INTELLIGENT CONTROL ENGINEERING BENCHMARK: AN EDUCATIONAL EXPERIENCE

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Abstract— This teaching testimony will share some experiences developing and designing an engineering control problem to assist our learning outcomes in the Mechatronics and Automatic Control curricula. The primary motivation is to bring a contextualized problem suitable to generate a learning environment where students can link the importance of abstracting a problem, solving it, and concretizing the real-world implications of their solutions. Its context is oriented to the automatic supply of propofol in children. Via simulation, the dynamics of different patients and their response to propofol infusion are analyzed to induce a state of unconsciousness. The general objective is to tune a minimum set of controllers to deal with inter-patient variability and build a regression model to identify control parameters for a new instance. Preliminary results with a pilot group showed the viability of using this benchmark for control engineering and machine learning education.

Keywords— Controller tuning, multi-objective optimization, intelligent control

Resumo— Este depoimento de ensino compartilhará algumas experiências no desenvolvimento e design de um problema de controle de engenharia para auxiliar em nossos resultados de aprendizado nos currículos de Mecatrônica e Controle Automático. A motivação principal é trazer um problema contextualizado adequado para gerar um ambiente de aprendizado no qual os alunos possam vincular a importância da abstração de um problema, resolvê-lo e concretizar as implicações do mundo real de suas soluções. Seu contexto é orientado para o fornecimento automático de propofol em crianças. Por meio de simulação, as dinâmicas de diferentes pacientes e sua resposta à infusão de propofol são analisadas para induzir um estado de inconsciência. O objetivo geral é ajustar um conjunto mínimo de controladores para lidar com a variabilidade inter-paciente e construir um modelo de regressão para identificar parâmetros de controle para uma nova instancia. Resultados preliminares com um grupo piloto mostraram a viabilidade de usar esse benchmark para educação em engenharia de controle e aprendizado de máquina.

Palavras-chave— Ajuste de controladores, otimização multiobjetivo, controle inteligente

1 Introduction

Control engineering is the hidden technology responsible for the automatic operation of a wide variety of devices (Åström, 1999). This technology is considered a differential in products, processes, and services (Samad and Annaswamy, 2011). However, many times its concepts and theory, of relevance and practical application, can be difficult to assimilate by the students involved in such courses (Kagami et al., 2020).

Problems known as engineering benchmarks are helpful in validating new tools, methodologies, solution strategies, or knowledge acquired in problem-solving. In the case of process control, they have shown a potential to validate research (Kroll and Schulte, 2014) and reinforce the learning process in engineering education (García-Sanz et al., 2010; Blasco Ferragud et al., 2012). This is due to their reproducibility context, where comparing solutions and evaluating their performance is possible. Likewise, they can constitute an attractive design platform to be incorporated into engineering courses through a competitive environment (Collins and Davis, 2017) and gamification (Markopoulos et al., 2015).

This work presents an intelligent control engineering benchmark proposal for educational purposes. The task consists of adjusting a control loop that minimizes inter-patient variability and identifying model parameters of patients. This benchmark offers a gamification environment where students can assimilate control and machine learning concepts, link such ideas with practical applications, and reflect on the physical implications of an engineering solution. The rest of the paper is organized as follows: in Section 2, the educational context of the proposal is commented on; in Section 3, the context of the problem is explained; in Section 4, the educational design is presented, and its results are discussed in Section 5. Finally, some conclusions and future work are commented on.

2 Educational context

The benchmark will be used within two courses of the Control Engineering (ECA) and Mechatronics (MEC) curricula at the Pontifical Catholic University of Paraná (PUCPR): the Control Systems Implementation and Operation (IOSC, 7th. period) and the Artificial Intelligence and Machine learning (IAAM, 8th. period) disciplines. Both courses have an ABET (Accreditation Board for Engineering and Technology) accreditation. This accreditation guarantees that a graduation program meets the essential standards to prepare and facilitate its students to enter the STEM (Science, Technology, Engineering, and Math) performance areas (ABET, 2020).

The IOSC discipline is the second control engineering discipline in the ECA course curriculum. Students from the Automation and Control, Mechatronics, Biomedical, Electrical, and Computer Engineering programs converge on it. In particular, the IOSC course focuses on two learning outcomes (student outcomes) specified by ABET:

- SO2. "An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors."
- SO6. "An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions."

The IAAM discipline is a discipline of the Mechatronics (MEC) curricula, which also attends (as elective) students from the ECA course. The IAAM course focuses on two learning outcomes (student outcomes) specified by ABET:

- SO5. "An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives."
- SO6. "An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions."

IOSC mainly deals with incorporating control requirements actively in the tuning phase (see the mental map of the syllabus in Figure 1); IAAM deals mainly with supervised learning for classification and regression. Therefore, a joint experience linking both courses is possible and could bring an opportunity to consolidate such outcomes.

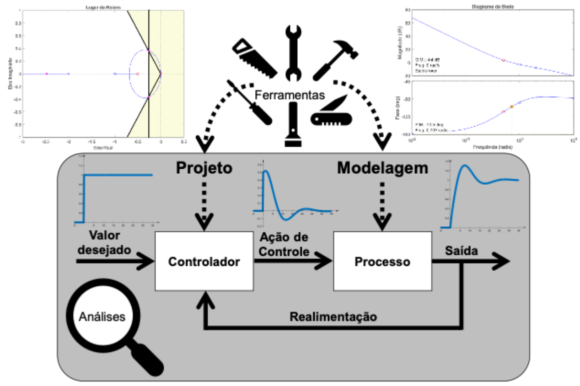

Figure 1: Mental map of the IOSC course (Portuguese) as appears in the syllabus.

3 Problem context

Propofol is a common intravenously administered anesthetic drug for general anesthesia. In an operating room, propofol is often used with fast-acting opioids such as remifentanil during surgery. The anaesthesiologist traditionally manually controls intravenous drug infusion rates for such purposes. Even when there are automatic open loop systems, the specialist usually compensates (adjusts) inter-patient variability. A closed-loop control system could reduce such variability and improve control of the general anesthetic state.

The laboratory activity is based on the automatic process of supplying propofol to induce a state of deep hypnosis in surgical procedures. The work developed by (van Heusden et al., 2013) will be used as scientific support. A study with 47 patients is developed (details in Figure 2, where it is desired to identify the models to obtain a state of deep hypnosis (DOH) measured by the WAV_NCS indicator controlled by the propofol infusion rate. After different supervised experiments in open and closed mesh, a first-order plus dead-time (FOPDT) model (Equation (1)) has been identified together with a Hill function $E(t)$ (Equation (2)) to capture the non-linearity of the process. Such equations are defined as follows:

$$P_i(s) = \frac{k}{s+k} e^{T_d} \qquad (1)$$

$$E(t) = E_0 - E0 \frac{E_{LTI}^{\gamma}}{E_{50}^{\gamma} + E_{LTI}^{\gamma}} \qquad (2)$$

where E_{LTI} is the effect predicted by the FOPDT model, E_0 is the minimum effect, E_{50} is the effect at which half of the maximum effect is achieved, γ the non-linearity, and the remaining parameters are identified in the clinical study (See Figure 2). The Hill function is a common way to fit a model to experimental data in biochemistry and biological sciences.

Control requirements, supporting SO2, are defined as follows:

- Settling time must be minimized;
- A state of deep anesthesia (defined in the range of 40-60%) must be guaranteed within the first 5 minutes;
- Hypnosis states below 40% should be avoided for more than 5 minutes;
- For any new child, the most suitable controller must be identified and proposed.

Defining a control strategy that can deal with the process's non-linearity, modeling, inter-patient variability, and meeting control constraints is necessary. Therefore, this is proposed for the students, aligned with SO5 and SO6.

4 Educational experience design

It is intended to design a learning environment that affects the personal dimension, defining an objective and a challenging puzzle for students, following the model of other control engineering benchmarks (Reynoso-Meza et al., 2020; Romero and Sanchis, 2011).

The system was implemented in SIMULINK© environment, as shown in Figure 3. The FOPDT models obtained by (van Heusden et al., 2013) were accompanied by a simple MATLAB script in MATLAB© to evaluate any of them.

The challenge for the IOSC discipline (7th. period) is determining the minimum number of controllers fulfilling the control requirements for the entire set. Furthermore, they are encouraged to present their results on the last day, when data for a new child will be provided. For such a child, the only information available is the age, weight, height, and gender. Therefore, the students are oriented to determine *somehow* the similarities with the already provided set to select the most suitable controller. The aim of this experience is two-fold: (1) to understand that the model is not always provided; and (2) that sometimes the model has to be inferred from other information. Figure 4 shows the response of patient 1 with a manually adjusted reference controller. In turn, Figure 5 shows a general visualization of 36 patients to certify the variability in the DOH response.

For the IAAM discipline (8th. period), this control experience was mobilized to remember the importance (and complexity) of bringing a model. Therefore, a new challenge was proposed: to determine a suitable machine learning regressor to effectively infer (from the controller point of view) the FOPDT parameters to determine the most suitable controller. That is, a suitable regression model capable of inferring E_0, E_{50}, γ, k and T_d values using information age, weight, height, and gender.

5 Educational experience results

The benchmark was implemented for the first time in 2022. In the first half of the year (7th. period, IOSC), the students were divided into working groups of up to 4 members (SO5). All the strategies displayed by the students were encouraged, and the course teachers acted as mentors (SO2, SO6). Four sessions of 1.5 hours were dedicated to the activity in the computer lab with the support of the Institutional Modernisation Project program of CAPES (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*) and the Fullbright Brazil Commission. On the last day, the groups presented their solutions (SO6).

The students mobilized concepts from the IOSC and the previous discipline of control (SO2): analysis of the temporal response, the structure of the identified transfer functions, and root locus diagrams. With this, various strategies were conveniently developed to group patients so that the control objectives could be met with a minimum of different controllers. Finally, a questionnaire was passed to the groups to collect feedback on the activity. Among the respondents, comments on the activity stand out, such as (translated from Portuguese):

- *I loved the fact of being able to emerge in a situation that makes complete sense*
- *The subject was very interesting; nevertheless, there were not enough classrooms to throw doubts.*
- *This is an interesting activity that involves other "outside" engineering areas, showing how the integration works in other areas.*
- *It is challenging to find a pattern, and you must think outside the box to unwrap a method to solve it.*

In the second half of the year (8th. period, IAAM), the students worked with the second part of the challenge in the same conditions as the IOSC. Students mobilized concepts such as linear regression (for baseline comparison), decision trees, artificial neural networks, and support vector machines. Again, a questionnaire was passed to the groups to collect feedback on the activity, with more expressive participation. Among the respondents, comments on the activity stand out, such as (translated from Portuguese):

Patient	Age	Weight	Height	Gender	PKPD models T_d	k_d	EC_{50}	E_0	γ	FOPTD models T_d	k	E_{50}	γ
	$[y]$	$[kg]$	$[cm]$		$[s]$	$[min^{-1}]$	$[mg/l]$			$[s]$	$[min^{-1}]$	$[\mu g/kg/min]$	
1	15	71	180.5	M	3	1.15	3.95	93.11	1.74	35	0.152	217	1.77
2	7	25.1	132	M	52	1.34	4.24	92.46	1.90	82	0.135	316	1.91
3	10	41.1	139	F	11	*60*	3.83	92.46	2.17	21	0.254	385	1.94
4	8	22	128	F	44	10.71	5.77	91.47	1.56	48	0.188	515	1.57
5	7	26.9	131.5	F	10	1.12	4.84	91.60	1.55	41	0.108	315	1.58
6	10	33.6	138	M	36	*60*	3.88	88.45	1.89	40	0.214	365	1.80
7	14	82.1	177	M	56	3.84	3.97	92.91	1.62	68	0.194	282	1.63
8	16	52.5	154.9	F	98	*60*	8.80	88.89	1.49	94	0.212	473	1.53
9	8	23.4	118.7		0	1.89	3.57	94.58	1.57	16	0.132	263	1.71
10	6	23	121	M	105	4.55	4.81	92.89	1.55	115	0.177	415	1.56
11	11	58.5			0	1.46	3.71	91.68	1.75	29	0.133	267	1.83
12	8	25.3	130	M	0	1.16	5.44	90.30	1.52	4	0.058	228	1.64
13	13	56.1	168	M	44	7.41	3.60	91.38	1.82	41	0.131	229	2.01
14	13	47.3	171.8	F	51	45.91	4.34	92.76	1.99	58	0.251	400	1.81

Figure 2: Patient database example (van Heusden et al., 2013).

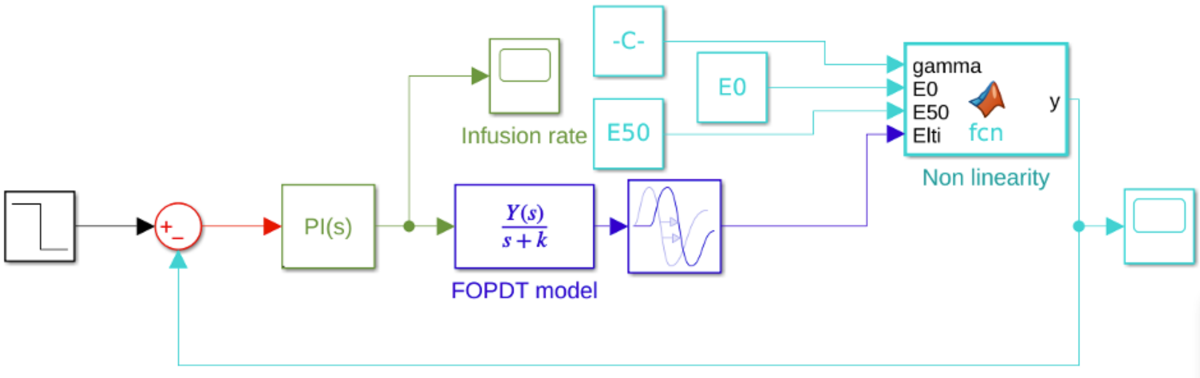

Figure 3: Simulink implementation of the educational benchmark. Colors reinforce the visual identification among students of the different elements of the control loop.

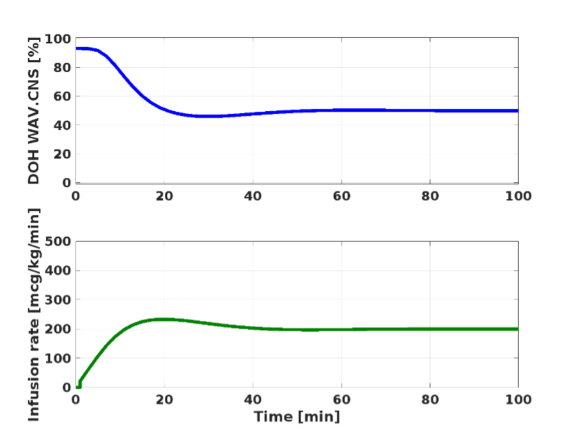

Figure 4: Dynamic response for patient 1. Note that the default controller does not fulfill the settling time requirement.

- *This subject has been the most interesting of the semester, in my opinion. I really enjoyed the activity that was passed on to the class. It was possible to learn better about control systems and to appreciate first-hand the application of this type of solution, in addition to encouraging the search for other types of solutions explored by other university students and programming dissemination channels.*

- *The application of these concepts in a real activity is very interesting. We verified the real difficulties of analyzing different data in finding similar parameters to develop a model.*

- *This activity was very interesting because it was the first time I saw the application of a controller in something related to the health area. The fact that you worked with this scenario was very fun because, in this activity, you can see some limits of the application of the controller in continuous time.*

- *I believe that this question was very interesting; the topic is very current. It was a little difficult to implement our AIs; they couldn't handle the low amount of data very well, so it ended up being a little frustrating. Regarding the control part, it was very good, since it was possible to control all the children very*

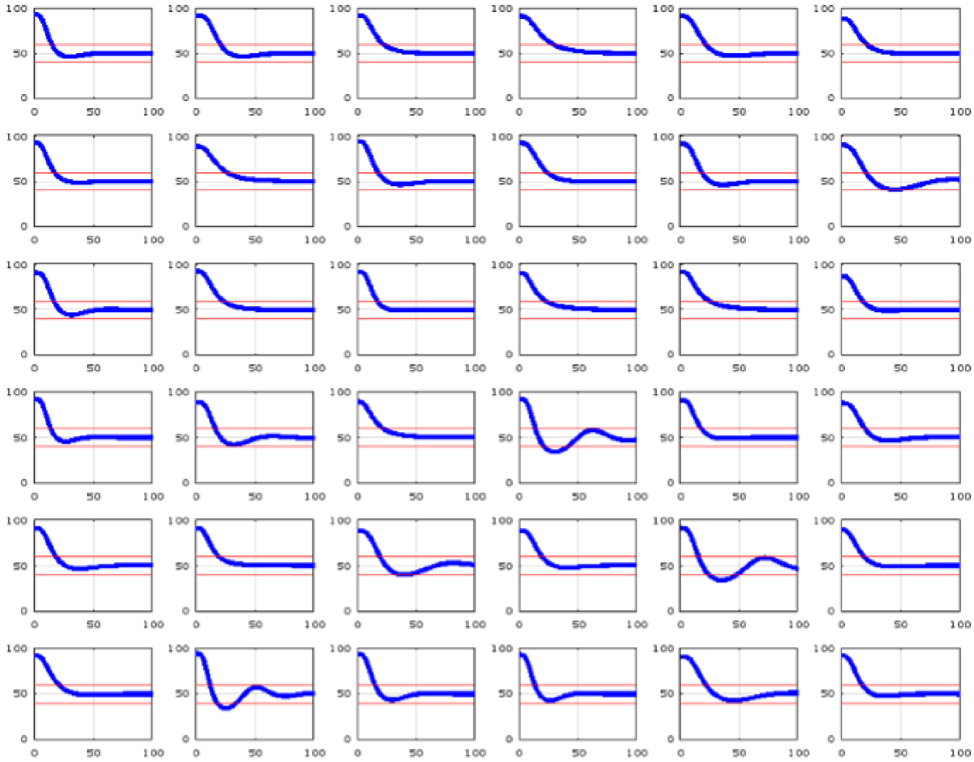

Figure 5: Patient variability response (y-axis) in 100 minutes of simulation (x-axis); a simple PI for reference is used.

> *well within the limits and requirements given to us.*

It is concluded that the activity has an exciting potential to link concepts and consequences of the implemented solutions.

6 Conclusion

This work presented a control engineering benchmark proposal for the IOSC and IAAM disciplines. It has been aligned with the PUCPR's learning philosophy and the guidelines of the ABET accreditation, explicitly for the learning outcomes SO2, SO5, and SO6. The benchmark has been contextualized as a biomedical problem, where the automatic supply of Propofol in infants is sought to induce a state of deep anesthesia. In the first moment, the activity seeks to create an environment where students have to deal with inter-patient variability, with different alternatives and control ideas, identifying the consequences of their solutions; in the second moment, to work again with this challenge, from the data science point of view. It is concluded with this proof of concept that the proposed benchmark can bring together both courses and offer an educational experience. Nevertheless, some points need to be addressed to improve the experience, such as the time window dedicated to the activity and the student interface. Therefore, at this moment, as future work is proposed to start an action-research process, initiating the second loop of this activity for the 2023 academic year.[1]

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