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Autonomous Human Body Control, Part IV: Skin Temperature Control using PD-I and PD-PI Controllers Compared with a PI Controller

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Abstract:
This paper investigates the tuning of PD-I and PD-PI controllers from the second generation of PID controllers when used to control the skin temperature of an autonomous human body. The paper presents a novel control scheme without using any chemicals through patient injection. The proposed controllers are tuned using a hybrid approach based on zero/pole cancellation, trial and error and MATLAB optimization technique using an ITAE performance index. The tuning results are presented and applied to generate the step time response for reference input tracking of a specific level. Transfer function for a patient skin temperature process is identified using experimental work from previous work. The characteristics of the step time responses are compared with those of a conventional PI controller from the first generation of PID controllers. The best controller for the control of the human skin temperature is assigned.

Keywords **— Autonomous human body control, skin temperature control, PD-I controller, PD-PI controller, PI controller, controller tuning.**

I. INTRODUCTION

This is the fourth paper of a 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 skin temperature of the human body where severe environmental temperature results in dizziness, fainting, sleep disruption, breathing difficulties, heart attacks and kidney damage [1]. On the other hand very low environmental temperature leads to shivering, mumbling, slow breathing, weak heart pulse, lack of coordination, drowsiness, confusion and loss of consciousness [2]. This is why controlling the human body temperature is important in case of deviation from normal value of 37°C.Here are some of the research efforts regarding the control of human body temperature:

Neghabat, Ringuest and Gulledge (1989) developed models for the controller mechanisms of the human temperature regulation system. They used time series modeling technique to develop ….. models for metabolic heat production and evaporative heat loss. They compared simulated skin temperature and experimental values showing the validity of the developed controller model [3]. Meyer (1992) outlined the different types of models of body temperature regulation which were used for the prediction of body's thermal behavior in changing environmental conditions. He presented block diagrams for all the studied body temperature models [4]. Candas and Yermakova (2008) investigated the quantitative evaluation of the dynamic physical changes during human physical activity in moderate heat. They implemented mathematical models for the prediction of human thermal state in an object oriented approach as a computer simulator. They presented graphically the dynamic variation of blood temperature and heat rate for 300 and 700 W human thermal activities [5]. Satoru, Hiraka and Takayuki (2009) investigated a thermal model that can predict the human body temperature under given environmental conditions and showed that the coefficients of the thermal model of the human body can be identified. They used six coefficients related to the regulation results for the entire thermal transient process including exposures to heat and cold [6].

Alonso (2012) investigated the responses and mechanisms of vascular convective heat exchange in exercising limbs to understand the loal tissue temperature regulated using exercise and environmental stress. He presented graphically the evolution of muscle, blood and core temperatures across a human leg during exercise over 10 minutes period [7]. Tansey and Johnson (2015) summarized the basic concepts of thrmoregulation and assessed

the physiological response to heat and cold stress. They presented graphically the discharge frequencies at different skin temperatures of thermo receptors between freezing cold (5-18 °C) and burning heat (50-60 °C) [8]. Melnikov, Krzhanovskaya, Lees and Sloot (2018) extended a classical two-node model of human body thermal regulation and gave detailed description of all concepts, parameter values and tested the dynamics of the model against experimental data. They analysed the sensitivity of the model to climate and personal parameters revealing the relative importance of air temperature, wind speed and clothing in various climate settings. They concluded that their model was validated for cool, warm and hot environments in terms of its dynamics. They presented the graphical change in skin and core temperatures for air temperature change between 19.5 and 38.9 °C [9]. 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].

Santeso, Hamzah, Syaifudin and Mujahid (2023) implemented PID control to regulate a heater maintaining the temperature of the blood tuned for a precise time response. They employed a fuzzy logic control for the same purpose and to handle nonlinearities and complex relationships. They compared both controllers for their effectiveness in regulating blood temperature during transfusion [10]. Yu, Delgado and Mezerville (2024) discussed the human body temperature locations for: accuracy, ease of use, advantages and drawbacks. They found the best location for core body temperature and discussed the latest temperature technologies: heat flux, telemetric ingestible temperature bills and body locations used to validate these devices [11]. Gue et al. (2025) introduced an approach leveraging a lauric acid with flexible styrene-ethylene-butylene-styrene thermoplastic as a matrix and grapheme nanoplatelets as a conductive filter. They stated that the flexible composite demonstrated significant potential for body temperature sensing, self-regulating heating and passive cooling in wearable health monitoring [12].

II. THE CONTROLLED BODY SKIN TEMPERATURE AS A PROCESS

In the work of Neghabat et al. (1989), they presented graphical variation of a human skin temperature variation from 34 to 28 °C (cooling process) and from 28 to 29.4 °C (heating process) according to environmental changes [3]. They didn't give any mathematical models for these temperature changes. Therefore, I considered the heating process with changes in skin temperature from 0 (at zero time to 3.7 °C (at 60 s time) for an environment temperature change from 17.4 to 29.4 °C. I have used MATLAB to fit a model for the body skin heating process using a code written by the author as one of a set of codes used as an '*identification toolbox*'. The heating process transfer function model for the body skin temperature during heating, $G_{st}(s)$ as obtained by the author with 0.99917 correlation coefficient is given by:

$$G_{st}(s) = 0.30833(1+19.05s)/[(1+10.25s)(1+21.95s)] \quad (1)$$

The unit step time response of the human body skin temperature during heating is drawn using the '*step*' command of MATLAB [13] and shown in Fig.1.

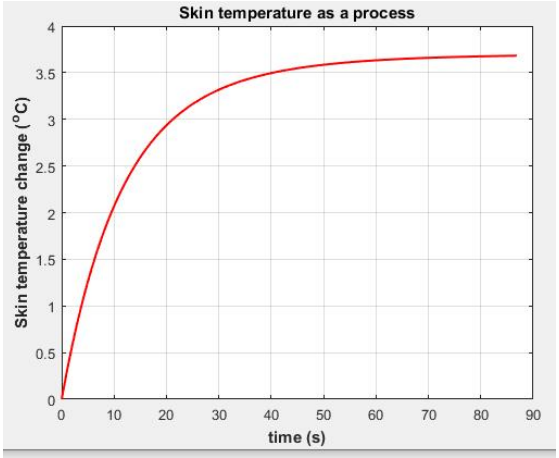

Fig.1 Unit step time response of the body skin temperature as a process.

COMMENTS:

- The skin temperature during heating is a stable process.
- Maximum overshoot: zero.
- Settling time: 54.20 s
- Steady-state error: 8.318 °C

III. NOVEL SCHEME FOR BODY SKIN TEMPERATURE CONTROL

Most of the automatic control strategies used to externally control the human body activities depend on injecting chemical liquid drugs inside the human body [14-16]. Here for the purpose of controlling the human body skin temperature without any chemicals injected inside the body I introduce a novel control system based on controlling the temperature of the environment around the patient. The control strategy depends on using a master controller to control the human skin temperature and a sub-controller to control the temperature of the patient single-accommodation room. The block diagram of the proposed control system is shown in Fig.2.

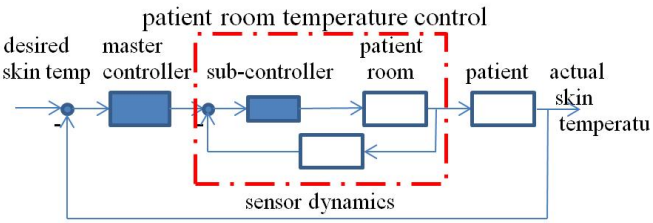

Fig.2 Skin temperature control structure.

The proposed control system works as follows:

- The desired skin temperature is set at the input of the error detector of the master controller.
- The master controller of the patient skin temperature receives an error signal from its error detector and depending on its dynamic model generates a control system fed to the error detector of the sub-controller of the patient room air conditioning system.
- The sub-controller of the air conditioned room received an error signal from its error detector and set the temperature of the patient room accordingly.
- Depending on the dynamics of the patient body in response to the room temperature its skin temperature is controlled using the feedback technology originated by Banu Musa bin-shaker in the 9th AC century [17].

A conventional PI controller is assigned to control the temperature of the patient room temperature. This of course depends of the dynamics of the room. The dynamics of the room was defined by a temperature transfer function $G_{PR}(s)$ and a temperature sensor transfer function $G_{TS}(s)$ given by [18]:

$$\left.\begin{aligned} G_{PR}(s) &= 1/(450s+1) \\ G_{TS}(s) &= 1/(30s+1) \end{aligned}\right\} \quad (2)$$

The PI controller transfer function, $G_{PI}(s)$ is given by:

$$G_{PI}(s) = K_{pc1}+(K_{i1}/s) \quad (3)$$

Where K_{pc1} and K_{i1} are its gain parameters.

The PI controller used to control the patient room temperature is tuned as follows:

- The transfer function of the controller is writer in the form:

$$G_{PI}(s) = (K_{i1}/s)[(K_{pc1}/K_{i1})s+1) \quad (4)$$

- The forward path transfer function of the patient room control loop, G(s) is given by:

$$G(s) = (K_{i1}/s)[(K_{pc1}/K_{i1})s+1) /(450s+1) \quad (5)$$

- Using the zero/pole cancellation technique [19], the zero $(K_{pc1}/K_{i1})s+1)$ cancels the pole (450s+1) providing the following relationship between the controller gain parameters:

$$K_{pc1} = 450\ K_{i1} \quad (6)$$

- Now, G(s) becomes:

$$G(s) = K_{i1}/s \quad (7)$$

- Also, the closed-loop transfer function of the control loop of the patient room, $M_1(s)$ becomes:

$$M_1(s) = [K_{i1}s+(K_{i1}/30)]/[s^2+s+(K_{i1}/30)] \quad (8)$$

- The tuning process using this procedure is reduced to the adjustment of only one controller parameter.
- With few manual trials, the value 0.98 was chosen as the tuned integral gain of the PI controller. Using Eq.6, the tuned controller parameters of the PI controller are:

$$K_{pc1} = 441.0 \quad , \quad K_{i1} = 0.98 \quad (9)$$

- The step time response of the patient room for a desired temperature of 20°C is generated using the step command of MATLAB [13] and shown in Fig.3.

COMMENTS:

- Maximum overshoot: zero.
- Settling time: 3.53 s
- Steady-state error: zero

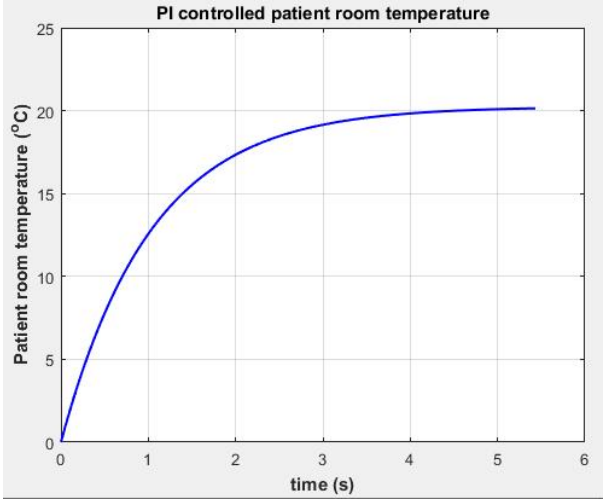

Fig.3 Patient room temperature control using a PI controller.

IV. PATIENT SKIN TEMPERATURE CONTROL USING A PI CONTROLLER

- The control scheme presented in Fig.2 is first applied using a conventional PI master controller to control the patient skin temperature. The PI controller transfer function in this case has the transfer function, $G_{PI2}(s)$ given by:

$$G_{PI2}(s) = K_{pc2}+(K_{i2}/s) = (K_{i2}/s)[(K_{pc2}/K_{i2})s+1) \quad (10)$$

- In the feedback control structure in Fig.2 there are three transfer functions: $G_{PI2}(s)$ for the PI master controller, $M_1(s)$ for the patient single-room transfer function and $G_{st}(s)$ for the patient skin temperature process defined by Eqs.10, 8 and 1 respectively.
- The three elements: $G_{PI2}(s)$, $M_1(s)$ and $G_{st}(s)$ are cascaded in series.
- Multiplying $G_{PI2}(s)$ by $G_{st}(s)$ and applying the zero/pole cancellation technique [19] gives the following relationships between the PI controller parameters:

$$K_{pc2} = T_1 K_{i2} \quad (11)$$

- Now, the open loop transfer function of the control system, $G_{PI2}(s)M_1(s)G_{st}(s)$ can be derived using Eqs.10, 8, 1, 11 leading the derivation of the closed-loop transfer function of the control system in Fig.2.
- The closed-loop transfer function of the control system will be function in one unknown which is the integral gain K_{i2} of the PI controller.
- The ITAE performance index [20] as function of the error signal of the control system is used to tune the PI controller using the MATLAB optimization toolbox [21]. The result of this process with the help of Eq.11 give the PI controller parameters as:

$$K_{pc2} = 30.17117, K_{i2} = 2.94353 \quad (12)$$

- The step time response of the patient skin temperature for a -3 °C desired skin temperature when using a PI controller is shown in Fig.4. The -3 °C means simply that the patient skin temperature was 40 °C and it is desired to bring it down to 37 °C, the step response will be like this shown in Fig.4.

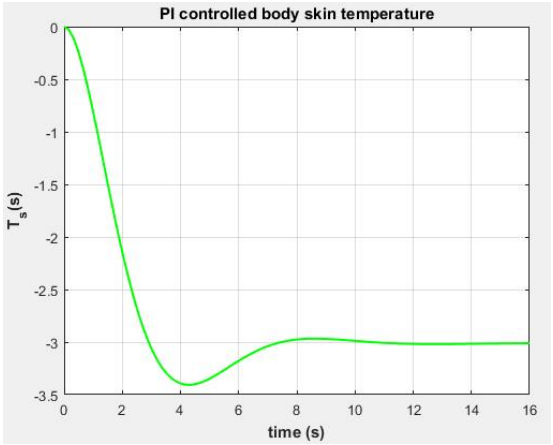

Fig.4 Patient skin temperature control using a PI controller.

COMMENTS:

- Maximum overshoot: 13.15 %
- Settling time: 6.7 s
- Steady-state error: zero

V. PATIENT TEMPERATURE CONTROL USING A PD-I CONTROLLER

- The PD-I controller is one of the second generation of PID controllers. It was introduced by the author in 2018 to control underdamped second-order-like processes

[22]. It has the transfer function, $G_{PDI}(s)$ given by [22]:

$$G_{PDI}(s) = (K_{pc3}+K_{d3}s)(K_{i3}/s)$$
$$= K_{pc3}K_{i3}[1+(K_{d3}/K_{pc3})s]/s \quad (13)$$

Where K_{pc3}, K_{d3} an K_{i3} are the proportional , derivative and integral gains of the PD-I controller.

- Multiplying $G_{PDI}(s)$ by $G_{st}(s)$ and applying the zero/pole cancellation technique [19] gives the following relationships between the PD controller element parameters K_{pc3} and K_{d3} as:

$$K_{d3} = T_1 K_{pc3} \quad (14)$$

- Now, the sub-open loop transfer function $G_{PDI}(s)G_{st}(s)$ becomes:

$$G_{PDI}(s)G_{st}(s) = K_{pc3}K_{i3}K_s(1+T_3s)/(T_2s^2+s)$$
$$= K_3(1+T_3s)/(T_2s^2+s) \quad (15)$$

Where $K_3 = K_{pc3}K_{i3}K_s$

- Now, the closed-loop transfer function of the control system in Fig.2 will be function only of one parameter K_3.
- Few manual trials of K_3 give good control performance without need to any optimization algorithm application. The result of this process assuming $K_{pc3} = 1$ and using Eq.14 is as follows:

$$K_{pc3} = 1, K_{d3} = 10.25, K_{i3} = 0.4865 \quad (16)$$

- The step time response of the patient skin temperature for a -3 ^oC desired skin temperature when using a PD-I controller is shown in Fig.5 using the *step* command of MATLAB [13].

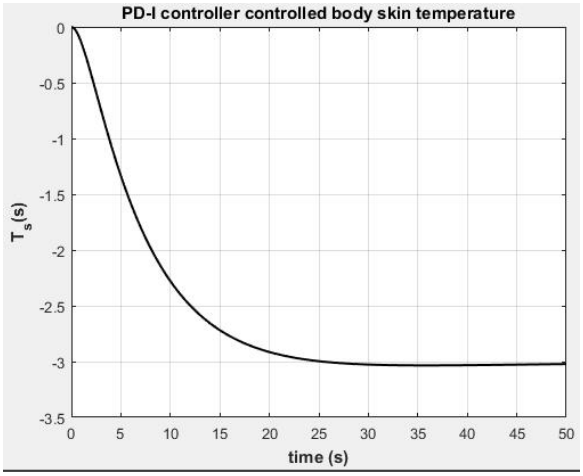

Fig.5 Patient skin temperature control using a PD-I controller.

COMMENTS:

- Maximum overshoot: zero (compared with 13.15 % for the PI controller)
- Settling time: 21.13 s (compared with 6.70 s for the PI controller)
- Steady-state error: zero

VI. PATIENT SKIN TEMPERATURE CONTROL USING A PD-PI CONTROLLER

- The PD-PI controller was introduced by the author starting from 2014 to replace the first generation of PID controllers through the control of a number of processes having bad dynamics [23]. The PD-PI controller is consisted of two cascaded control modes: PD and PI set in the single-loop block diagram of a linear control system just after the error detector. It has a transfer function $G_{PDPI}(s)$ given by:

$$G_{PDPI}(s) = (K_{pc4}+K_{d4}s)[K_{pc5}+(K_{i5}/s)]$$
$$= K_{pc4}K_{pc5}[1+(K_{d4}/K_{pc4})s][1+(K_{pc5}/K_{i5})s]/s \quad (17)$$

Where K_{pc4}, K_{d4}, K_{pc5} and K_{i5} are the gain parameters of the PD-PI controller.

- Multiplying $G_{PDPI}(s)$ by $G_{st}(s)$ and applying the zero/pole cancellation technique [19] gives the following relationships between the PD and PI control elements parameters K_{pc4} , K_{d4} and K_{pc5} , K_{i5} as:

$$K_{d4} = T_1 K_{pc4}, K_{pc5} = T_2K_{i5} \quad (18)$$

- The closed-loop transfer function of the control system incorporating the PD-PI controller is derived using the block diagram in Fig.2.
- Now, the sub-open loop transfer function $G_{PDPI}(s)G_{st}(s)$ becomes:

$$G_{PDPI}(s)G_{st}(s) = K_{pc4}K_{pc5}K_s(1+T_3s)/s$$
$$= (K_4+K_4T_3s)/s \quad (19)$$

Where $K_4 = K_{pc4}K_{pc5}K_s$

- Now, the closed-loop transfer function of the control system in Fig.2 will be function only of one parameter K_4.

- Few manual trials of K_4 have given excellent control performance without need to any optimization algorithm application. The result of this process assuming $K_{pc4} = 1$ and using Eq.18 is as follows:
  $K_{pc4} = 1$, $K_{d4} = 10.25$
  $K_{pc5} = 50.2708$, $K_{i5} = 2.2902$ (16)
- The step time response of the patient skin temperature for a -3 °C desired skin temperature when using a PD-I controller is shown in Fig.6 using the *step* command of MATLAB [13].

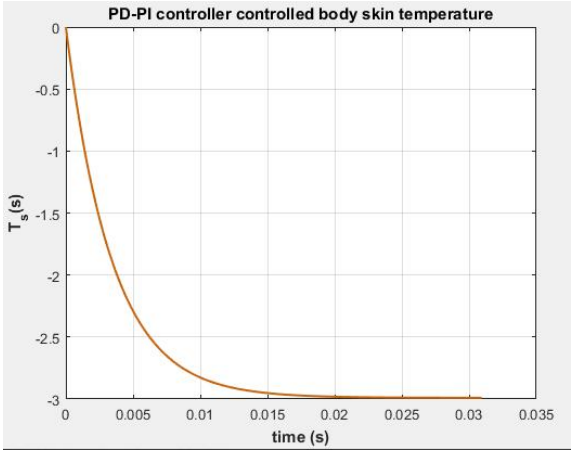

Fig.6 Patient skin temperature control using a PD-PI controller.

COMMENTS:

- Maximum overshoot: zero (compared with 13.15 % for PI controller)
- Settling time: 0.014 s (compared with 6.7 s for the PI controller)
- Steady-state error: zero

VII. COMPARISON OF TIME BASED CHARACTERISTICS

Graphical Comparison:

- The time-based characteristics of the control systems incorporating the proposed controllers proposed to control the patient skin temperature are compared graphically through the step time response as depicted in Fig.7 for – 3 °C step input tracking.

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 controllers is presented in Table 1 with comparison with the application of a conventional PI controller used to control the same process.

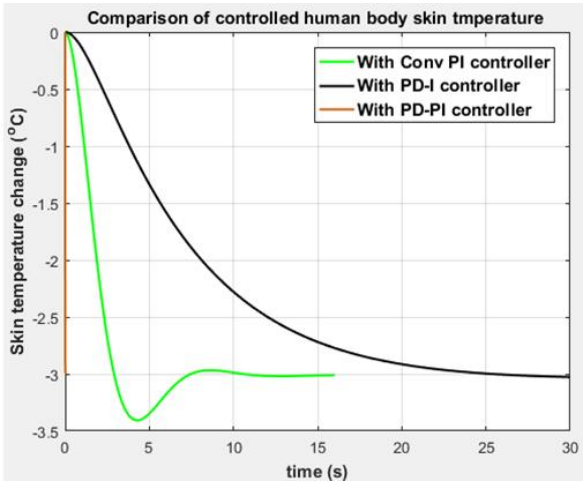

Fig.7 Patient skin temperature control using three controllers.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF PATIENT SKIN TEMPERATURE CONTROL

Controller	OS_{max} (%)	T_s (s)	e_{ss} (°C)
PD-I	0	21.13	0
PD-PI	0	0.014	0
PI	13.15	6.7	0

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

VIII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of two controllers proposed to control an autonomous patient skin temperature.
- The paper presented two controllers from the first generation of PID controllers and one controller from the second generation of PID controllers compared with a PI controller from the first generation.
- The proposed control system was a novel control scheme based on external activity acting on the human body without any chemicals.
- The controlled process (patient skin temperature) was a stable one having 54.2 s settling time and 8.318 °C steady-state error to a reference input of 12 °C. This means that this process has relatively bad dynamics

and puts more challenge on the proposed controllers to produce a good performance control system.

- The three controllers (PI, PD-I and PD-PI) were tuned using a hybrid approach based on zero/pole cancellation, trial and error 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-I and PD-PI controllers succeeded to eliminate completely the maximum percentage overshoot of the control system compared with 13.15 % for the PI controller.
- All the proposed controllers succeeded to eliminate completely the steady-state error of the control system.
- The PD-PI controller succeeded to reduce the settling time of the control system to only 0.014 s compared with 6.7 s for the PI controller.
- The PD-PI controller was selected as the best controller regarding reference input tracking providing zero steady-state error, zero maximum overshoot and minimum settling time compared with the other controllers investigated in the present study.

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DEDICATION

Prof. Hesham Hussain

- I dedicate this research work to Prof. Hesham Hussain, Why?
- Consultant General Pediatric Surgery.
- Promotion to the degree of general surgery professor.
- Head of the Pediatric surgery unit at Benha University Hospitals.
- Renovation of a pediatric laparoscopic hernia technique.
- Presented clinical research papers at international conferences in Egypt and Germany.
- Published numerous clinical research studies in prestigious international journals.
- Completed over 3500 successful surgeries.
- Participation in continual medical education.
- Conduction and Supervision of clinical and academic research works.
- I have conducted valuable discussions with Prof. Hesham Hussain regarding my recent research series about the autonomous human body control.
- Good luck, Prof. Hesham Hussain.

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.
- Chief Justice of the International Journal of Computer Techniques.
- Member of the Editorial Board of IJET.
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