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Autonomous Human Body Control, Part VIII: Blood pH Control using PD-I, PD-PI controllers and I-first order Compensator compared with a PID Controller

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Abstract:

This paper is the eighth in a series of research papers presenting the control of an autonomous human body. It handles the control of the pH level in the human blood as an indication of acid and alkali in the blood using a PD-I controller, PD-PI controller and I-first order compensator. Some efficient tuning techniques for the proposed controllers/compensator are proposed based on zero/pole cancellation and fulfilling some time-based characteristics for the closed-loop control system. The step time response of the control system using the investigated controllers/compensator is presented and compared with that of a conventional PID controller from the first generation of PID controllers tuned by PSO in a previous research work and the time-based characteristics are extracted and compared. The comparison reveals the best controller/compensator among the four ones presented depending on a graphical and quantitative comparison study for reference input tracking.

Keywords — Autonomous human body control, pH level control, PD-I controller, PD-PI controller, I-first order compensator, , PID controller, controllers/compensator tuning.
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I. INTRODUCTION

Human blood has a normal pH range between 7.3 and 7.5. Below 7.3 acidosis occurs while above 7.5 alkalosis occurs [1]. Symptoms of metabolic acidosis include: fatigue, nausea and vomiting while symptoms of metabolic alkalosis include: confusion, fatigue, headache, nausea, vomiting, loss of appetite, rapid heartbeat and heart palpitations [2]. These symptoms clarify the need to accurate and efficient control strategy to force pH to stay within its normal limits. We start by presenting a literature review about pH measurement, modeling and regulation since 2004:

Yeo,and Kwon (2004) proposed a PID control strategy based on genetic algorithm coupled with cubic spline interpretation method for the control of pH processes. They claimed that through simulation and control experiments, they could achieve better control performance compared with conventional PID with fixed gains [3]. Kemmitt et al. (2006) tested the relationship between soil pH and rates of carbon and nitrogen cycles and dissolved organic nitrogen in two field experiments. They concluded that changes in soil pH affects the rate of soil carbon and nitrogen cycling and plant productivity [4]. Moleinero, Prieto, Brionges and Palancar (2014) presented the use of a feedback PID-like fuzzy controller scheme for pH control near the equivalence point in neutralization processes. They used simulated and experimental runs to test the controller performance [5]. Karthick and Satheesh (2015) stated that advanced tuned PID controllers are suited for a pH control process to control the plant to the desired set point with high quality performance over the entire operating range. They obtained a pH mathematical mdel and tuned the PID controller using Ziegler-Nichols, automatic tuning and PSO tuning techniques through simulation using MATLAB [6].

Fadzlullah et al. (2020) elaborated the performance of the transient response for pH neutralization process using a PID controller tuned by Ziegler-Nichols technique. They modeled the neutralization process as a first-order plus time delay and tuned the PID controller for this process model [7]. Goldoni et al. (2021) reported the performance analysis of a real-time, non-invasive pH measuring system for extracorporeal circulation. They proposed a linear correction factor for temperature compensation allowing the measurement error within ± 0.04 for the pH range [8]. Fu, Ma and Zhang (2022) proposed a fuzzy PID control based on PSO and claimed that significant improvement occurred in in system performance due to the application of their approach a different pH values. They compared the step time response of the control system for PID, fuzzy, fuzzy PID and PSO fuzzy PID [9].

Lum and Jin (2023) explored the possibility and effectiveness of using supervised machine learning models such as neural network to predict pH values by recognizing the RGB(red-green-blue) profile data of pH test strips. They claimed that the accuracy of the machine learning-based pH color recognition demonstrated promise in detecting the chronic kidney disease [10]. Tiwari and Mahalpure (2025) explained the essential aspects needed to use pH measurements effectively and provided detailed look at factors necessary for practical testing. They highlighted the various ways of using pH measurements [11].

II. THE CONTROLLED BLOOD PH AS A PROCESS

This application of blood pH control was one of the difficult processes I faced because of its lack of information about its modeling and control. I found mathematical models only for pH of other liquids such as water. To overcome this problem I made conversation with one of the artificial intelligence sites providing data and information for researchers (Chat GPT) where a first-order model was deduced from available date similar to that for pH neutralization of water by Karthick and Satheesh for the increase of pH of a water solution using sodium hydroxide [6]. The conversation with '*chat GPT*' revealed almost the same transfer function model for the human blood except the time constant of the process [12]. I used the transfer function model in [6] to compare with its application a PID controller to control the pH process which was a first-order model without time delay giving a process transfer function $G_p(s)$ given by [6]:

$$G_{pH}(s) = K_p/(T_{pH}s+1)] \quad (1)$$

Where K_p = process gain = 0.04912 pH/(L/min)

T_{pH} = pH time constant = 320 s

The unit step time response of the pH process defined by Eq.1 is shown in Fig.1 as generated by the step command of MATLAB [13].

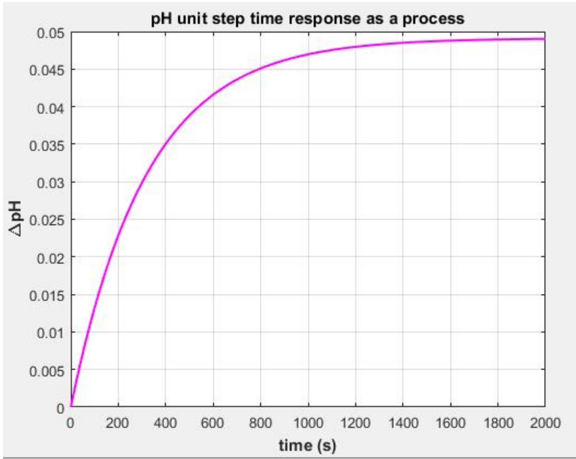

Fig.1 Step time response of the blood pH as a process.

The blood pH process defined by Eq.1 has the following time-based characteristics associated with unit step input of sodium hydroxide:

- Maximum percentage overshoot; zero
- Settling time to ± 2 % tolerance: 1223 s
- Steady-state time response: 0.049

III. CONTROLLING THE BLOOD PH USING A PID CONTROLLER

- The conventional PID controller is one of the controllers of the first generation of PID controllers. It is still in use in controlling various industrial process and control applications [9, 14-16].

- Karthick and Satheesh used PSO to tune the PID controller gain parameters for the optimal control of pH neutralization process providing the PID gain parameters [6]:
  $K_{pc1} = 72.56$; $K_{i1} = 0.721$
  $K_{d1} = 23.25$ (2)
- The closed-loop transfer function of the control system structure with a single control loop incorporating the PID controller and the pH process defined by Eq.1 is derived and used to plot the step time response of the pH control system using the controller gain parameters in Eq.2 and MATLAB step and plot commands [13] providing the step time response shown in Fig.2 for a desired pH of 7.4.

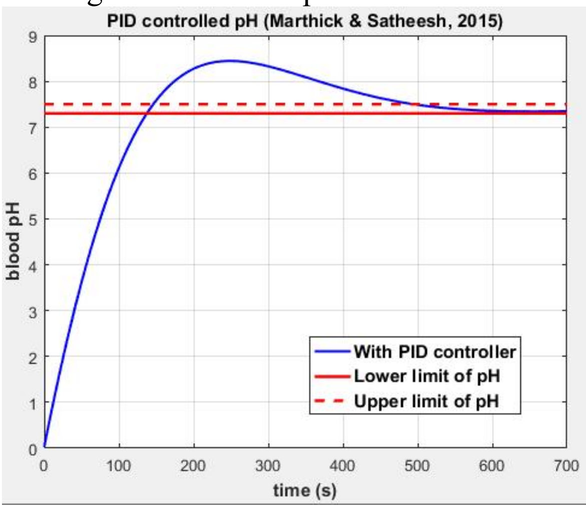

Fig.2 Step time response of a PID controlled blood pH.

COMMENTS:

- Maximum overshoot: 14.04 %
- Settling time: 500 s
- Steady-state error: zero

IV. CONTROLLING THE BLOOD pH USING A PD-I CONTROLLER

- The PD-I controller is one of the second generation of PID controllers introduced by the author since 2014. The author used a PD-I controller in March 2018 to control underdamped second-order-like processes [17]. It has the transfer function $G_{PDI}(s)$ given by [17]:

$G_{PDI}(s) = (K_{pc2}+K_{d2}s)(K_{i2}/s)$ (3)

Where:

K_{pc2} = proportional gain of the PD-I controller
K_{d2} = derivative gain of the PD-I controller
K_{i2} = integral gain of the PD-I controller

- The three parameters of the PD-I controller are tuned as follows:
  - We write the transfer function of the PD-I controller in another form suitable for the tuning technique as follows:
    $G_{PDI}(s) = (K_{pc2}K_{i2}/s)[(K_{d2}/K_{pc2})s+1]$ (4)
  - The zero/pole cancellation technique [18] is applied to the open-loop transfer function of the block diagram loop for the blood pH control. The controller zero (in Eq.4) cancels the simple pole of the pH process (in Eq.1) providing the following relationship between K_{d2} and K_{pc2}:
    $K_{d2} = 320\ K_{pc2}$ (5)
  - The transfer function $M_2(s)$ of the closed-loop control system is deduced using Eqs.1 and 4 in a unit feedback single loop control system. It is given by:
    $M_2(s) = 1/(T_2s+1)$ (6)

Where: T_2 is the time constant of the closed-loop control system given as:

$T_2 = 1/(K_pK_{pc2}K_{i2})$ (7)

  - As a first-order control system, its settling time to ± 2 % tolerance T_s is related to its time constant T2 through the relationship [19]:
    $T_s = 3.9\ T_2$ (8)
  - Depending on the desired settling time of the control system, T_2 can be assigned. Let the desired settling time is 20 s, Eq.8 gives T_2 as:
    $T_2 = 5.128$ s (9)
  - Now, to use Eq.7 to assign the value of the PD-I controller integral gain K_{i2}, K_{pc2} has to be known. Here, we select K_{pc2} as:
    $K_{pc2} = 1$ (10)
  - Combining Eqs.5,7,9,10 reveals K_{d2} and K_{i2} as:
    $K_{d2} = 320$, $K_{i2} = 3.96987$ (11)
- The step time response for reference input tracking using the compensator transfer function in Eq.6, and the tuned PD-I controller parameters in Eqs.10 and 11 is obtained using the command 'step' of MATLAB [13] as shown in Fig.3 for a

desired blood pH of 7.4. The figure depicts the lower and upper limit of blood pH as: $7.3 \leq pH \leq 7.4$ [1].

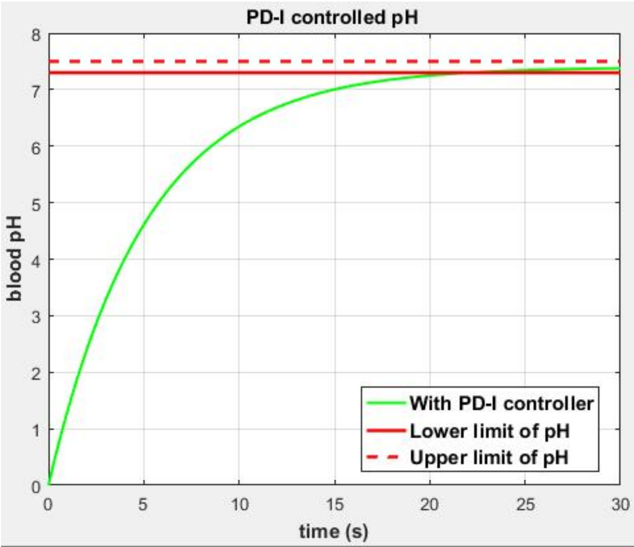

Fig.3 Step time response of a PD-I controlled blood pH.

COMMENTS:

- Maximum overshoot: zero (compared with 14.04 % for the PID controller).
- Settling time: 20.06 s (compared with 500 s for PID controller).
- Steady-state error: zero

V. CONTROLLING THE BLOOD pH 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 [20]. 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:
  $G_{PDPI}(s) = (K_{pc3}+K_{d3}s)[K_{pc4}+(K_{i4}/s)]$ (12)
- It has four gain parameters K_{pc3}, K_{d3}, K_{pc4} and K_{i4} tuned as follows:
  - The transfer function of the PD-PI controller is written in a form suitable for the proposed tuning procedure as follows:

$G_{PDPI}(s) =$
$(K_{pc3}K_{i4}/s)[(K_{d3}/K_{pc3})s+1][(K_{pc4}/K_{i4})s+1]$ (13)

  - The PD-PI transfer function in Eq.13 has two simple zeros.
  - The zero/pole cancellation technique [18] is used to cancel the controller simple zero $(K_{d3}/K_{pc3})s+1$ in Eq.13 with the simple pole T_p+1 of the pH process in Eq.1 in the open-loop transfer function of the control system giving:
    $K_{d3} = T_pK_{pc3}$ (14)
  - Now, with this application of the zero/pole cancellation technique, the closed-loop transfer function $M_3(s)$ of the control system becomes:

$M_3(s) = (K_3's+K_3')/[(1+K_3'T_{i4})s+K_3']$ (15)

Where:

$K_3' = K_pK_{pc3}K_{i4}$, $T_{i4} = K_{pc4}/K_{i4}$ (16)

  - The closed-loop transfer function of the closed-loop control system incorporating the PD-PI controller in Eq.15 is written in a standard form as follows:
    $M_3(s) = (T_{i4}s+1)/\{[(1+K_3'T_{i4})/K_3']s+1\}$ (17)
  - In Eq.17, we assume that the time constant of the denominator equals αT_{i4} providing the following relationships:
    $K_{pc3}K_{pc4} = 1/[K_p(\alpha-1)]$ (18)
    $M_3(s) = (T_{i4}s+1)/(\alpha T_{i4}+1)$ (19)
  - With few trials $\alpha = 1.2$ is reasonable and assuming $K_{pc3} = 1$ gives the controller parameters as:
    $K_{pc3} = 1$, $K_{d3} = 320$
    $K_{pc4} = 101.7915$, $K_{i4} = 67.861$ (20)
- Using the closed-loop transfer function of the closed-loop control system in Eq.19 and the PD-PI controller gain parameters in Eq.20 for a desired pH of 7.4, the step time response is generated using the MATLAB command '*step*' [13] and shown in Fig.4.

COMMENTS:

- Maximum overshoot: zero (compared with 14.04 % for the PID controller).

- Settling time: 3.817 s (compared with 500 s for PID controller).
- Steady-state error: zero

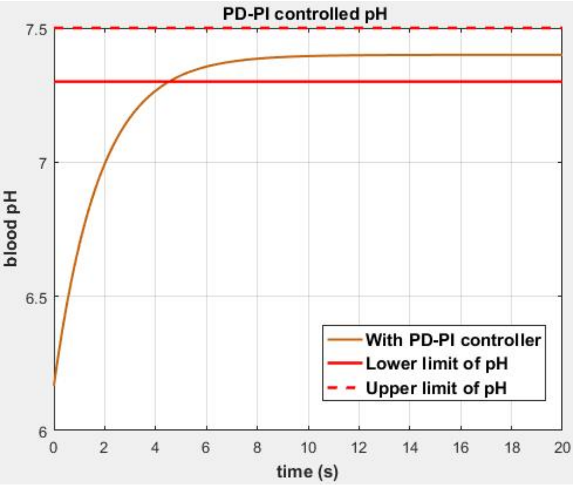

Fig.4 Step time response of a PD-PI controller controlled blood pH.

VI. CONTROLLING THE BLOOD pH USING A 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 [21]. It has the transfer function $G_{I1st}(s)$ given by:

$G_{I1st}(s) = (K_{i5}/s)[(T_{z5}s+1)/(T_{p5}s+1)]$ (21)

Where:

K_{i5} = integral gain of the compensator
T_{z5} = time constant of the compensator zero
T_{p5} = 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 [18] is applied of the open-loop transfer function of the block diagram loop for the blood pH control. The compensator zero (in Eq.21) is chosen to cancel the simple pole $(T_p s+1)$ of the pH process (in Eq.1) providing the value of the compensator zero as:
    $T_{z5} = 320$ s (22)
  - The transfer function of the closed-loop control system, $M_5(s)$ is deduced using Eqs.1 and 20 in a unit feedback single loop control system. It is given by:
    $M_5(s) = K_5'/[s^2+(1/T_{p5})s+K_5']$(23)
    Where:
    $K_5' = K_pK_{i5}/T_{p5}$ (24)
  - Eq.23 depicts a standard second-order control system having natural frequency ω_{n5} and damping ratio ζ_5. In terms of ω_{n5} and ζ_5, Eq.23 becomes:
    $M_5(s) = \omega_{n5}^2 /(s^2+2\zeta_5\omega_{n5}s+ \omega_{n5}^2)$ (25)
  - 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 ($\zeta_5 = 1$), Eqs.23 and 25 provides the control system natural frequency, ω_{n5} as:
    $\omega_{n5} = 0.5/T_{p5}$ (26)
- Now, we go to another important characteristic of the control system, its settling time. The settling time of a second-order control system, T_{s5} is related to its $\zeta_5\omega_{n5}$ parameter through the relationship [22]:
  $T_{s5} = 4/ \zeta_5\omega_{n5}$ (27)
- Suppose that design settling time of the control system is 4 s, then Eq.27 with unit damping ratio gives the damping ratio of the control system as:
  $\omega_{n5} = 1$ rad/s (28)
- Now, combining Eqs.26 and 28 gives the compensator pole time constant T_{p5} as:
  $T_{p5} = 0.5$ s (29)
- For the K_5' parameter in Eq.23, comparing Eqs.23 and 25 gives K_5' as:
  $K_5' = 1$ (30)
- Now, Eq.24 gives K_{i5} as:
  $K_{i5} = 10.17915$ (31)

- The step time response for reference input tracking using the compensator transfer function in Eq.21, process in Eq.1 and the tuned compensator parameters in Eqs.22, 29 and 31 is obtained using the command 'step' of MATLAB [13] as shown in Fig.5 for a desired pH of 7.4.

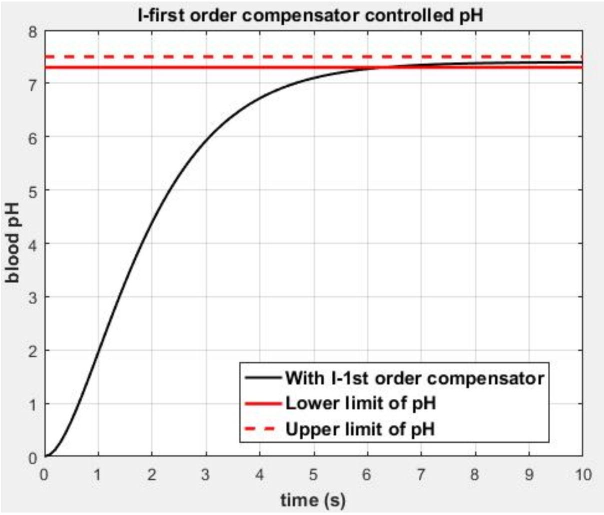

Fig.5 Step time response of a I-first order compensator controlled blood pH.

COMMENTS:

- Maximum overshoot: zero (compared with 14.04 % for the PID controller).
- Settling time: 5.835 s (compared with 500 s for PID controller).
- Steady-state error: zero

VII. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed controllers/compensator, the step time response for a desired blood pH is compared with that using a PID controller tuned by Karthick and Satheesh [6].
- 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 pH given in Table 1 for reference step input tracking.

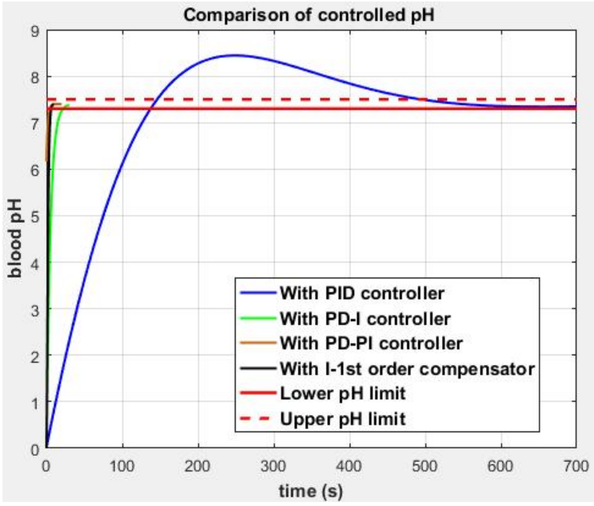

Fig.6 Blood pH control using three controllers and one compensator.

TABLE 1
COMPARISON OF CONTROLLERS/COMPENSATOR TIME-BASED CHARACTERISTICS

Controllers/ compensator	OS_{max} (%)	T_s (s)	e_{ss}	Order of Best Controller/ compensator
PID controller	14.04	500	0	4
PD-I controller	0	20.06	0	3
PD-PI controller	0	3.817	0	1
I-first order compensator	0	5.835	0	2

OS_{max} = maximum percentage overshoot
T_s = settling time to 2 % tolerance.
e_{ss} = steady-state error.

VIII. CONCLUSIONS

- This research paper investigated the use of PD-I controller, PD-PI controller and I-first order compensator from the second generation of PID controllers and control compensators to control the blood pH of a human body.
- The process under control (blood pH) was assumed to be a first-order one without time delay.
- The performance of the proposed controllers/compensator was compared with that of a PID controller from the first generation of PID controllers tuned and

used in a previous work for the same pH process.
- Two tuning techniques were used in this study: using the zero/pole cancellation technique and fulfilling specific values for the maximum percentage overshoot and settling time.
- The four analyzed controllers/compensator succeeded to eliminate completely the steady-state error of the closed-loop control system for reference input tracking.
- The proposed controllers/compensator from the second generation succeeded to eliminate completely the maximum percentage overshoot.
- The settling time of the step input tracking time response was 20.06, 3.817 and 5.835 s for the PD-I, PD-PI controller and I-first order compensator respectively compared with 500 s for the PID controller.
- The PD-PI controller proved in this application to be the best controller/compensator because it provided the least settling time of 3.817 s 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

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- Graduated from the Faculty of Arts (Bani-Sweif University, Egypt) in 1998.
- Had Master of Arts with '*distinction grade*' (Bani-Sweif University, Egypt) in 2013.
- Had Ph. D. in Arts with '*distinction grade*' (Bani-Sweif University, Egypt) in 2018.
- Head of an External Review Team at the National Authority for Quality Assurance and Accreditation, Egyptian Council of Ministers.
- Expert in Arabic Literary Criticism.
- Daughter of Prof. Galal Ali Hassaan.
- Wife of Mr Sayyed Mohammed ElGamil, Accounting Manager, Al-Sultan Hyper Market, 6 October, Egypt.
- Good luck Iman 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 350 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Honourable Chief Editor of the International Journal of Computer Techniques.
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