two simple poles

- The 1 / 2 orders compensator is set in a single-loop control system block diagram just before the process and after the error detector receiving the error signal and as input.
- The four parameters of the 1 / 2 orders compensator are tuned as follows:
  - The zero/pole cancellation technique [15] is applied to the open-loop transfer function of the block diagram loop for the blood pCO2 control. The compensator zero (in Eq.13) is chosen to cancel the simple pole ($T_{p0}s+1$) of the pCO2 process (in Eq.1) and the first compensator pole in Eq.13 is chosen to cancel the process zero ($T_{z0}s+1$) in Eq.1

providing the values of the compensator zero and first simple pole as:

$T_{z3} = 2.40$ s , $T_{p3} = 6.75$ (14)

- The resulting closed-loop transfer function of the control system using the 1 / 2 compensator, $M_3(s)$ will be:

$M_3(s) = K_{31}\ \omega_{n3}^2 /(s^2+2\zeta_3\omega_{n3}s+ \omega_{n3}^2)$ (15)

Where:

$K_{31} = K_pK_{c3}/(1+K_pK_{c3})$ (16)

$\omega_{n3}^2 = (1+K_pK_{c3})/(T_{p0}T_{p4})$,

$2\zeta_3\omega_{n3} = (T_{p0}+T_{p4})/(T_{p0}T_{p4})$ (17)

- The settling time of this control system for ± 2 % tolerance is given before in Eq.10. With critical damping condition for step time response without maximum overshoot.
- Selecting the performance conditions: unit damping ration and 0.05 s settling time for ± 2 % tolerance reveals the following remaining compensator parameters:

$T_{p4} = 0.006266$, $K_{c3} = 0.149288$ (18)

- The closed-loop transfer function gain K_{31} in Eq.16 and ω_{n3} in Eq.17 become :

$K_{31} = 95.25065$, $\omega_{n3} = 80$ rad/s (19)

- Now, using the transfer function in Eq.15, parameters in Eqs.19 and critical damping coefficient condition plots the step time response of the control system for a desired pCO2 of 15 mmHg as shown in Fig.4.

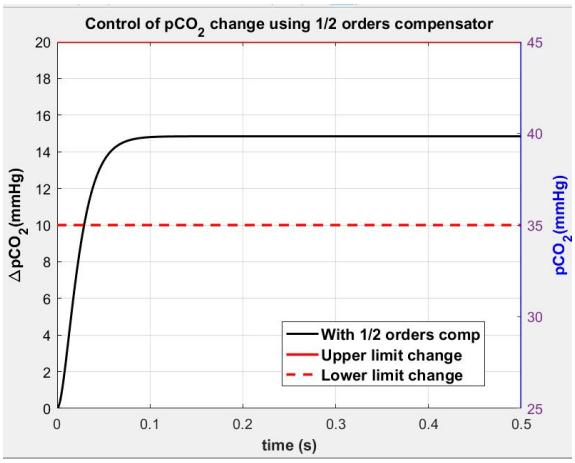

Fig.4 Step time response of a 1 / 2 orders compensator controlled blood pCO2.

COMMENTS:

- Maximum overshoot: zero
- Settling time to ± 2 % tolerance: 0.073 s
- Settling time to pCO2 limits: 0.0256 s
- Steady-state error: 0.1558 mmHg

VI. CONTROLLING THE BLOOD PCO2 USING A PD-PI CONTROLLER

- The PD-PI controller is a controller from the second generation of PID controllers presented by the author starting from 2014. The author applied the PD-PI controller in April 2014 to control first-order-delayed processes [18]. A PD-PI controller is composed of two feedforward cascaded control mode elements: a PD control mode of gain parameters K_{pc4} and K_{d4} and a PI control mode of gain parameters K_{pc5} and K_{i4}.
- The PD-PI controller has a transfer function $G_{PDPI}(s)$ given by:

$G_{PDPI}(s) = (K_{pc4}+K_{d4}s)[K_{pc5}+(K_{i5}/s)]$ (20)

- It has four gain parameters K_{pc4}, K_{d4}, K_{pc5} and K_{i5} tuned as follows:
  - The transfer function of the PD-PI controller is written in a form suitable for the proposed tuning procedure as follows:

$G_{PDPI}(s) = (K_{pc4}K_{i5}/s)[(K_{d4}/K_{pc4})s+1][(K_{pc5}/K_{i5})s+1]$ (21)

  - The PD-PI transfer function in Eq.21 has two simple zeros.
  - The zero/pole cancellation technique [15] is used to cancel the controller simple zero $(K_{d4}/K_{pc4})s+1$ in Eq.21 with the simple pole $T_{p0}s+1$ of the pCO2 process in Eq.1 in the open-loop transfer function of the control system giving:

$K_{d4} = T_{p0}K_{pc4}$ (22)

  - The other simple zero $(K_{pc5}/K_{i5})s+1$ in Eq.21 cancels the other simple pole $T_{p0}s+1$ of the pCO2 process in Eq.1 in the open-loop transfer function of the control system giving:

$K_{pc5} = T_{p0}K_{i5}$ (23)

  - Now, with this application of the zero/pole cancellation technique, the closed-loop transfer function $M_4(s)$ of the control system becomes:

$M_4(s) = (T_1s+1)/(T_2s+1)$ (24)

Where:

$T_1 = T_{z0} = 6.75$, $T_2 = [1+(1/K_4')]$

$K_4' = K_p K_{pc4} K_{i5}$ (25)

- Now, we are left with only one compensator parameter K_4'. Few trial and error values fix a good performance system for the closed-loop control system with a PD-PI controller. Here we are using a trial and error technique [19]. With few trials, K4' was chosen to be:

  $K_4' = 40$ (26)

- Now Eqs.25 and 26 with $K_{pc4} = 1$ (assumed), give:

  $T_2 = 6.775$, $K_{i5} = 0.06269$ (27)

- Using the closed-loop transfer function of the closed-loop control system in Eq.24 and the time constants in Eqs.25 and 27, the step time response is generated using the MATLAB command '*step*' [13] and shown in Fig.5 for a desired pCO2 change of 15 mmHg.

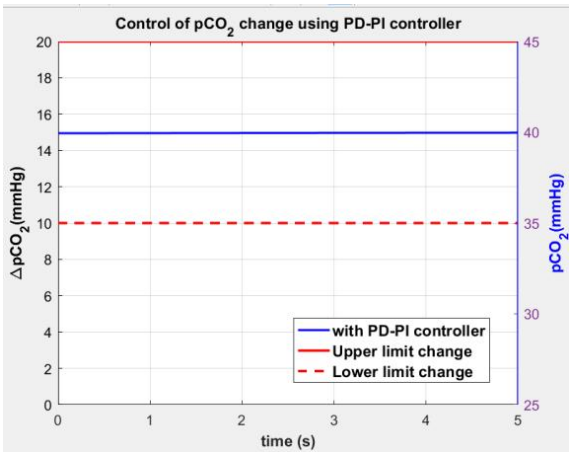

Fig.5 Step time response of a PD-PI controller controlled blood pCO2.

COMMENTS:

- Maximum overshoot: zero
- Settling time to ± 2 % tolerance: zero
- Settling time to pCO2 limits: zero
- Steady-state error: zero
- The PD-PI controller is an ideal perfect controller for the pCO2 process.

VII. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed compensators/controllers, the step time response for a desired blood pCO2 is compared with that using a PID controller tuned in this research work using the MATLAB optimization toolbox [11].
- A graphical comparison is presented in Fig.6.
- A quantitative comparison for the time-based characteristics of the control systems proposed to control the human blood pCO2 given in Table 1 for reference step input tracking (desired pCO2).

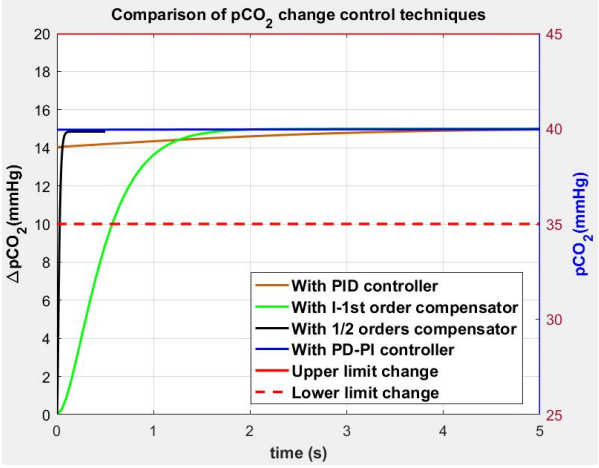

Fig.6 Blood pCO2 control using two controllers and two compensators.

TABLE 1
COMPARISON OF COMPENSATORS/CONTROLLERS TIME-BASED CHARACTERISTICS

Compensator /controller	PID controller	I-1st order compensator	1 / 2 orders compensator	PD-PI controller
OS_{max} (%)	0	0	0	0
$T_{s2\%}$ (s)	2.512	1.459	0.073	0
$T_{sLimits}$ (s)	0	0.573	0.0256	0
e_{ss} (mmHg)	0	0	0.1553	0

OS_{max} = maximum percentage overshoot
$T_{s2\%}$ = settling time to 2 % tolerance.
$T_{sLimits}$ = settling time to pCO2 limits.
e_{ss} = steady-state error.

VIII. CONCLUSIONS

- This research paper investigated the use of I-first order, 1/ 2 orders compensators from the second generation of control compensators and PD-PI controller from the second generation of PID controllers to control the blood pCO2 of a human body.

- The process under control (blood pCO2) was identified in this research work as a 1/ 2 orders process transfer function without time delay.
- The performance of the proposed compensators/controllers was compared with that of a PID controller from the first generation of PID controllers tuned in this work using the MATLAB optimization toolbox.
- Four tuning techniques were used in this study: using the zero/pole cancellation technique, fulfilling specific values for the maximum percentage overshoot and settling time, trial and error and MATLAB optimization toolbox.
- The four analyzed compensators/controllers succeeded to eliminate completely the maximum percentage overshoot of the closed-loop control system for reference input tracking.
- The settling time of the step input tracking time response (for 2 % tolerance) was remarkably small indicating fast time response. It was 1.459, 0.073 and zero s for the I-first order, 1/ 2 orders compensators and PD-PI controller respectively compared with 2.512 s for the PID controller.
- The settling time with respect to the normal limits of the pCO2 was 0.573, 0.1553 and zero s for the I-first order, 1/ 2 orders compensators and PD-PI controller respectively compared with zero for the PID controller. This indicated the very high efficiency of the tuning technique used to tune the PID controller compared with other techniques used in previous research work.
- All the investigated compensators/ controllers provided step time response to step input tracking without steady-state error except the 1/ 2 orders compensator which provided 0.1553 mmHg steady-state error.
- The PD-PI controller proved in this application to be the best compensators/controllers because of its ideal step shape without any overshoot, undershoot or steady-state error.
- The next best one was the I-first order compensator.
- Future work is required for accurate modeling of the human blood pH process for more accurate and effective control and application possibility.

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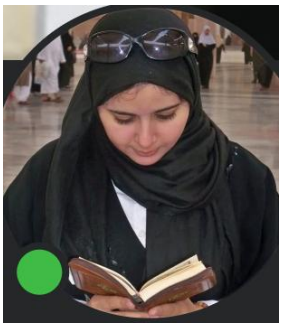
DEDICATION



SHAIMAA GALAL HASSAAN

- Graduated from the Faculty of Education, Arabic Language Department (Bani-Sweif University, Egypt) in 2007 (*honor grade*).
- Had a professional diploma in curriculum development in 2008.
- Had a Diploma in specialized psychology in 2009.
- Had a Master Degree in Educational Psychology with '*distinction grade*' (Bani-Sweif University, Egypt) in 2016.
- Attended three training courses in Arabic Language Skills, Proofreading and Grammatical Skills in the Faculty of Dar El-Alum, Cairo University in 2008.
- Attended a leadership preparation training course in the American University in Cairo in 2018.
- Researcher in Helwan Governorate (2011) and South Cairo Governorate (2023-now)
- Daughter of Prof. Galal Ali Hassaan.
- Good luck Shaimaa and happy to dedicate this work to you.

BIOGRAPHY

GALAL ALI HASSAAN

- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.
- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 355 research papers in international journals and conferences.
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- Honourable Chief Editor of the International Journal of Computer Techniques.
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