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AUTONOMOUS HUMAN BODY CONTROL, PART VII: BLOOD OXYGEN SATURATION CONTROL USING I-FIRST ORDER, I-SECOND ORDER AND I-1/2 ORDERS COMPENSATORS COMPARED WITH MRAC CONTROLLER

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ABSTRACT

This paper is the seventh in a series of research papers presenting the autonomous control of the human body. It handles the control of blood oxygen saturation (SpO2) using I-first order, I-second order and I-1/2 orders compensators from the second generations of control compensators. The proposed compensators are tuned using multiple approaches including zero/pole cancellation and trial & error. The step time response of the control system using the proposed compensators is presented and compared with using a model-reference adaptive controller (MRAC) using the same patient dynamic characteristics and the time-based characteristics are compared. The comparison reveals the best compensator among the four compensators/controller depending on a graphical and quantitative comparison study.

KEYWORDS: Autonomous human body control, blood oxygen saturation control, I-first order compensator, I-second order compensator, I-1/2 orders compensator, MRAC controller, compensators tuning.

INTRODUCTION

Low level of oxygen in the human blood (hypoxemia) causes some symptoms such as: headache, difficult of breathing, rapid heart rate, coughing, wheezing and confusion.[1] This means that the situation deserves great attention from scientists to compensate for oxygen shortage in the blood through the application of autonomous control systems capable of taking the SpO2 (oxygen saturation) level to a normal range of 95 to 100 %.[2] First of all we will have a look into some of the international research regarding this important aspect since 2010.

Misgeld, Werner and Hexamer (2010) presented an automatic control strategy for the control of oxygen and carbon dioxide gas partial resources for use during cardiopulmonary bypass surgery with heart-lung machine support. They used a feedback linearization with time delay compensation and two external linear gain scheduled controllers tuned and tested in situations with artificial lung model.[3] Kim et al. (2013) investigated changes cognitive ability, blood oxygen saturation and heart rate in normal elderly subjects at three levels of oxygen. They showed that blood oxygen saturation increased, heart rate decreased and response time decreased as the concentration and amount of administrated oxygen increased.[4]

Abraham, et al. (2016) developed and tested the regulation of oxygen flow intake based on patient oxygen blood saturation. They concluded that closed-loop control system application will improve the health of many patients. They presented patient's SpO2 and oxygen supply pressure profiles for time up to 250s.[5] Hansen et al. (2018) tested the closed-loop control system O2matic for the control of oxygen saturation in patients with exacerbations of COPD during admission. They compared with manual control by nursing staff. They monitored patients with continuous measurement of SpO2 and concluded that the control system was better than manual control in maintaining SpO2 within target interval.[6] Zhang et al. (2020) built a mobile continuous blood oxygen saturation monitor and explored key design principles for daily application. They explored SpO2 model building principles and their experimental results indicated the effectiveness of their monitoring system facilitating the continuous monitoring of SpO2 of patients with clinical indications.[7] Charvatova et al. (2022) studied the effect of face masks and respirators on blood oxygen concentration, breathing frequency and heart rate changes. They concluded that mask wearing had minimum effect on blood oxygen concentration and substantial influence on the breathing frequency and heart rate. They concluded also that using a respirator substantially increased the respiratory rate under load.[8]

Naskar, Pal and Jana (2023) proposed an intelligent set point modulated fuzzy PI-based model reference adaptive controller to control the oxygen supply to uncomfortable breathing or respiratory infected patients. They enhanced the effectiveness of the model reference adaptive control (MRAC) using fuzzy-based tuning and set-point modification strategy. They modeled and simulated nonlinear mathematical formulations of the respiratory system and the exchange of oxygen with time delay. They linearized the nonlinear model and derived the transfer function model for the SpO2 process and used it in the control of SpO2 for 95 % desired level.[9] Choudhary, Shivdeep and Das (2024) presented the design and development of a printed circuit board prototype of a pulse oximeter integrated with an oxygen concentration for automated oxygen flow rates. The designed pulse oximeter measured the blood oxygen levels and heart rate providing voltage signals supplied to a PC.[10] Luo et al. (2025) presented a SpO2 measurement method from fingertip videos covering an estimation range from 70 to 100%. Their measurement approach incorporated a transformer encoder mixed with squeeze and excitation block network architecture and signal quality assessment module with filtering. They concluded that their approach offered an effective method for users to conduct SpO2 measurements based on electronic devices.[11]

Controlled Oxygen Saturation SpO2 as a Process

Naskar, Pal and Jana modeled infected area of patient's alveoli for the oxygen saturation (SpO2) and casted this model in the form of a transfer function composing of two elements of 0/2 and 2/3 orders as a process $G_{SpO2}(s)$ to be controlled as presented below.[9]

$$G_{SpO2}(s) = [1/(s^2+2.5s+1)][(20s^2+200s+62)/(s^3+110s^2+350s+67)] \qquad (1)$$

To investigate the dynamics of this medical human process for a desired oxygen saturation of 95%, Eq.1 is used with the step and plot commands of MATLAB.[12]

COMMENTS

- The SpO2 as a process is stable.
- It has non-zero steady-state error of 7.107 %.
- It has zero maximum percentage overshoot.
- It has a settling time of 17.453 s.

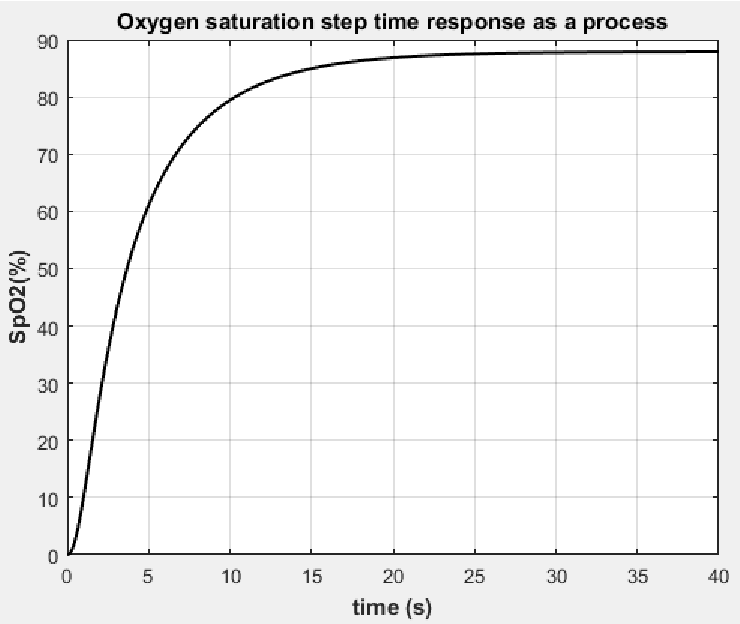

Figure 1: Step time response of Oxygen saturation as a process.

Controlling the Blood Oxygen Saturation using a Model Reference Adaptive Controller (MRAC)

Naskar, Pal and Jana[9] used a Model Reference Adaptive Controller (MRAC) to control the oxygen saturation (SpO2) of a patient with an infected inspiratory system based on the use of the transfer function in Eq.1. His step time response for 95 % desired SpO2 was digitized and presented in Fig.2 with the lower and upper limits of the oxygen saturation of 95 and 100 %.[13]

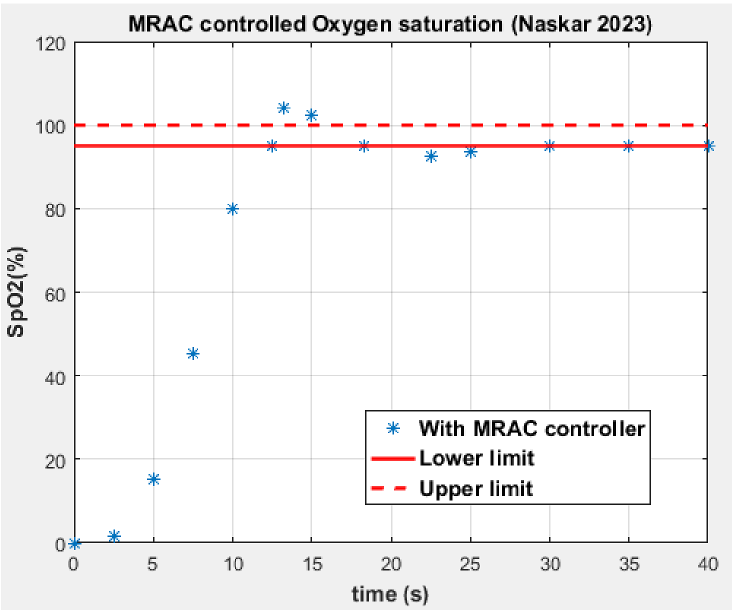

Figure 2: Control of the Oxygen Saturation using a MRAC controller.[9]

COMMENTS

The step time response of the SpO2 controlled by a tuned MRAC controller for a reference input tracking with 95 % desired SpO2 had the following time-based characteristics:

- Maximum percentage undershoot: 7.40%
- Settling time within ± 2 % tolerance: 30 s
- Steady-state error: zero

Controlling the Blood Oxygen Saturation using an I-first Order Compensator

- The I-first order compensator was used by the author in September 2024 controlling the car longitudinal velocity.[14] It consists of an integrator cascaded with a first-order compensator set just after the error detector of a single-loop control system block diagram.
- It has the transfer function, $G_{I1st}(s)$ given by[14]:

$$G_{I1st}(s) = (K_{i1}/s)(s+z_1)/(s+p_1) \quad (2)$$

Where:

K_{i1} is the compensator integral gain.

z_1 is the compensator simple zero.

p_1 is the compensator simple pole.

- The I-first order compensator has three parameters K_{i1}, z_1 and p_1 to be tuned to provide accepted performance of the closed-loop control system of the oxygen saturation.
- The transfer function of the oxygen saturation process in Eq.1 is written in another form suitable for the tuning approach as follows:

$$G_{SpO2}(s) = 20(s+0.32)(s+9.68)/[(s+0.2045)(s+0.5)(s+2)(s+3.069)(s+106.706) \quad (3)$$

- The open-loop transfer function of the control system is obtained by multiplying Eq.2 and Eq.3.
- The zero/pole cancellation technique[15] is used to provide the zero and pole of the compensator by equating $s+z_1$ and $s+0.2045$, $s+p_1$ and $s+0.32$ giving:

$$z_1 = 0.2045, \quad p_1 = 0.32 \quad (4)$$

- We are left now with one parameter K_{i1} to be tuned. Few trial and error values provide good performance for the control system with:

$$K_{i1} = 0.185 \quad (5)$$

- The step time response of the control system with the I-first order compensator with 95 % desired SpO2 and gain parameters given by Eqs.4 and 5 is shown in Fig.3.

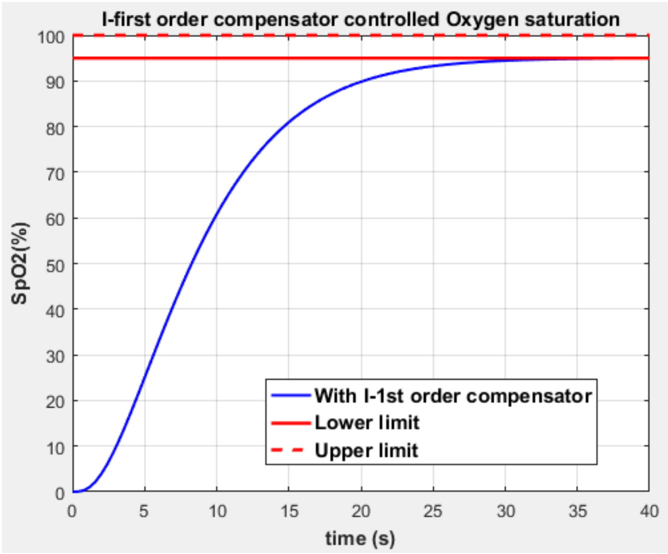

Figure 3: Control of the Oxygen Saturation using an I-first order compensator.

COMMENTS

- Maximum percentage undershoot: zero
- Settling time within ± 2 % tolerance: 24.65 s
- Steady-state error: zero

Controlling the Oxygen Saturation using an I-second Order Compensator

The I-second order compensator is one of the second generation control compensators introduced by the author since 2014 to replace the first generation compensators. It was used by the author in November 2024 to control the car yaw rate.[16] It is composed of two control cascaded elements: integral control mode and a 2/2 second order compensator. It has a transfer function $G_{I2nd}(s)$ given by:

$$G_{I2nd}(s) = (K_{i2}/s)(s+z_2)(s+z_4)/[(s+p_2)(s+p_3)] \qquad (6)$$

Where: K_{i2} = integral gain of the compensator.

z_2, z_3 = simple zeros of the compensator.

p_2, p_3 = simple poles of the compensator.

- The I-second order compensator gain parameters (K_{i2}, z_2, z_3, p_2, p_3) have to be tuned to satisfy the objectives of using the compensator to achieve good performance characteristics. It is tuned as follows:

- To facilitate the use of the zero/pole cancellation technique[15], the open-loop transfer function of the control system is derived using Eqs.3 and 6. In the resulting equation, compensator zeros $s+z_2$, $s+z_3$ cancel the process poles s+0.2045, s+0.5 and the compensator poles $s+p_2$, $s+p_3$ cancel the process zeros s+0.32, s+9.68. This step reveals:

$z_2 = 0.2045$, $z_3 = 0.5$, $p_2 = 0.32$, $p_3 = 9.68$ (7)

- Now, we are left with the integral gain K_{i2}. Few manual trials provided good control system performance with:

$K_{i2} = 12.50$ (8)

- Now, the closed-loop transfer function is deduced from the single-loop block diagram comprising the I-second order compensator and the oxygen saturation process to plot the step time response of the control system for a desired SpO2 of 95 % generated by the step command of MATLAB[12] and shown in Fig.4.

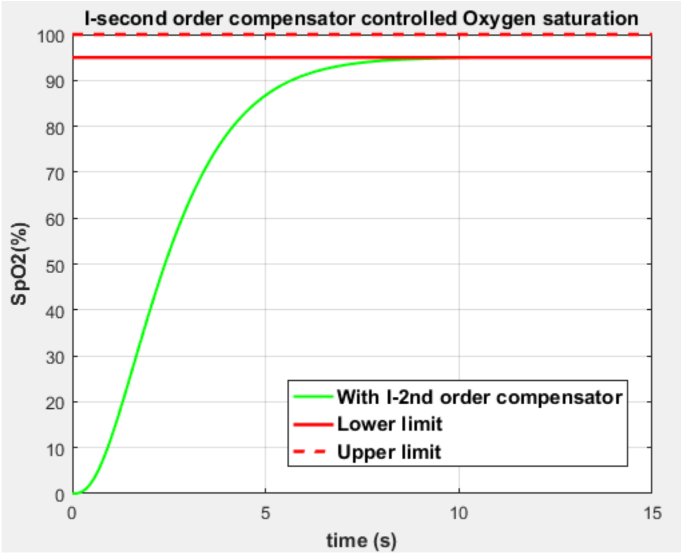

Figure 4: Control of the Oxygen Saturation using an I-second order compensator.

COMMENTS

- Maximum percentage undershoot: zero
- Settling time within ± 2 % tolerance: 6.88 s
- Steady-state error: zero

Controlling the Oxygen Saturation using an I-1/2 Orders Compensator

The I-1/2 orders compensator is one of the second generation control compensators introduced by the author since 2014 to replace the first generation compensators. It was used by the author in April 2025 to control the human blood pressure.[17] It is composed of two control cascaded elements: integral control mode and a 1/2 orders compensator. It has a transfer function $G_{I1by2}(s)$ given by:

$$G_{I1by2}(s) = (K_{i3}/s)(s+z_4)/[(s+p_4)(s+p_5)] \quad (9)$$

Where: K_{i3} = integral gain of the compensator.

z_4 = simple zero of the compensator.

p_4, p_5 = simple poles of the compensator.

- The I-1/2 orders compensator gain parameters (K_{i3}, z_4, p_4, p_5) have to be tuned to satisfy the objectives of using the compensator to achieve good performance characteristics. It is tuned as follows:

- To facilitate the use of the zero/pole cancellation technique[15], the open-loop transfer function of the control system is derived using Eqs.3 and 9. In the resulting equation, compensator zero $s+z_4$ cancels the process pole s+0.2045 and the compensator poles $s+p_4$, $s+p_5$ cancel the process zeros s+0.32, s+9.68. This step reveals:

$$z_4 = 0.2045, \quad p_4 = 0.32, \; p_5 = 9.68 \tag{10}$$

- Now, we are left with the integral gain K_{i3}. Few manual trials provided good control system performance with:

$$K_{i3} = 1.910 \tag{11}$$

- Now, the closed-loop transfer function is deduced from the single-loop block diagram comprising the I-1/2 orders compensator and the oxygen saturation process to plot the step time response of the control system for a desired SpO2 of 95 % generated by the step command of MATLAB[12] and shown in Fig.5.

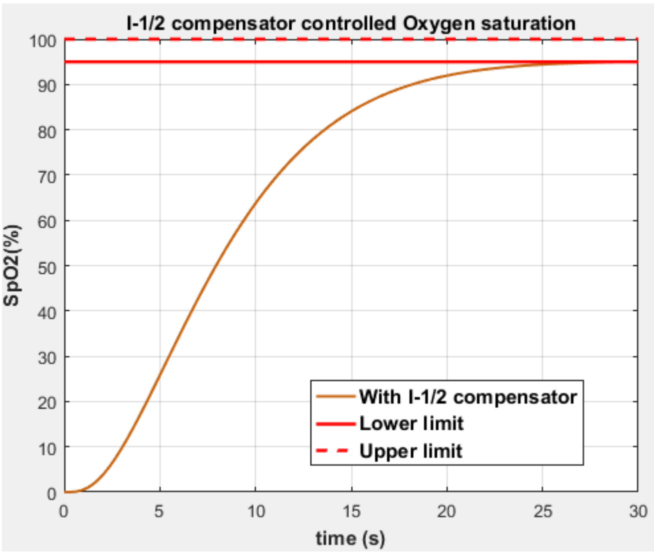

Figure 5: Control of the Oxygen Saturation using an I-1/2 orders compensator.

COMMENTS

- Maximum percentage undershoot: zero
- Settling time within ± 2 % tolerance: 21.60 s

- Steady-state error: zero

Characteristics Comparison of the Three Compensators and One Controller for Blood Oxygen Saturation Control

- The time-based characteristics of the control system for the human blood oxygen saturation are graphically and quantitatively compared in Fig.6 and Table 1 for reference input tracking of 95 %.

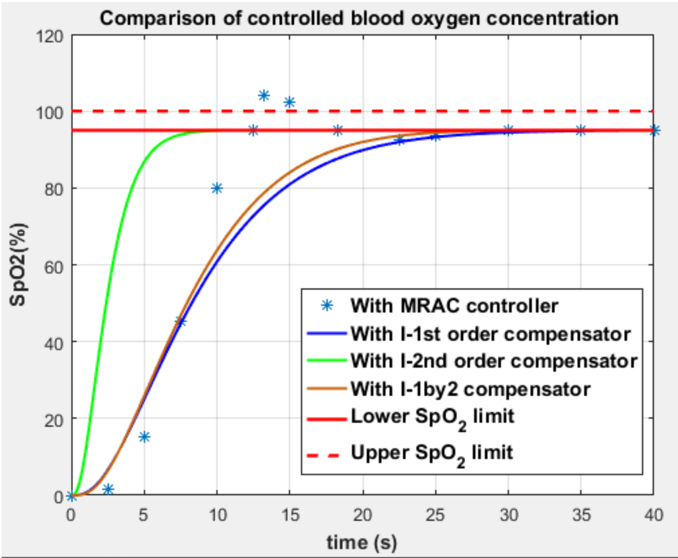

Figure 6: Compared step time response of the oxygen saturation.

Table 1: Characteristics of reference input tracking of blood oxygen saturation using MRAC controller and I-first order, I-second order, I-1/2 orders compensators

Controller/ compensators	MRAC controller	I-first order compensator	I-second order compensator	I-1/2 orders compensator
OS_{max} (%)	7.40	0	0	0
T_s (s)	30	24.65	6.88	21.60
e_{ss} (%)	0	0	0	0

CONCLUSION

- The objective of the paper was to investigate the use and tuning of I-first order, I-second order and I-1/2 orders compensators to control human blood oxygen saturation with comparison with using MRAC controller.
- The human blood oxygen saturation was a stable process without overshoot and with steady-state error.

- The proposed three compensators were from the second generation of control compensators introduced by the author since 2014 onward.
- The three compensators were tuned using a hybrid technique based on zero/pole cancellation and trial and error.
- A range of normal blood oxygen saturation level was imposed on the step time response for all the investigated controllers to help in selecting the best controller/compensator among the four ones.
- The MRAC controller provided a maximum overshoot violating the upper limit of the SpO2 range with settling time greater than that for all the proposed compensators.
- The proposed compensators succeeded to eliminate completely the maximum percentage undershoot.
- All the investigated controller/compensators could eliminate completely the steady-state error.
- The proposed I-first order, I-second order and I-1/2 orders compensators could generate step time responses with settling time to ± 2 % tolerance of 24.65, 6.88 and 21.6 s respectively compared with 30 s for MRAC controller.
- The I-second order compensator was chosen as the best compensator for the control of blood oxygen saturation for its perfect time-based characteristics compared with the other compensators and MRAC controller.

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