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Autonomous Human Body Control, Part I: Heart Rate Control using First-order, Second-order Compensators and PD, 2DOF-3 Controllers Compared with a Fuzzy PID Controller

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Abstract:

This paper investigates the tuning of first-order, 2/2 second-order compensators and PD, 2DOF-3 controllers from the first and second generations of control compensators and PID controllers when used to control the heart rate of an autonomous human body. The proposed compensators/controllers are tuned using a hybrid approach based on zero/pole cancellation, specific performance measures and an optimization technique using an ITAE performance index. The tuning results are presented and applied to generate the unit step time response for reference input tracking. Transfer functions for a pacemaker and heart rate process from previous work are used. The characteristics of the step time responses are compared with those of a fuzzy-PID conventional controller from the first generation of PID controllers. The best compensator/controller for the control of the human heart rate is assigned and compared with six modern controllers.

Keywords — **Autonomous human body control, heart rate control, first-order compensator, 2/2 second-order compensator, PD controller, 2DOF-3 controller, compensator/controller tuning.**

I. INTRODUCTION

This is the starting paper of a new series of research papers oriented towards the study of autonomous human body control to help reducing the human suffering due to the deficiencies in his operating physical elements such as heart, liver, kidney, lung, prostate, etc. The paper deals with the control of heart rate where deviation of its normal rate results in chest pain, memory problems, dizziness, fainting, shortness of breath, heart failure and sudden cardiac death [1], [2]. Controlling the heart rate helps in overcoming all those problems and health troubles through proposing efficient controlling techniques with good performance levels. Here are some of the research efforts regarding the control of heart rate:

Kannathal, Lim, Acharya and Sadesivan (2006), used an adaptive neuro-fuzzy network to classify heart abnormalities in 10 different cardiac states. They claimed that the results of their technique indicated high level of efficacy of tools used with accuracy above 96 % [3]. Ting et al. (2008) presented a framework for studies into online monitoring and adaptive control of workers relating to human operators working under stress. They used a fuzzy model linking heart rate variability and task load index with operator optimal performance validated by real-time experiments involving process control through using the model as basis for an online control system [4]. Yadav, Rani and Gang (2011) described the design of a control system for regulation of heart rate. The developed control system was composed of a cardiovascular system energized by a pacemaker system operated in a closed-loop manner. They designed a PID controller tuned by Ziegler-Nichols, Tyreus-Luyben and relay methods. They used also a fuzzy controller to improve the time response performance. They used a pacemaker with 0/1 first-order transfer function model and a heart having a 0/1 first-order model plus an integrator [5].

Shi (2013) presented the design of a fuzzy PID controller for dual-sensor cardiac pacemaker to control the heart rate to track a desired preset profile. He claimed that simulation results confirmed the effectiveness of his proposed system for heart rate recovery and maintenance [6]. Castro and Malathi (2016) presented a bio inspired optimization algorithm to tune PID controller parameters to control the pacemaker. They compared with Ziegler-Nichols tuning providing better performance with overshoot reduction from 31.7 to 6.26 %. They used the same models of the pacemaker and heart used by reference [5] [7]. Momani and Batiha (2019) proposed a robust fractional order PID controller to improve the pacemaker performance. They used a particle swarm optimization algorithm, assigned the objective function and presented the results of using their proposed controller with the conventional PID controller and recommended using the ITAE performance index. They used the same models as in reference [5] and could reduce the maximum overshoot to 0.86 % [8]. Wang and Hunt (2021) compared the use of first and second-order models in heart rate control using a control system design strategy shaping the input sensitivity function. Their results didn't provide evidence that controllers based on the second-order model lead to better tracking accuracy [9].

Verma, Saeed and Mishra (2024) outlined that the pacemaker was invented to control the irregularities of the heart rate. They proposed the design of an optimal system for a cardiac pacemaker to generate a controlled desired response through using integer and fractional order PID controller tuned using particle swarm optimization offering good control characteristics. They used the same models for the pacemaker and heart as in reference [5]. They could obtain a step time response with maximum overshoot of 13.3 % for conventional PID and 27.6 % for fractional PID [10].

II. THE CONTROLLED HEART RATE AS A PROCESS

Yadav, Rani and Gang (2011) used a simple pole transfer function for a pacemaker and a first-order + integrator for a human heart [5]. Their transfer functions models for the pacemaker, $G_p(s)$ and heart, $G_h(s)$ are given by [5]:

$G_p(s) = 8/(s+8)$ (1)

$G_h(s) = 169/[s(s+20.8)]$ (2)

The structure of a control system for heart rate control incorporating both controller and pacemaker is shown in Fig.1 [5].

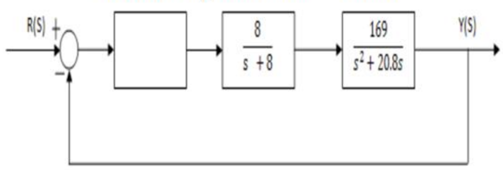

Fig.1 Heart rate control system structure [5].

In the present work I consider the pacemaker as an integrated part with the heart. This leads to considering the process transfer function $G_p(s)$ as $G_c(s)G_h(s)$ given by:

$G_p(s) = 1352/[s(s+8)(s+20.8)]$

$= 1352/[s(s^2+28.8s+166.4)]$ (3)

The unit step time response of the heart rate process using the transfer function model in Eq.3 is evaluated and drawn using the '*step*' command of MATLAB [11] and shown in Fig.2.

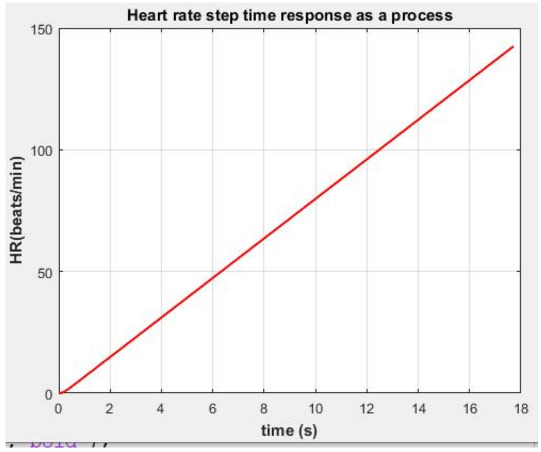

Fig.2 Heart rate step time response.

COMMENTS:

- The controlled process is unstable.
- There is a need for a compensator or controller to satisfy control system stability.
- Optimal performance of the control system is also of utmost importance because the control system is for a human being.

III. HEART RATE CONTROL USING A FEEDFORWARD FIRST-ORDER COMPENSATOR

A feedforward first-order compensator has a transfer function model given by [12]:

$G_c(s) = K_c(s+z)/(s+p)$ (4)

Where:

K_c = compensator gain

z = compensator simple zero

p= compensator simple pole

- The open-loop transfer function of the control system, $G_c(s)G_p(s)$ using Eqs.3 and 4 is given as:

$G_c(s)G_p(s) = 1352K_c(s+z)/[s(s+8)(s+20.8)(s+p)]$ (5)

- The first-order compensator has three parameters to be tuned for optimal performance of the control system as follows:

- The zero/pole cancellation technique is adopted [13]. The compensator zero s+z is set to cancel the pole s+20.8 of the process. This step reveals:
  $z = 20.8$ (6)
- The ITAE performance index [14] is chosen to be minimized by the MATLAB optimization toolbox to tune the compensator two parameters (K_c and p) [15]. The tuning result is as follows:
  $K_c = 1576.6057$; $p = 92789.4$ (7)
- The step response of the heart rate for an 85 beats/min desired heart rate when using a feedforward first-order compensator is shown in Fig.3.

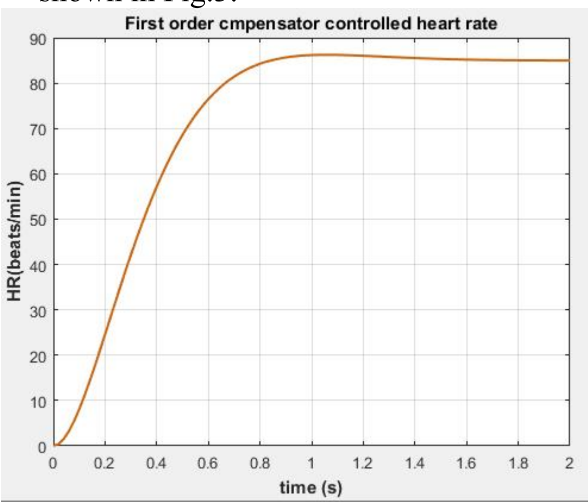

Fig.3 Heart rate control using a feedforward first-order compensator.

COMMENTS:

- Maximum overshoot: 1.47 % (compared with 3.585 % for a fuzzy-PID controller)
- Settling time: 0.76 s (compared with 0.763 s for a fuzzy-PID controller)
- Steady-state error: zero

IV. HEART RATE CONTROL USING A FEEDFORWARD 2/2 SECOND-ORDER COMPENSATOR

- The feedforward second-order compensator has a transfer function, $G_{c2}(s)$ adapted from the presentation of K. Ogata and given by [16].

$$G_{c2}(s) = K_{c2}(s^2+b_1s+b_2)/(s^2+a_1s+a_2) \quad (8)$$

- Using Eqs.3 and 8, the open-loop transfer function of the control system for heart rate control $G_{c2}(s)G_p(s)$ becomes:

$$G_{c2}(s)G_p(s) = 1352K_{c2}(s^2+b_1s+b_2)/[s(s^2+a_1s+a_2)(s^2+28.8s+166.4)] \quad (9)$$

- The second-order compensator has five parameters to be tuned for optimal performance of the control system as follows:

- The zero/pole cancellation technique is adopted [13]. The compensator quadratic zero $s^2+b_1s+b_2$ is set to cancel the quadratic pole $s^2+28.8s+166.4$ of the process. This step reveals:
  $b_1 = 28.8$; $b_2 = 166.4$ (10)
- Now, with b_1 and b_2 as in Eq.10, Eq.9 becomes:
  $G_{c2}(s)G_p(s) = 1352K_{c2}/[s(s^2+a_1s+a_2)]$ (11)
- The parameters of the quadratic pole in Eq.11 are set for a critical damping (unit damping ratio). This condition reveals the following relationship between a_1 and a_2:
  $a_1 = 2a_1\sqrt{a_2}$ (12)
- The ITAE performance index [14] is chosen to be minimized by the MATLAB optimization toolbox to tune the compensator two parameters (K_{c2} and a_2) [15]. The tuning result is as follows:
  $K_{c2} = 0.146866$; $a_1 = 20.151528$
  $a_2 = 101.521123$ (13)
- The step response of the heart rate for an 85 beats/min desired heart rate when using a feedforward second-order compensator is shown in Fig.4.

COMMENTS:

- Maximum overshoot: 0.87 % (compared with 3.585 % for a fuzzy-PID controller)
- Settling time: 1.147 s (compared with 0.763 s for a fuzzy-PID controller)
- Steady-state error: zero

Fig.4 Heart rate control using a feedforward 2/2 second-order compensator.

V. HEART RATE CONTROL USING AN A PD CONTROLLER

- The PD controller is one of the first generation of PID controllers. It has the transfer function, $G_{c3}(s)$ given by:
  $G_{c3}(s) = K_{pc3}+K_{d3}s$ (12)
  Where K_{pc3} and K_{d3} are the proportional and derivative gains of the PD controller.
- The open-loop transfer function of the control system for controlling the heart rate using a PD controller $G_{c3}G_p(s)$ is obtained using Eqs.3 and 12 and given by:
  $G_{c3}G_p(s) = 1352K_{d3}[s+(K_{pc3}/K_{d3})] / [s(s+8)(s+20.8)]$ (13)

- The first-order compensator has three parameters to be tuned for optimal performance of the control system as follows:

- The zero/pole cancellation technique is adopted [13]. The PD controller zero $s+K_{pc3}/K_{d3}$ is set to cancel the pole s+20.8 of the process. This step reveals the relationship:
  $K_{pc3} = 20.8K_{pc3}$ (14)
- Now, the closed-loop transfer function of the control system in Fig.1 becomes:
  $M_3(s) = 1352K_{d3}/(s^2+8s+1352K_{d3})$ (15)
- The transfer function in Eq.15 is for a standard second-order control system of the form:
  $M_3(s) = \omega_n^2/(s^2+2\zeta\omega_n s+\omega_n^2)$. (16)
- Comparing the parameters of Eqs.15 and 16 reveals the derivative gain of the controller K_{d3} as:
  $K_{d3} = 0.011831$ (17)
- Now, using Eq.14 gives Kpc3 as:
  $K_{pc3} = 0.246154$ (18)
- The step response of the heart rate for an 85 beats/min desired heart rate when using a PD controller is drawn using Eqs.15 and 17 and the *step* command of MATLAB and shown in Fig.5.

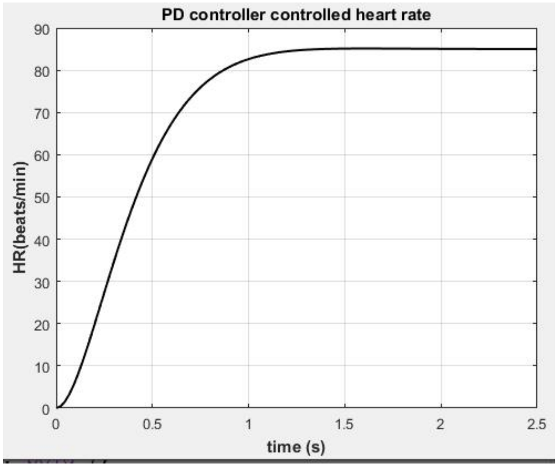

Fig.5 Heart rate control using a PD controller.

COMMENTS:

- Maximum overshoot: zero (compared with 3.585 % for a fuzzy-PID controller)
- Settling time: 1.05 s (compared with 0.763 s for a fuzzy-PID controller)
- Steady-state error: zero

VI. HEART RATE CONTROL USING A 2DOF-3 CONTROLLER

- The 2DOF-3 controller was introduced by the author starting from 2015 to replace the first generation of PID controllers through the control of a number of processes having bad dynamics. The block diagram of a 2DOF-3 controlled process is shown in Fig.6 [17]. It is composed of two PD control mode elements, one in the feedforward path receiving the reference input and the secong in the feedback path receiving the controlled variable.

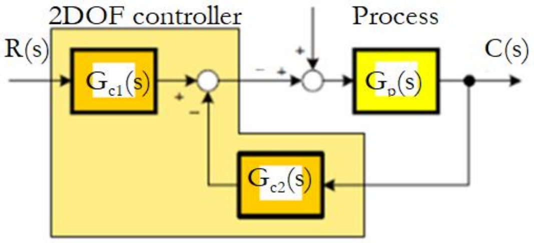

Fig.6 Heart rate control using a 2DOF-3 controller [17].

- The two elements of the 2DOF-3 controller have the transfer functions:

$G_{c4}(s) = K_{pc4}+K_{d4}s$, $G_{c5}(s) = K_{pc5}+K_{d5}s$ (19)

- The 2DOF-3 controller has four gain parameters K_{pc4}, K_{d4}, K_{pc5} and K_{d5} to be tuned to adjust the performance of the closed-loop control system.
- The transfer function of the closed-loop control system is derived from the block diagram using Eqs.3 and 19.
- The 2DOF-3 controller is tuned as follows:
  - A hybrid tuning approach is used.
  - The zero/pole cancellation technique [13] is used to relate some of the controller parameters to each other. In the transfer function of the closed-loop in Fig.6, the controller zero $s+K_{pc5}/K_{d5}$ is set to cancel the process simple pole s+20.8. This step reveals:

    $K_{pc5}=20.8K_{d5}$ (19)
  - Now, in the closed-loop transfer function of the control system, a performance condition is used to produce step time response with zero steady-state error. This step reveals the following relationship between the proportional gain K_{pc4} and derivative gain K_{d5}. That is:

    $K_{pc4} = 20.8K_{d5}$ (20)
  - The above steps leave the transfer function of the control system function of only K_{d4} and k_{d5}. They are tuned through using an ITAE performance index [14] and MATLAB optimization toolbox [15]. The hybrid tuning approach followed reveals the following tuned parameters of the 2DOF controller:

    $K_{pc4} = 6.2579x10^5$; $K_{d4} = 8.012455$

    $K_{pc5} = 6.2579x10^5$; $K_{d5} = 0.3008x10^5$ (21)
  - The step response of the heart rate for an 85 beats/min desired heart rate when using a 2DOF-3 controller is drawn using the controller parameters in Eq.21 and the *step* command of MATLAB and shown in Fig.7.

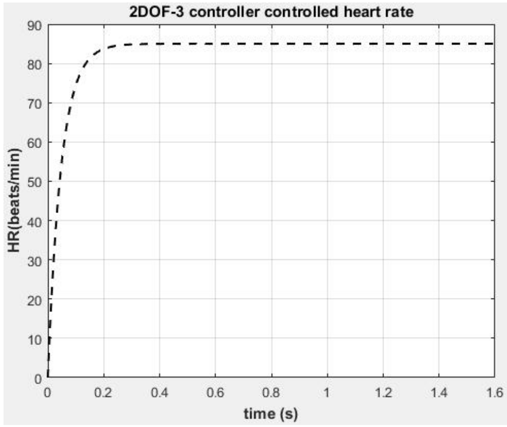

Fig.7 Heart body control using a 2DOPF-3 controller.

COMMENTS:

- Maximum overshoot: 0.026 % (compared with 3.585 % for a fuzzy-PID controller)
- Settling time: 0.188 s (compared with 0.763 s for a fuzzy-PID controller)
- Steady-state error: zero

VII. HEART RATE CONTROL USING A FUZZY PID CONTROLLER

- Yadav, Rani and Gang used a fuzzy PID controller to control the pacemaker and heard rate models used in this research paper [5]. Their step time response using the fuzzy PID controller for an 85 beats/min desired output is shown in Fig.8 when it is digitized.

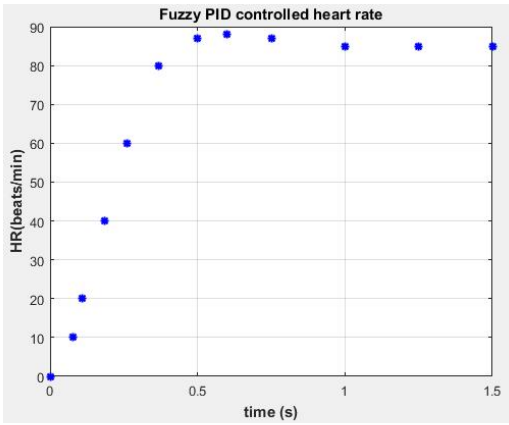

Fig.8 Heart body control using a fuzzy PID controller [5].

COMMENTS:

- Maximum overshoot: 3.585 %
- Settling time: 0.763 s
- Steady-state error: zero

VIII. COMPARISON OF TIME BASED CHARACTERISTICS

Graphical Comparison:

- The time-based characteristics of the control systems incorporating the proposed compensators/controllers proposed to control the heart rate are compared graphically through the step time response as depicted in Fig.9 for 85 beats/min step input tracking.

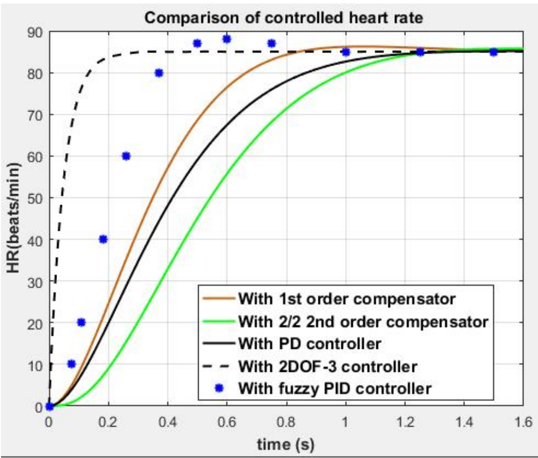

Fig.9 Heart rate control using five compensators/controllers.

Numerical Comparison:

Numerical comparison for the time-based characteristics of the step time response for reference input tracking of the control system with the proposed compensators/controllers is presented in Table 1 with comparison with the application of a fuzzy PID controller used to control the same process.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF A HEART RATE CONTROL

Compensator/ controller	OS_{max} (%)	T_s (s)	e_{ss} (beats/min)
First-order compensator	1.47	0.760	0
2/2 second-order compensator	0.87	1.147	0
PD controller	0	1.050	0
2DOF-3 controller	0.026	0.188	0
Fuzzy PID controller	3.585	0.763	0

OS_{max}: Maximum overshoot.
T_s: Settling time to ± 2% tolerance
e_{ss}: steady-state error.

IX. CHARACTERISTICS COMPARISON WITH OTHER CONTROLLERS

- There are many modern controllers tried by some researchers to control human heart rates.
- For sake of investigating the effectiveness of the 2DOF-3 controller selected in the present work as the best among the four compensators/controllers studied in the present work, five controllers are used: Fuzzy-PID [5], BIO-PID [7], fractional-order PID controller [8], fractional order PID-Particle swarm optimization tuned (PSO-PID$^{\lambda}$)[10], sliding mode controller (SMC) [18] and adaptive neural network (NN) controller [19]. The model of the heart rate may differ from that in reference [5] and the comparison covers only the maximum percentage overshoot and the settling time. Table 2 presents the comparison of both characteristics for the six controllers and the 2DOF-3 controller proposed in the present work.

TABLE 2: NUMERICAL OF MAXIMUM OVERSHOOT AND SETTLING TIME OF SOME HEART RATE CONTROL SYSTEMS

Controller	Reference number	OS_{max} (%)	T_s (s)
Fuzzy-PID	5	3.585	0.763
BIO-PID	7	5.930	6.290
Fractional-order PID	8	0.860	0.357
PSO-PID	10	27.600	0.693
SM-controller	18	0	0.900
Adaptive NN-controller	19	0	38
2DOF-3 controller	present	0.026	0.188

BIO: Bioinspired
PSO: Particle Swarm Optimization
NN: Neural Network

X. CONCLUSIONS

- The research work presented in this research paper handled the tuning of first-order compensator, 2/2 second-order compensator, PD controller and 2DOF-3 controller proposed to control an autonomous heart rate.
- The paper presented three controllers/compensators from the first generation of compensators/PID controllers and one controller from the second generation of PID controllers compared with a fuzzy PID controller from the first generation.
- The controlled process (heart rate) was an unstable putting more challenge on the proposed compensator/controller besides the desired good performance of the control system.
- The four compensators/controllers were tuned using a hybrid approach based on zero/pole cancellation, specific closed-loop system characteristics and MATLAB optimization with an ITAE performance index aiming at providing a good dynamic performance for the control system.
- All the proposed compensators/controllers succeeded to eliminate completely the steady-state error of the control system.
- The proposed PD controller succeeded to eliminate completely the maximum percentage overshoot of the control system compared with 3.585 % for the fuzzy PID controller.
- All the proposed controllers/compensators succeeded to eliminate completely the steady-state error of the control system.
- The first-order compensator could compete with the fuzzy-PID controller regarding the maximum overshoot (1.47 % compared with 3.585 % for the fuzzy PID controller).
- The 2/2 second-order compensator could compare with the fuzzy-PID controller regarding the maximum overshoot (0.870 % compared with 3.585 % for the fuzzy PID controller), but couldn't compete with it regarding the settling time (1.147 s compared with 0.763 s for the fuzzy PID controller).
- The 2DOF-3 controller could compare with the fuzzy-PID controller regarding the maximum overshoot and settling time (0.026 % and 0.188s compared with 3.585 % and 0.763 s for the fuzzy PID controller),
- The 2DOF-3 was selected as the best compensator/controller regarding reference input tracking providing zero steady-state error, very small maximum overshoot and minimum settling time compared with the other compensators/controllers investigated in the present study.
- When compared with six controllers (fuzzy-PID, BIO-PID, fractional-order PID, PSO-PID, SMC and NN-controller) the 2DOF-3 controller selected here as the best controller could compete with the six controllers providing the best performance in heart rate control.

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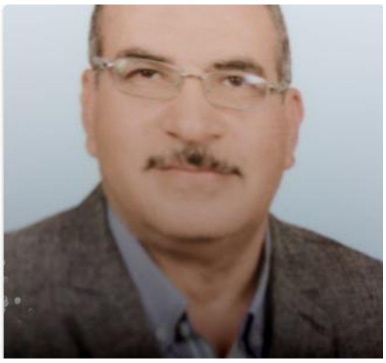
DEDICATION



Dr. ASHRAF AMMAR

- I dedicate this research work to Dr. Ashraf Ammar. Why?
- He is a Consultant of Cardiology and Internal Medicine, Beni-Suef General Hospital.
- Dr. Ammar has extensive experience in the long-term treatment of cardiology and internal medicine diseases.
- He is keen on attending medical conferences to further his professional development and provide the best care for his patients.

- He has worked for 20 years and has extensive expertise in CCU and ICU units.
- He has also spent a significant amount of time working in the nephrology department and HD units.
- I am confident that, as a cardiology specialist, he will strive to benefit from this research and be among the first to apply the presented technologies.
- Good luck, Dr. Ashraf Ammar.

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 340 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Chief Justice of the International Journal of Computer Techniques.
- Member of the Editorial Board of IJET.
- Reviewer in some international journals.
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