MECH 436 Control Systems

Spring 2021 Project

Drug Delivery System

The purpose of this project is to apply the control design techniques learned in the course to design a feedback control system for drug delivery to patients. In particular, the goal is to design a control system capable of delivering propofol for anesthesia purposes. Children are the target population in the studies on which this project is based. However, similar control systems can be designed for patients of all ages.

This project consists of three parts, namely, introduction and literature review, system identification, and control system design.

I. Introduction and Literature Review:

In the first part of the project, you will survey the literature for works that deal with the problem of drug delivery for patients. Your literature review should focus on the evolution of such systems. For example, you start by discussing how doctors typically deliver propofol to their patients, and how more recent drug delivery systems are based on open-loop control schemes, while still requiring some inputs and adjustments from their users. Then, you discuss the potential benefits of employing closed-loop control systems for drug delivery, as well as the technical challenges, e.g., interpatient variability, modeling, and data acquisition, and nontechnical challenges, e.g., acceptance by the medical community.

This part of the project serves as the motivation for the later parts of the project. In your literature review, you should discuss and summarize the various approaches for modeling, system identification, and control in the context of drug delivery systems. For instance, you should obtain equations that model the effect of propofol infusion on the patient. Nonlinearities in the system model should be highlighted, as well as the difficulty of performing system identification, i.e., experimentally obtaining a Bode plot, from limited available observations. Typical simplifying assumptions in the system model should be mentioned. For feedback purposes, measurements of the patient state or the drug effect are required. Your literature review should discuss the measurement and sensor technologies available in the context of closed-loop delivery of hypnotic anesthetic drugs.

Finally, the literature review concludes with the various control strategies that can be adopted, and a discussion on how typical performance requirements are specified (along with typical values). The importance of the robustness of the proposed controllers to interpatient variability should be emphasized.

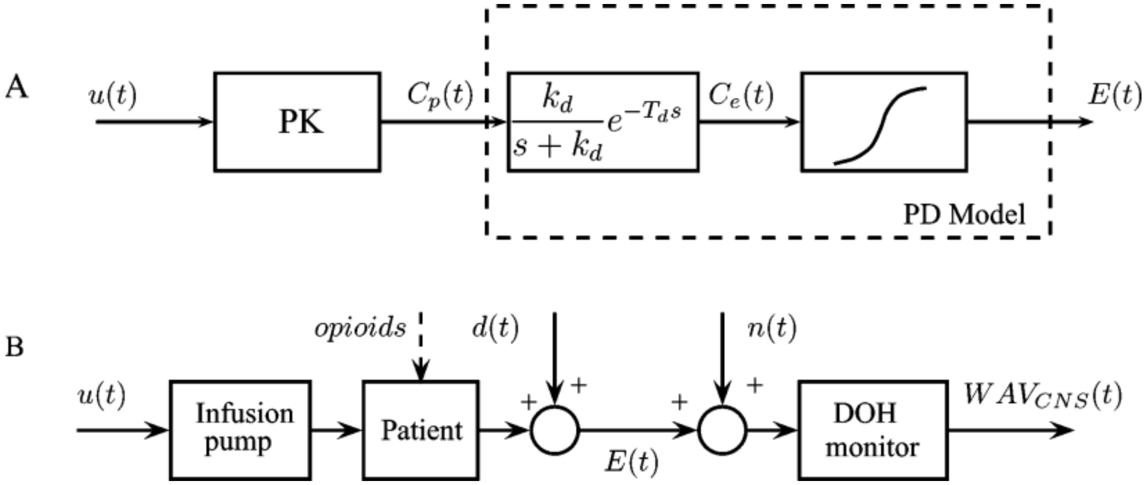

Figure 1: (A) PKPD model structure. (B) Block diagram representing propofol anesthesia in open-loop. *(van Heusden, et al., 2014)*

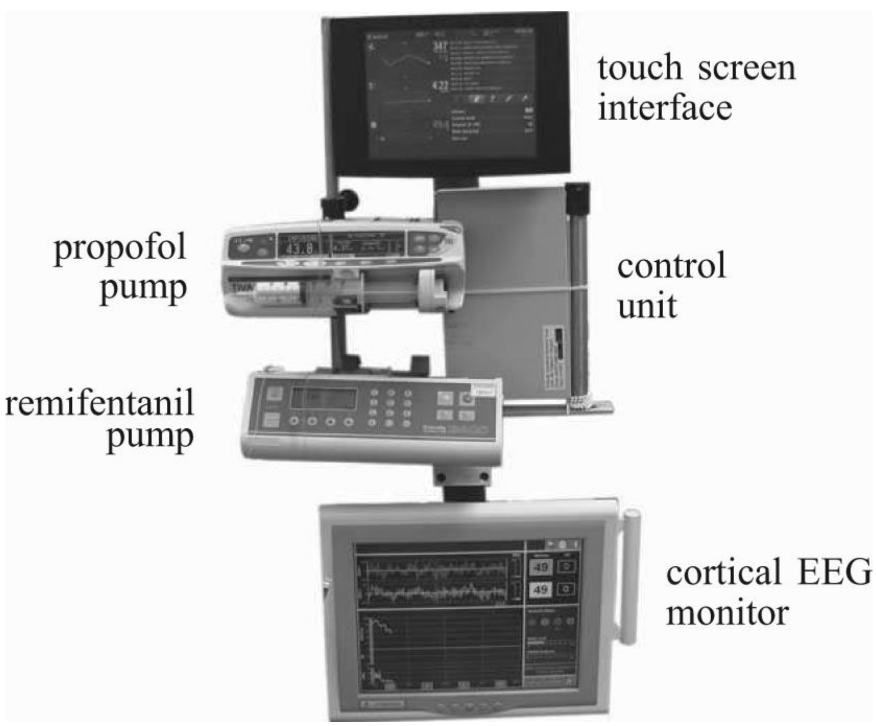

Figure 2: iControl closed-loop anesthesia system. *(van Heusden, et al., 2014)*

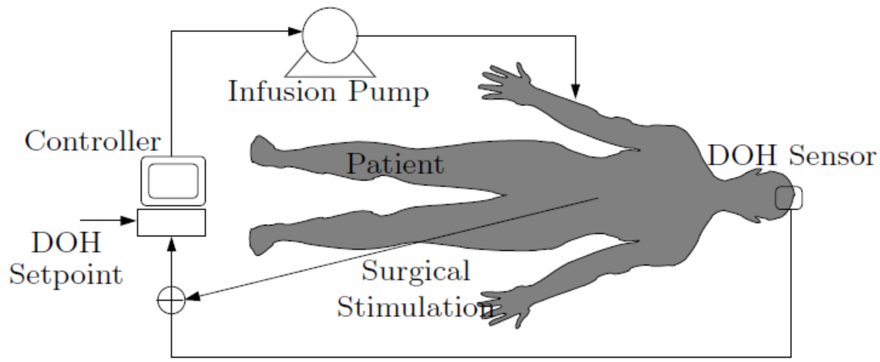

Figure 3: Closed-loop DOH control system. *(Soltesz, et al., 2012)*

II. System Identification:

Consider the open-loop system transfer function given by

$$G(s) = Ke^{-T_d s}\,\frac{(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)(s+p_3)(s+p_4)},$$

where

$$K = 1.4\times10^{-4},$$

$$z_1 = 1.5\times10^{-3},$$

$$z_2 = 3.6\times10^{-5},$$

$$p_1 = 2.87\times10^{-2},$$

$$p_2 = 7.75\times10^{-3},$$

$$p_3 = 2.85\times10^{-4},$$

$$p_4 = 8\times10^{-5},$$

$$T_d = 8.5.$$

The term $e^{-T_d s}$ in the transfer function represents a time-delay of 8.5 seconds.

Some of these parameters are similar to the ones determined from real patient system identification in (Dumont, Martinez, & Ansermino, 2009).

The task in this part of the project is to repeat the system identification task to determine the open-loop transfer function of the system.

Namely, you are asked to build a Simulink model to show how to perform the system identification task. In particular, assume that the transfer function $G(s)$ was not given to you, i.e., assume that you are given an inaccessible Simulink block that implements $G(s)$. The question to be answered is the following: what is the setup that you must implement in Simulink to generate the system transfer function? That is, you have to show how to experimentally (in the idealized Simulink setting) generate the Bode plot of the black-box that implements $G(s)$, and from the generated Bode plot, obtain the expression of $G(s)$. **You must show one detailed sample computation using the built setup, and take a sufficiently large number of points to obtain an accurate approximate expression of $\boldsymbol{G(s)}$.**

For comparison, use the Pade function in MATLAB to obtain a 1st-order Pade approximation of the delay term $e^{-T_d s}$. That is, consider the transfer function

$$G_{pade}(s) = Delay(s) K \, \frac{(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)(s+p_3)(s+p_4)},$$

where $Delay(s)$ is the Pade approximation of $e^{-T_d s}$.

Repeat the above system identification procedure for $G_{pade}(s)$.

Using the given (exact, not approximated from system ID) expressions for $G(s)$ and $G_{pade}(s)$, further answer the following questions:

- Comment on the similarities and differences between the Bode plots of $G(s)$ and $G_{pade}(s)$.
- Comment on the changes in the Bode plot observed as the order of the Pade approximation is increased.
- Plot and comment on the root-locus diagram for $G_{pade}(s)$ for various approximation orders. Are you able to use MATLAB to obtain the root-locus diagram for $G(s)$?
- Use the linmod command to obtain a linearized expression for the transfer function $G(s)$.

III. Control System Design:

In this part, consider the plant transfer function given by

$$G(s) = Ke^{-T_d s}\ \frac{(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)(s+p_3)(s+p_4)},$$

where

$$K = 1.7 \times 10^{-1},$$

$$z_1 = 5 \times 10^{-2},$$

$$z_2 = 8 \times 10^{-2},$$

$$p_1 = 10 \times 10^{-2},$$

$$p_2 = 3 \times 10^{-2},$$

$$p_3 = 4 \times 10^{-3},$$

$$p_4 = 0.5 \times 10^{-3},$$

$$T_d = 8.5.$$

Design and compare both a lead-lag controller and a PID controller to achieve the following closed-loop performance specifications:

- Settling time $t_s = 20\ mins$.
- Maximum overshoot $M_p = 3\%$.
- Steady-state error for a step-input less than or equal to 2%.

Explain any trade-offs in the closed-loop systems responses.

In the design step, use $G_{pade}(s)$, the approximation of $G(s)$ obtained by approximating $e^{-T_d s}$ by its 1st-order Pade approximation. However, in the simulations and the below verification steps, use the original transfer function $G(s)$. **You must show all the details of the compensators' design steps. You have to design both compensators rigorously (not through autotune).**

Verification steps:

- Show that the systems satisfy the performance requirements by simulating the closed-loop systems subject to a unit-step input.

- The compensators are designed by assuming the existence of a pair of dominant closed-loop poles. Compare the obtained step responses of the actual closed-loop systems with the step response of an ideal second-order system (whose closed-loop poles are at the desired location).
- Draw the Bode plots of the open-loop transfer functions of both compensated systems (using lead-lag and PID), and determine the systems' gain margin and phase margin.

Implement the transfer function $G(s)$ and both designed compensators on Simulink. Now implement the following modifications to the basic Simulink model:

- Insert a scope at the output of the compensator to determine the correction/actuation input to the plant $G(s)$. Compare the control input needed using the lead-lag compensator and PID compensator. For both compensators, mark u_{max} as the maximum of the control input over time.
- Add a saturation block at the compensators' output to limit the control command u between $0 \leq u(t) \leq 2 \times 10^{-5}$ for all time $t \geq 0$. What is the effect of adding this saturation block on the closed-loop system performance? (see Figure 4 below for setup visualization)
- Add sensor noise to the output of the plant $G(s)$ that is compared to the reference step input. Use the Band-Limited White noise Simulink block. Set the sample time to 1 and the noise power to 0.001. What is the effect of adding sensor noise on the closed-loop system performance? What is the effect of increasing the noise power to higher levels? (see Figure 5 below for visualization) **Hint**: In previous questions, you might have built your own PID controller block and implemented it in Simulink. While an idealized measurement setup was considered in the previous questions, it is expected that the addition of sensor noise might cause problems due the numerical differentiation block $\frac{\Delta u}{\Delta t}$ in the PID controller. For this reason, a filter is typically added to the derivative term in the PID controller; see the built-in Simulink PID compensator block. This filter adds a parameter N that you need to design. In this question, in addition to comparing between the performance of the lead-lag and PID compensators in presence of sensor noise, compare the performance of your own implementation of the PID

controller to that of the built-in PID controller block in Simulink. Make sure to choose the parameter N carefully, for instance, what do you need to filter out from the measurement signal (given system dynamics), pay attention to the required compensator output (it should be comparable to that of the lead-lag and your own PID implementation determined from previous questions, e.g., as measured by u_{max}.)

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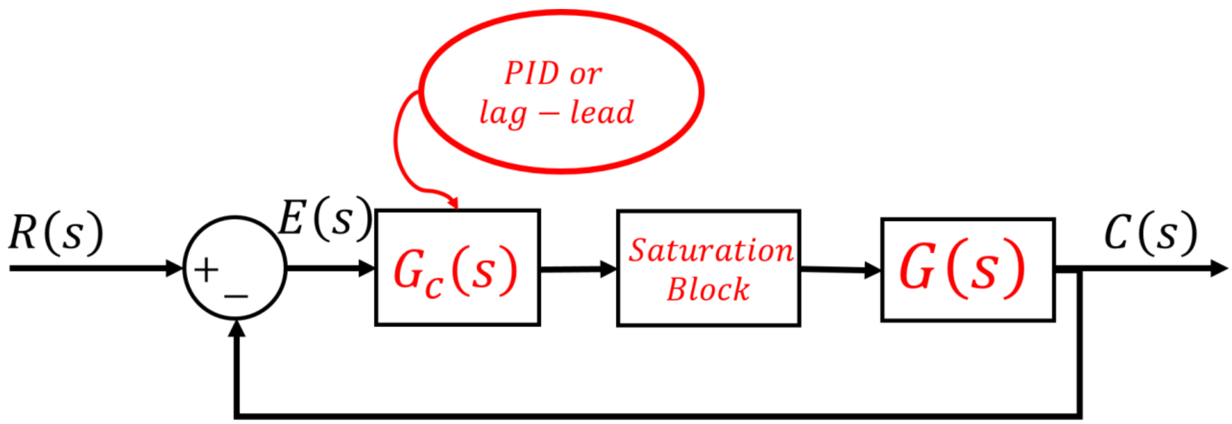

Figure 4: Control system setup with saturation block at compensator output

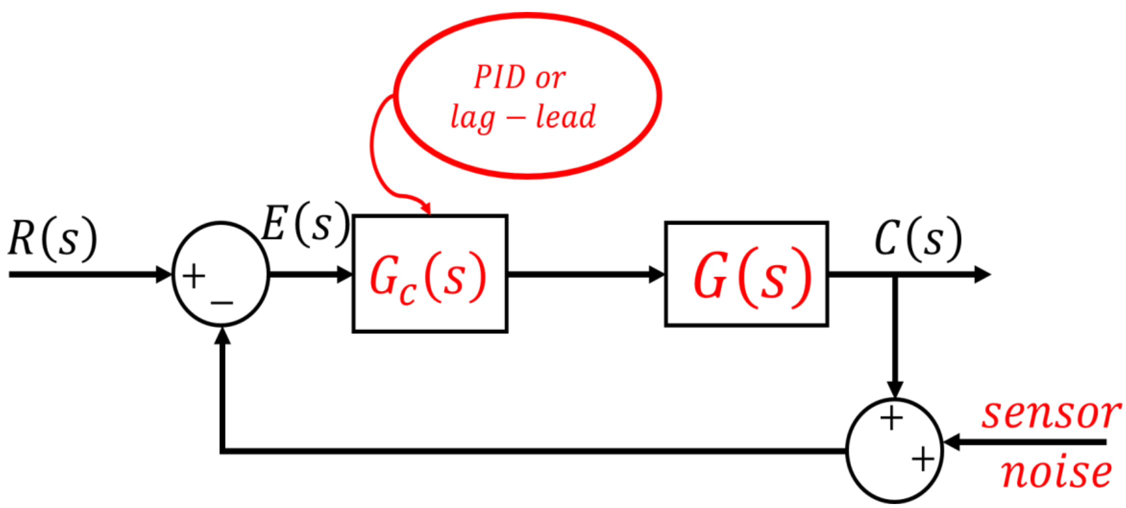

Figure 5: Control system setup with sensor noise added to plant measured output

IV. Project Deliverables:

- **A project report** detailing the various tasks performed in the three project parts. You should use a 12 pts font size and double-spaced text.
- Concise, yet comprehensive, reports will receive high grades. Verbose and excessively long reports will be penalized.
- The project report should contain a cover page, a table of contents, a list of figures, a list of tables (if any), and a list of bibliographic works consulted in the introduction. All figures, tables, and bibliographic works should be referred to explicitly in the body of the report.
- The figures should all be high quality figures (e.g., produced in MATLAB and not output from Simulink scope). By high quality figures, it is meant that all axes must be labeled, appropriate legends and titles should be present, and so on. If more than one quantity are plotted on the same figure, you must make sure that both quantities are clearly visible by using different line styles and colors.
- All the works referenced in the introduction must be properly cited using complete citations. Your report will be checked for similarity and plagiarism. Some references may be old seminal works, but the report must also contain modern works. The references have to be from high quality, peer-reviewed journals and conference venues. AUB libraries and citations from google will prove very helpful in assessing the quality of papers.
- The equations should be written using the built-in Word's equation environment. Latex documents (optimized for equations) are also allowed for those of you who know how to use Latex.
- **Working MATLAB and Simulink codes and files that can be automatically run by the graders without any modification nor debugging.**
- Block diagrams, if needed, must also be professionally produced.
- **Report sections:** Abstract, Introduction and Literature Review, System Identification, Control System Design, Conclusions, Bibliography, Appendix (if applicable).

V. Grading Rubric:

Grading Item	Grade Percentage
Introduction and Literature Review	20%
System Identification	20%
Control System Design	40%
Report Quality: conciseness, comprehensiveness, equations, figures, writing, grammar and syntax, appropriate bibliography, etc.	20%

VI. Deadlines and Regulations:

Project Due Date	**Tuesday April 27, 2021.** ***Projects will be accepted without penalty until May 4, 2021 (last day of reading period).*** ***Extra grades for teams that submit complete projects by the original deadline.***
Team Members	**3 members per team.** **Team can be formed by students from sections 1,2,3,6,7 (Dr. Dany's sections) or by students from sections 4,5 (Dr. Naseem's sections).** ***Teams should be emailed to respective professor by Sunday April 4, 2021.***
Project Questions and Answers	**To be submitted on Moodle Forum created for the purpose for the benefit of entire class.**

Bibliography:

Dumont, G. A., Martinez, A., & Ansermino, J. M. (2009). Robust control of depth of anesthesia. *International Journal of Adaptive Control and Signal Processing, 23*, 435-454. doi:10.1002/acs.1087

Soltesz, K., van Heusden, K., Dumont, G. A., Hägglund, T., Petersen, C. L., West, N., & Ansermino, J. M. (2012). Closed-Loop Anesthesia in Children using a PID controller: A Pilot Study. *IFAC Proceedings Volumes, 45*(3), 317-322. doi:10.3182/20120328-3-IT-3014.00054

van Heusden, K., Dumont, G. A., Soltesz, K., Petersen, C. L., Umedaly, A., West, N., & Ansermino, J. M. (2014). Design and Clinical Evaluation of Robust PID Control of Propofol Anesthesia in Children. *IEEE Transactions on Control Systems Technology, 22*(2), 491-501. doi:10.1109/TCST.2013.2260543