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AUTONOMOUS DRUGS OPTIMAL MANAGEMENT, PART IV: ELECTRODE POSITION CONTROL IN RADIOFREQUENCY ABLATION FOR FEMALE- BREAST-TUMORS USING I-FIRST ORDER AND I-2/2 ORDERS COMPENSATORS COMPARED WITH A PI CONTROLLER

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ABSTRACT

This paper is the fourth in a series of research papers presenting the autonomous optimal management of drugs for the human being. It handles the control of the RFA-Electrode position using I-first order and I-2/2 orders compensators from the second generation of control compensators with an electro-hydraulic drive system. The proposed compensators are tuned using multiple approaches including zero/pole cancellation and optimization techniques. The step time response of the control system using the two proposed compensators is presented and compared with using a PI controller from the first generation of PID controllers to control the controlled process of electrode position and the time-based characteristics are compared. The comparison reveals the best compensator among the three compensators/controller depending on a graphical and quantitative comparison study.

KEYWORDS: Autonomous drugs optimal management, RFA-electrode position control, electro-hydraulic drive, I-first order compensator, I-2/2 orders compensator, PI controller, compensators/ controller tuning.

INTRODUCTION

The success of the radiofrequency ablation (RFA) of breast tumors in early stages depends on the precise insertion of the RFA-electrode into the geometrical center of the tumor. It has been shown that slight-error in electrode positioning resulted in significant mismatch in the shape of the ablated volume by RFA and healthy tissue damage is possible in this case.[1] Accurate positioning of the RFA-electrode can be achieved by using a robotic-needle steering.[2] based on various drive techniques such as servo-hydraulic drives,[3] servo-pneumatic drives.[4] and servo-electric drives.[5] First of all, we will have a look into some of the international research regarding this important aspect since 2009.

Kokes et al. (2009) explored the feasibility of developing a magnetic resonance imaging (MRI) compatible needle drive system for RFA of breast tumors. They performed experiments for position control accuracy using hydraulic actuation and concluded that their 1DOF needle driver system demonstrated the feasibility of implementing a MRI-compatible robot for RFA of breast tumors with feedback capability.[6] Seifabad et al. (2012) handled the workspace optimization and phantom evaluation of a 5DOF pneumatically actuated robot for MRI-guided prostate biopsy. They concluded that the needle insertion was feasible and accurate.[7]

Ayvali (2014) outlined that needle-based procedures require needle guidance to a target region to deliver therapy or remove tissue samples for diagnosis and some sites in the tumor body are inaccessible using straight line trajectory. He developed a discretely actuated steerable cannula to achieve accurate targeting in needle-based procedures.[8] Harrith et al. (2016) found that there was a gradual decrease in serum magnesium levels over a two months period. They showed that patients had 3.29 mg/dL serum magnesium level at pre dialysis and 3.22 mg/dL post dialysis.[5] Li et al. (2019) investigated the clearance of magnesium in peritoneal dialysis patients and its influencing factors. They concluded that serum magnesium could be partly cleared by peritoneal dialysis and negatively correlated with the residual renal function and positively correlated with the nutritional status and daily peritoneal protein loss.[6] Garcia et al. (2020) investigated magnesium concentration in hemodialysis patients covering their predictive mortality rate and factors associated with hypomagnesemia and mortality in hemodialysis. They presented a graph for the variation of magnesium concentration with albumin and phosphorous.[7]

Correa et al. (2021) studied the data examining electrolyte changes during and immediately after hemodialysis and their relationships with dialysate prescriptions. They presented a magnesium concentration profile decreasing from 2.4 to 1.8 mg/dL from predialysis to 30 min after dialysis.[8] Arnolli (2017) developed a precise system for CT-guided needle placement in thorax and abdomen to improve the freehand technique. He concluded that in a comparative phantom study, the performance of the system-guided method was proven superior to the freehand method in a single insertion with lower placement error, faster CT-scans and shorter placement time.[9] Mohammed et al. (2020) proposed a sliding mode control to handle the nonlinearity problem of the controlled process and used the pulse width modulation to convert the control signal action into a digital signal to drive the solenoid of the electrohydraulic servovalve. They used MATLAB to model the system and optimize a PID and the sliding mode controllers.[10] Mozaryn, Winnick and Suski (2021) investigated the mathematical model for an electro-hydraulic servovalve, proposed a simplification for the model, presented simulation results and compared with data from a real servo-drive.[11] Zavaleta and Zavaleta (2023) described a new robot-assisted 3D ultrasonic guided needle placement for breast biopsy. They analyzed the forward and reverse kinematics using the screw axis-based theory and geometric-algebraic formulation. A collision free path algorithm was computed to assess target reachability.[12] Li et al. (2025) proposed the structure and control scheme of a robotic system based on breast-target-point manipulation and analyzed the workspace of the robotic system. They proposed an optimal control point selection method based on minimum resultant force for precise manipulation of the breast target point and developed a model reference adaptive control system to perform force control for the breast tissue.[13]

Hydraulic Cylinder-rod Position as a Process

Kokes et al. analyzed the use of a proportional hydraulic system to actuate the electrode of a RFA-electrode for breast tumor under continuous magnetic resonance imaging (MRI).[6] They fitted a second-order transfer function model for the piston-rod of the hydraulic cylinder, $G_p(s)$ given by.[6]

$$G_p(s) = K_p/(1 + 2\varsigma T_w s + T_w^2) \qquad (1)$$

Where:

$$K_p = process\ gain = \ 0.33\frac{mm}{V}\ ;\ \ \varsigma = 2.738\ ;\ T_w = 0.18\ s \qquad (2)$$

Eq.1 is not in the standard form of a second-order transfer function. We replace T_w by the natural frequency ω_n of the hydraulic drive systems as follows:

$$G_p(s) = K_p\omega_n^2/(s^2 + 2\varsigma\omega_n s + \omega_n^2) \quad (3)$$

Where $\omega_n = 1/T_w = 5.5555$ rad/s

Eq.3 represents an overdamped second-order dynamic system since its damping ration is greater than 1. The denominator of the transfer function in Eq.3 can be replaced by two simple poles as follows:

$$G_p(s) = K\omega_n^2/[(s + 1.05084)(s + 29.37108)] \quad (4)$$

The step time response of this process for a step input of 12 V to the solenoid driving the hydraulic system using Eq.4 is generated using the „*step*" command of MATLAM.[14] and shown in Fig.1.

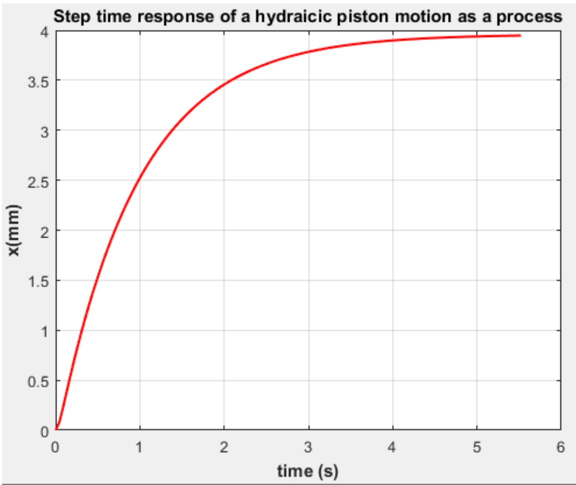

Figure 1: Step time response of the hydraulic piston-rod.

The RFA electrode is directly secured to the piston rod representing a single-degree of freedom dynamic system. Therefore, when we talk about the piston-rod position we mean directly the electrode position. The hydraulic piston-rod investigation as a process has the following time-based characteristics evaluated mostly by the„ *stepinfo*" command of MATLAB.[15]

- Maximum percentage overshoot: zero
- Settling time within ± 2 % tolerance: 3.7576 s
- Rise time: 2.0918 s
- Steady-state error: 0.329 mm

Controlling the Hydraulic Cylinder Piston-rod using a Conventional PI Controller

For sake of comparison with other controllers/compensators we start the analysis by considering a conventional PI controller from the first generation of PID controllers. Kokes et al. used a PI controller to control the position of the hydraulic system piston-rod having gain parameters 250 and 300 for the proportional gain K_{pc1} and integral gain K_{i1} respectively.[6] A PI controller has the transfer function, $G_{PI}(s)$ given by:

$$G_{PI}(s) = K_{pc1}+(K_{i1}/s) \quad (5)$$

- Using the block diagram of the control system in a single-loop structure with controller coming after the error detector and cascaded by the controlled process, the transfer function is derived using Eqs.3 and 5 and the step time response of the control system using the step command of MATLAB.[14] given in Fig.2 for a desired electrode position of 50 mm.

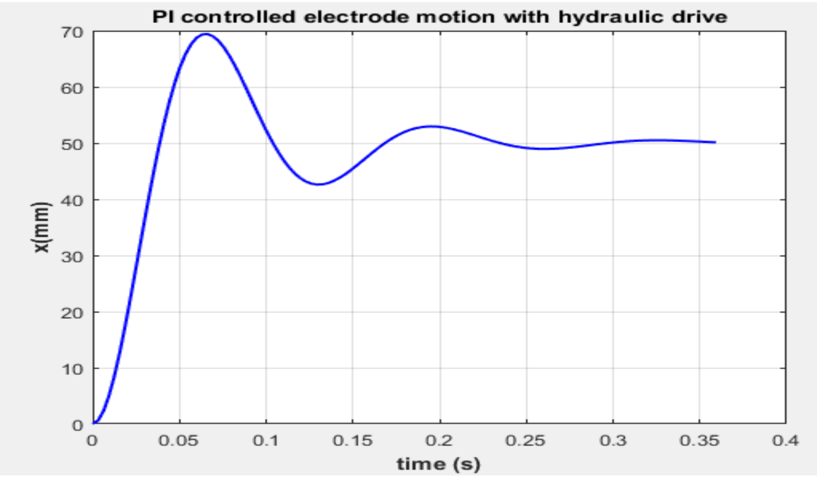

Figure 2: Step time response of the hydraulic piston-rod using a PI controller.

COMMENTS

- Maximum percentage overshoot: 38.8 % (compared with zero without external control)
- Settling time within ± 2 % tolerance: 0.2666 s (compared with 3.7576 s without external control).
- Rise time: 0.0259 s (compared with 2.0918 s without external control).
- Steady-state error: zero (compared with 0.329 mm without control).

Controlling the Hydraulic Cylinder piston-rod Position using an I-first Order Compensator

The I- first order compensator is one of the second generation compensators presented by the author since 2014.[16,18] The I- first order compensator has a transfer function $G_{I1st}(s)$ given by.[16]

$$G_{I1st}(s) = \left(\frac{K_{i2}}{s}\right)[(s+z_2)/(s+p_2)] \qquad (6)$$

The I-first order compensator has three parameters to be tuned: K_{i2}, z_2 and p_2. They are tuned as follows:

- The open-loop transfer function of the closed-loop control system of the hydraulic piston-rod $[G_{I1st}(s)G_p(s)]$ is obtained using Eqs.4 and 6.
- The zero/pole cancellation technique.[19] is used to cancel the compensator zero with the process pole s+1.05084 giving the compensator zero as:

  $$z_2 = 1.05084 \qquad (7)$$
- The closed-loop transfer function, $M_2(s) = G_{I1st}(s)G_p(s)/[1+ G_{I1st}(s)G_p(s)]$ for a unit feedback control system reveals a 0/3 orders third-order dynamic system in the compensator parameters K_{c2} and p_2.
- An ITAE performance index.[20] function of the error between the desired piston rod position and the simulated piston-rod position is minimized using the MATLAB optimization toolbox.[21] providing the remaining compensator parameters as:

  $$K_{pc2} = 198.5541 \text{ , } p_2 = 16.58287 \qquad (8)$$
- The step time response of the control system incorporating the I-first order compensator and the piston-rod position process is drawn using the step command of MATLAB.[14] as shown in Fig.3.

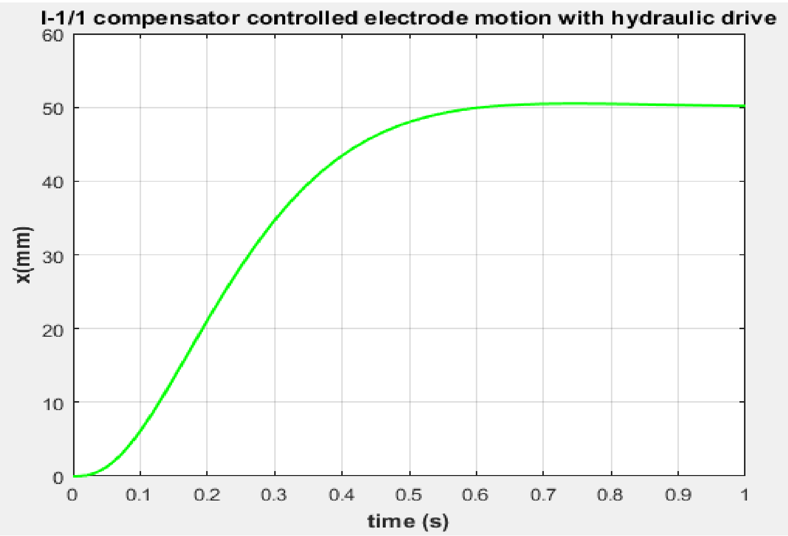

Figure 3: Step time response of the piston-rod position using an I-first order compensator.

COMMENTS

- Maximum percentage overshoot: 1.01 % (compared with zero without control)

- Settling time within ± 2 % tolerance: 0.5405 s (compared with 3.7576 s without external control).
- Rise time: 0.335 s (compared with 2.0918 s without external control).
- Steady-state error: 0.17 mm (compared with 0.329 mm without external control).

Controlling the Hydraulic Piston-rod Position using an I-2/2 Orders Compensator

The I-2/2 orders compensator was introduced by the author as one of the second generation compensators introduced by Prof. Galal Hassaan since 2014.[22,23] It is a feedforward compensator set in the forward path just after the error detector (summing point) in a single-loop control system structure. It has a transfer function $G_{I2nd}(s)$ given by:

$$G_{I2by2}(s) = (\frac{K_{c3}}{s})(s^2 + 2\varsigma_{z3}\omega_{nz3}s + \omega_{nz3}^2)/(s^2 + 2\varsigma_{p3}\omega_{np3}s + \omega_{np3}^2) \quad (9)$$

This compensator has five gain parameters: K_{c3}, ς_{z3}, ω_{nz3}, ς_{p3} and ω_{np3} to be tuned to adjust the performance of the control system for the RFA-electrode position control. The compensator parameters are tuned as follows:

- The open-loop transfer function of the control system, $G_{I2d}(s)G_p(s)$ is obtained using Eqs.3 and 9.
- The zero/pole cancellation technique [19] is applied to cancel the compensator zero with the process pole revealing:

$$\varsigma_{z3} = 2.738\,, \omega_{nz3} = 5.5555 \quad (10)$$

- The remaining three gain parameters of the I-2/2 compensator are obtained using the MATLAB optimization toolbox[21] and a novel performance index based on the difference between the maximum overshoot of the control system step response and the desired maximum percentage overshoot. The result of this approach is as follows:

$$K_{c3} = 6.660607\,, \varsigma_{p3} = 1.283072\,, \omega_{np3} = 5.096402\ rad/s \quad (11)$$

- Using the closed-loop transfer function of the control system and the compensator parameters given by Eqs.10 and 11, the step time response of the control system is obtained using the MATLAB command „*step*"[14] for a desired electrode position of 50 mm as shown in Fig.4.

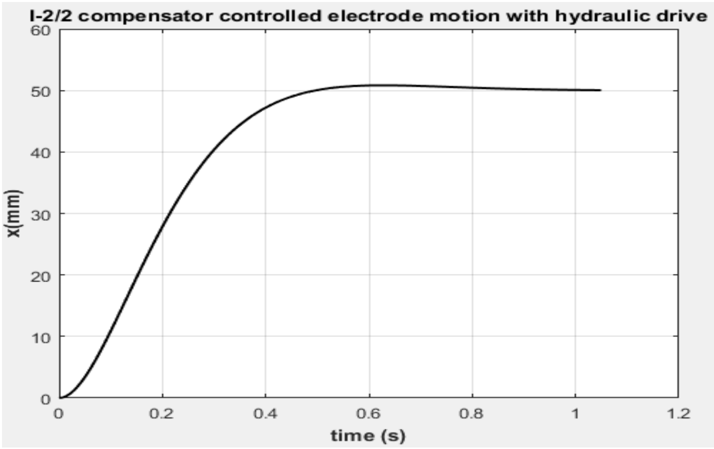

Figure 4: Step time response of the cylinder piston-rod position using an I-2/2 orders compensator.

COMMENTS

- Maximum percentage overshoot: 1.654 % (compared with zero without control)
- Settling time within ± 2 % tolerance: 0.4503 s (compared with 3.7576 s without external control).
- Rise time: 0.2968 s (compared with 2.0918 s without external control).
- Steady-state error: zero (compared with 0.329 mm without external control).

Characteristics Comparison of the Two Compensators Compared with the PI Controllers and the Hydraulic Drive with Proportional Valve

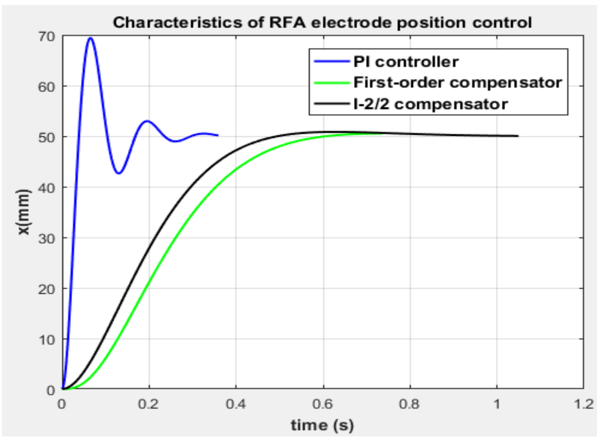

Figure 5: Compared step time response of the piston-rod position.

- The time-based characteristics of the control system for the hydraulically actuated RFA-electrode position are graphically and quantitatively compared in Fig.5 and Table 1 for reference input tracking.

Table 1: Time-based characteristics of the piston-rod position using PI, I-first order and I-2/2 orders compensators.

Characteristics	Without external control	PI controller	I-first order compensator	I-2/2 orders compensator
OS_{max} (%)	0	38.8	1.01	1.654
T_s (s)	3.7576	0.2666	0.5405	0.4503
T_r(s)	2.0918	0.0259	0.335	0.2968
e_{ss}(mm)	0.329	0	-0.170	0

OS_{max}: Maximum overshoot.

T_s: Settling time to 2% tolerance. T_r: Rise time.

e_{ss}: steady-state error.

CONCLUSION

- The objective of the paper was to investigate the use and tuning of I-first order and I-2/2 orders compensators to control the RFA-electrode position for breast tumor ablation with comparison with using a proportional valve integrated with the hydraulic drive and a PI controller.
- The hydraulic drive-electrode position process was a stable one without any overshoot and 3.7576 s settling time and 0.329 mm steady-state error because of the characteristics of the proportional valve used in the hydraulic drive.
- The proposed two compensators were from the second generation of control compensators introduced by the Prof. Galal Hassaan since 2014 onward.
- The two controllers were tuned using the zero/pole cancellation technique and the MATLAB optimization through its optimization toolbox.
- The hydraulic drive was modelled in a previous research work and they used a tuned PI controller to control the electrode position.
- The proposed compensators succeeded to reduce the maximum percentage overshoot to 1.01 and 1.654 % for the I-first order and I-2/2 orders compensators respectively compared with 38.8 % for the PI controller.
- All the investigated controllers could eliminate completely the steady-state error.
- The PI controller could generate step time responses with settling time to ± 2 % tolerance of 0.2666 s compared with 0.54 and 0.45 s for the I-first order and I-2/2 orders compensators respectively.
- The PI controller provided a step time response with a rise time much less than that associated with the two proposed compensators.

- A novel error function was introduced to tune the I-2/2 orders compensator based on the maximum percentage overshoot.
- The I-2/2 orders compensator was chosen as the best compensator/controller for the control of the RFA-electrode position because of its good time-based characteristics compared with the other compensator/controllers.
- The real application of the proposed compensators requires clinical trials on animals or volunteer females.

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Dedication

ENGINEER: OSAMA AL-DALIL

- One of my early students in the Faculty of Engineering, Cairo University.
- Graduated in early 1980‟s.
- Finished his graduation project Under my supervision in about 1983.
- Left our life in Friday 12th December 2025.
- He was a brilliant student.
- He was a successful engineer.
- He was an intimate friend.
- He was a beloved fellow to everyone around him.
- This is why I dedicate this work to him. Sorry Osama. I don‟t have more information about you beloved character.