Teaching Modern Control System Analysis and Design

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Abstract

In today s university classroom, the process by which classical and modern control theory is taught must address the issue of integrating the theory with pertinent design issues, including modeling, implementation, complexity, and cost. In this paper the authors discuss a control system analysis and design approach adopted in their textbooks in which a series of steps embodied in a block diagram is suggested to guide students through the design process. Two examples are presented to highlight the use of the design process block diagram.

I. Introduction

Most engineering professors understand that a design paradigm shift has occurred in recent years wherein product performance issues are overshadowed by manufacturing and cost issues. Practical matters are paramount. As might be expected, the various engineering disciplines have been impacted to varying degrees. In the systems and controls area, the design paradigm shift emphasizes the need for students to understand the *practical* issues (such as modeling and implementation) associated with control system design. In the past, these practical issues have been the forte of mechanical, chemical, and aerospace engineering departments, while the delivery of systems and control theory has been the strength of electrical engineering departments. This comment is based on anecdotal (hence debatable) evidence and certainly there are exceptions. What is clear, however, is that to prepare students for productive careers in systems and controls, engineering courses must address the issue of integrating the theory with relevant design issues, including modeling, implementation, complexity, and cost. As always, we must remain cognizant of the fact that every student should design control systems upon a firm foundation of mathematics and systems theory. So in the end it is a *question of balance*. We believe that the control system analysis and design approach adopted by the authors in their learning materials, including the textbook entitled *Modern Control Systems*[1], the supplemental text *Modern Control Systems Analysis and Design Using MATLAB and Simulink*[2], and the website http://www.prenhall.com/dorf achieves this balance, hence can play a significant role in presenting practical notions of design of control systems in a chalk-and-talk lecture.

It is important to introduce students to the process of control system design in a fashion that is familiar and inviting. To this end, for students studying control systems we suggest a series of steps embodied in the familiar block diagram form shown in Fig. 1 to guide students through the design process. Since design is a creative endeavor, there is not a unique design approach that always leads to a good design for different classes of problems. Recognizing this fact, we present in our learning materials a reasonably structured methodology to guide professors and their students. Can the design approach based on the structured flow of steps illustrated in Fig.1 be applied in areas other than control system design? The answer is probably not. Obviously, control system design is only one important example of design, but since control systems are the focus of our efforts here, we concentrate on classification and description of techniques applicable to controls. Can the design methodology presented here be directly used in the design of control systems in the world outside of the classroom? Again, the answer is probably not. The physical world is in general more complex than can be presented in the classroom without obsfucation of the main control theoretic ideas and methods. So, what is the proper balance? The answer is to utilize an approach that, while simple enough to be useful in the classroom setting and allows the usual emphasis on control theory, addresses the main deficiency that many students recognize when confronted with real-world control design problems, namely, the lack of sufficient skills in modeling of physical systems. How many times have we heard students ask, Where does the transfer function come from? We can address this question by presenting the derivations of interesting examples in supplementary material in more detail than

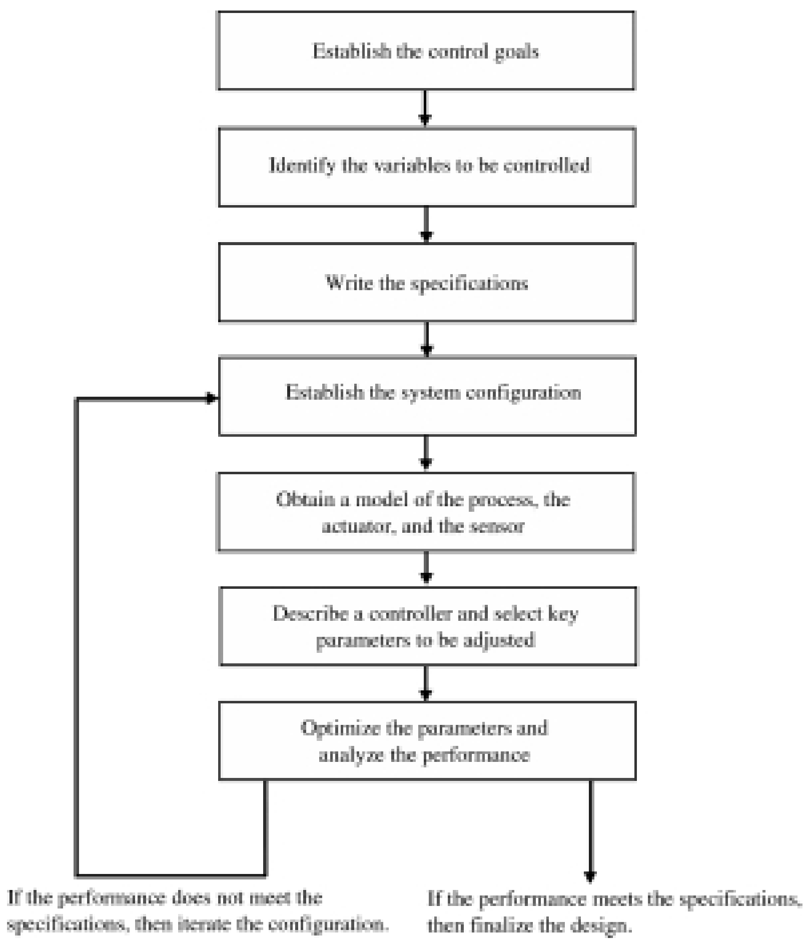

Figure 1. The design process block diagram.

possible in the main text. A controls class is not the optimal place to address physical system modeling, but nevertheless, it does provide a means for introducing the subject and for pointing out its importance.

With the advent of powerful computers and software for control system design, students are sometimes tempted to bypass modeling simplification and controller design and analysis techniques, and use MATLAB[1] (or equivalent program) to iterate on certain controller parameters (e.g., the three controller gains in a PID controller). This is especially true with the development of very interactive SISO design tools such as *SISO Design Tool* and *LTI Viewer* available in recent versions of the MATLAB Controls Toolbox. There are many reasons why it is important to develop a basic understanding of the underlying characteristics and fundamental relationships of the problem, including hand-sketching root locus and Bode diagrams. For example, suppose the design specifications change. Or maybe the plant changes in response to other than engineering pressures (e.g., management decisions for cost considerations). Then which controller gains change to meet the new design specifications? Is a completely different controller structure needed? With a fundamental understanding of the underlying control theory and coupled with knowledge of the physical system dynamics, students can more readily obtain practical design solutions. MATLAB and Simulink are valuable *tools* in the design process effectively performing repetitive design steps quickly. Time saved in performing mundane computations can be better spent confirming engineering intuition regarding the design variables and how they affect the system response. Traditional lectures on control system design using root locus, frequency response techniques, and state-space design methods should not be replaced with lectures on computer programming.

In our design approach, we emphasize the use of analytic methods based on the notion of dominant poles to obtain initial control system designs (using root locus methods, for example). The idea is to design the controller such that the closed-loop system response is dominated by poles placed appropriately to meet the design specifications. Then, MATLAB and Simulink are used to verify that he design specifications have indeed been satisfied and to fine-tune the design, if necessary. Thus, in the design block diagram in Fig. 1, the use of MATLAB becomes a factor only in the final block to Optimize the parameters and analyze the performance of the controlled system.

II. Pedagogy

Our teaching materials are continually evolving and improving with the advent of new tools (such as low-cost, high-performance desktop computers), advancements in software (such as MATLAB and Simulink), especially with regard to the effective uses of graphical user interfaces, and increased access to the Internet. Some of us can envision the day when students will effectively interact with their computers to such an extent that hand-sketching of root locus will be unnecessary—we are not there yet, but moving in that direction.

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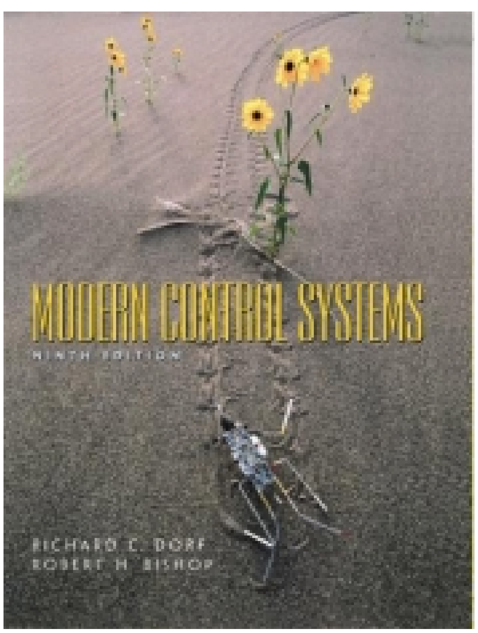
[1] MATLAB, Simulink, and the Control Toolbox are registered trademarks of The Mathworks, Inc.

Effective use of the Internet provides yet another avenue for efficient transmission of new and additional material to students. For those students that need more practice with modeling physical systems, the latest edition of *Modern Control Systems* utilizes the Internet to provide that additional material. The website also offers the opportunity for students to *practice* their problem-solving skills. Many students need extra time honing their problem-solving skills and benefit by having instant feedback. In the old days this was provided by showing answers to odd-problems at the end of the book. It is preferable to utilize the Internet since problems can be easily added, modified, and improvements do not wait for future editions. The *MCS* website hosts a set of true-and-false exercises, multiple-choice problems, and word matching games. Also, access to the Internet by students allows authors to transfer important, space-consuming appendices for hosting on the website. This then provides more room to increase the coverage of design issues, including a greater variety of real-world examples, more complete coverage of modeling, and so forth. In the latest edition of *Modern Control Systems*, five appendices were moved to the website, leaving room for increased coverage of operational amplifiers and the introduction of Simulink in the main text. Students are alerted to the existence of supplemental web-based information via the margin icon  .

For the foreseeable future, however, the main textbook will focus on the basics of control systems (mathematical fundamentals, root locus, Bode plots, and so forth), while the design supplement and the Internet will be used to deliver related information (such as modeling, design methods, and so on). We organize the presentation of topics in design according to following pattern: early on, we focus on modeling, design specifications, and identification of important variables to be to controlled. Only later does the focus change to controller selection and design and analysis of the controlled system.



One important characteristic of our teaching materials is our *connections*. That is, connections between control theory presented in the classroom and control system design in practice outside the classroom, connections between the main text *Modern Control Systems* and the supplement *Modern Control Systems Analysis and Design Using MATLAB and Simulink*, connections between the MATLAB scripts and the surrounding text in the books, and connections between problem statements and associated visual references (such as photographs or schematics). The connections begin on the cover where the interrelationship between the world around us (represented by the flower), the past and present (represented by the tracks in the sand), and the future (represented by the small electro-mechanical insect) are depicted. The photo is taken from the book by Menzel and D Aluisio[3], but the interpretation is ours. There are numerous other connections that can be considered, but we want to focus here on those that impact directly the control design issues.

Each design example in the supplement is adapted from the main text *Modern Control Systems*, thereby establishing the relationship between the MATLAB design supplement and the main textbook. The connection between the supplement and the main text has been an important aspect to the success our approach in the classroom. One of the strengths of our approach to introducing students to design is to make a direct connection between the theory in the main textbook and the analysis and design " in the supplement. This provides continuity of material for the students, and also supports the learning process by reinforcing important concepts. The relationship between the chapter design problems in the supplement (denoted by *MCS A&D*) and the main text (denoted by *MCS*) is shown in Table 1. In this paper, we discuss two of our design examples: Fluid Flow Modeling and Blood Pressure Control.

Table 1. Relationship between design problems in the supplement and the main text.

***MCS A&D* Chapter**	**Design Problem**	***MCS* Problem**
1	Space Shuttle	P9.9
2	Fluid Flow Modeling	P2.12
3	Space Station Modeling	website
4	Blood Pressure Control	AP4.5
5	Airplane Lateral Dynamics	DP5.1
6	Robot-controlled Motorcycle	DP6.6
7	Automobile Velocity Control	DP7.12
8	Six-legged Ambler	DP8.2
9	Hot Ingot Robot Control	DP9.10
10	Milling Machine Control	P10.36
11	Diesel Electric Locomotive	DP11.3
12	Digital Audio Tape Control	DP12.2
13	Fly-by-wire Control Surface	AP13.2

III. Example: Fluid Flow Modeling

The fluid flow example (taken from Chapter 2 of *Modern Control Systems Design and Analysis*) demonstrates the application of basic physical principles, such as the conservation of mass, to the development of pertinent equations of fluid motion. This problem is adapted from P2.12 in the main text *Modern Control Systems*. The development of the underlying equations of motion requires making important simplifying assumptions, such as steady, inviscid, and irrotational fluid flow. Students need to become familiar with the concept of making appropriate assumptions as a natural part of the design process. Obviously, not all students will be experts in fluid dynamics, but many may be one-day required to design control systems for such physical plants. We hope that they can locate and read the appropriate literature and develop reasonable models from the published materials. Each example in *Modern Control Systems Design and Analysis* comes with an appropriate list of references[4-6]. The obtained equations of motion are then linearized about an equilibrium condition to obtain linear, constant coefficient equations for which transfer functions models can be obtained using Laplace transform methods.

The design process in this example focuses on the two elements: (i) Establish the system configuration, and (ii) Obtain a model of the process, the actuator, and the sensor. The students are presented with the design block diagram, shown in the center of Fig. 2. The block diagram has the two blocks highlighted to indicate that these are the emphasized design elements for that chapter. Notice that the design block diagram also contains a list (running down the right hand-side) that connects equation numbers, figures, and so on in the text with elements of the design block diagram. This connects the design process elements with specific information in the written text.

Each example in the book utilizes three main teaching elements: (i) the text itself, which includes system descriptions, equations, numbers, etc., (ii) figures and diagrams, and (iii) MATLAB scripts and associated graphs. All three elements are illustrated in Fig. 2. The MATLAB scripts include call-outs that provide additional information. For example, in Fig. 2, we see that one of the lines of the MATLAB script corresponds to Eq. (2.33) of the supplement, and that more information on the **step** function utilized in the m-file can be found in the main text. We are assisting the students to again connect the material, this time, the material text with the MATLAB scripts.

IV. Example: Blood Pressure Control

In this example (taken from Chapter 4 of *Modern Control Systems Design and Analysis*), the students work through the design process block diagram from the top down (skipping only the controller block, as this topic comes later in the book). This exercise is adapted from AP4.5 in the main text *Modern Control Systems*. The first step in the process is to establish the control goal. In a modern operating room, the anesthetist utilizes an automated system to control the depth of anesthesia. This is an example of human computer interaction. Most anesthetists regard mean arterial pressure (MAP) as the most reliable measure of the depth of anesthesia and the level of the MAP serves as a guide for the delivery of the anesthesia[7-11]. As indicated in the design process block diagram in Fig.3, the goal here is to *regulate the mean arterial pressure to any desired set point and maintain the prescribed set point in the presence of unwanted disturbances*. Associated with the stated control goal, the variable to be controlled is the mean *arterial pressure (MAP)*.

If the overall system is to function in a real-world setting, the closed-loop system should respond rapidly and smoothly to changes in the MAP set point (made by the anesthetist) without excessive overshoot. The closed-loop system should also minimize the effects of unwanted disturbances. There are two important categories of disturbances: surgical disturbances, such as skin incisions, and measurement errors, such as calibration errors and random stochastic noise.

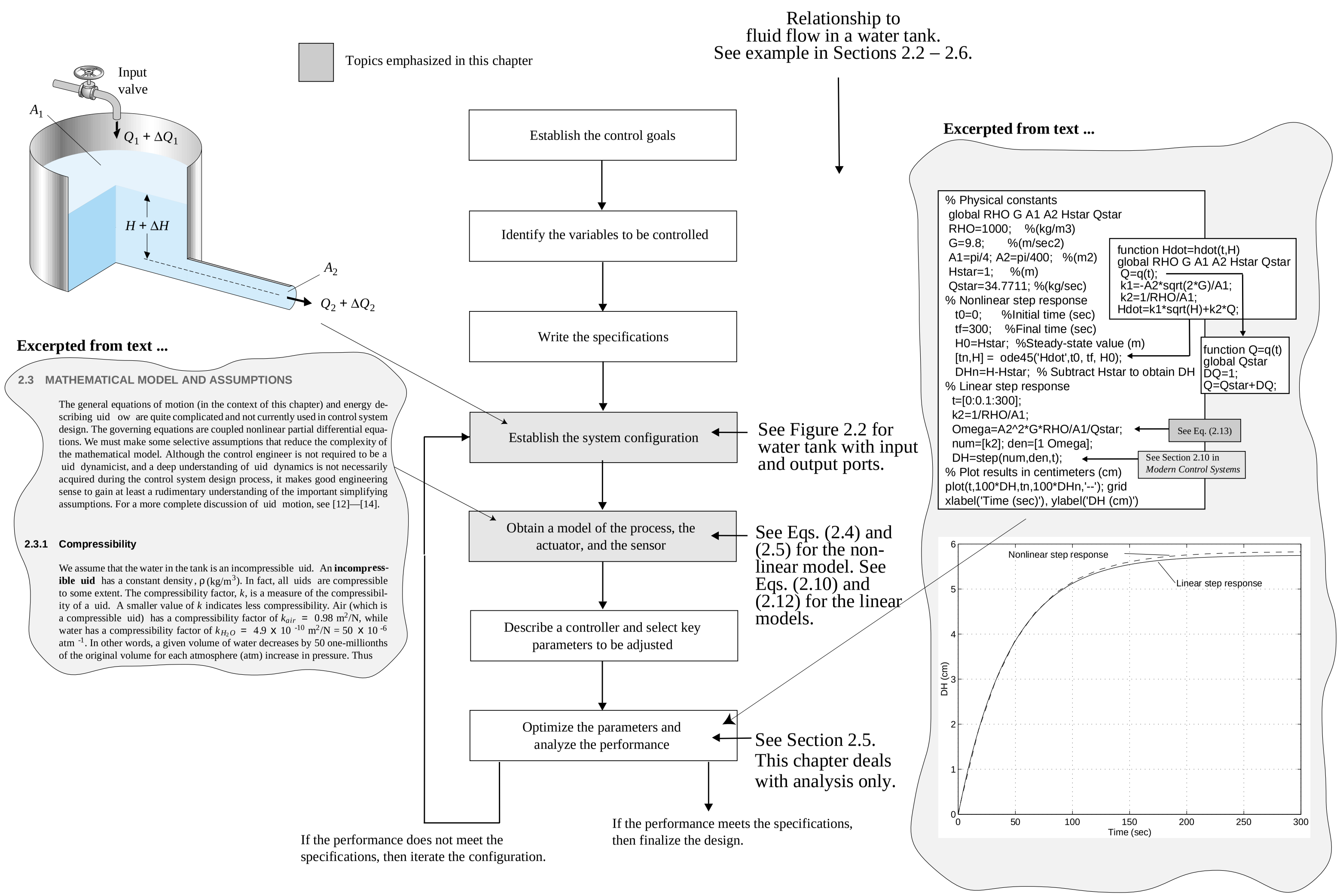


Figure 2: A fluid flow modeling exercise.

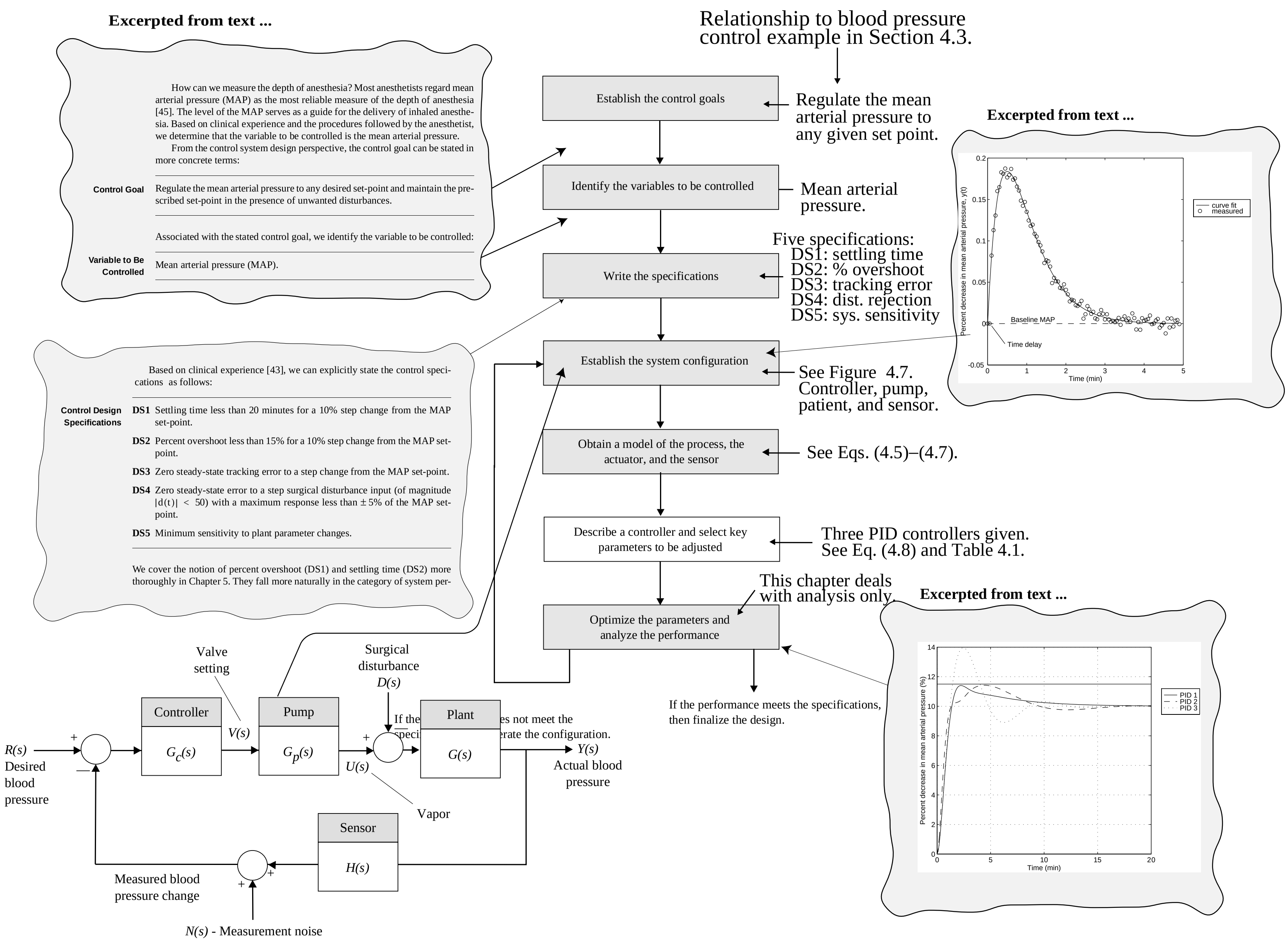


Figure 3: A blood pressure regulation system.

For example, a skin incision can increase the MAP rapidly by 10 mmHg. Finally, since we want to apply the same control system to many different patients and we cannot (for practical reasons) have a separate model for each patient, we must have a closed-loop system that is insensitive to changes in the plant parameters (that is, it meets the specifications for many different people).

With these thoughts in mind, we determine that reasonable (for use in our classroom setting) control specifications are: (i) settling time less than 20 minutes for a 10% step change from the MAP set-point, (ii) percent overshoot less than 15% for a 10% step change from the MAP set-point, (iii) zero steady-state tracking error to a step change from the MAP set-point, (iv) zero steady-state error to a step surgical disturbance input (of magnitude $|d(t)| \leq 50$) with a maximum response less than –5% of the MAP set-point, and (v) minimum sensitivity to plant parameter changes (see Fig. 3). The last specification is somewhat vague, although that is a characteristic of many real-world specifications.

In the system configuration, depicted in Fig. 3, we identify the major system elements as the controller, anesthesia pump/vaporizer, sensor, and patient. The system input, $R(s)$, is the desired mean arterial pressure change, and the output, $Y(s)$, is the actual pressure change. The difference between the desired and the measured blood pressure change is used by the controller to determine value settings to the pump/vaporizer that delivers the anesthesia.

Developing an accurate model of a sick patient starting from basic principles of physiology is difficult. Since the physiological systems in the patient (especially in a sick patient) are not well understood and not easily modeled, a modeling procedure based on knowledge of the underlying natural processes is not practical. Even if such a model could be developed, it would, in general, be a nonlinear, time-varying, multi-input, multi-output model. This type of model is not directly applicable here in our linear, time-invariant, single-input, single-output system setting. On the other hand, if we take an input/output viewpoint, we can use impulse response methods to obtain a patient model experimentally. Then if we restrict ourselves to small changes in blood pressure from a given set point (such as 100 mmHg), we might make the case that in a small region around the set point the patient behaves in a linear time-invariant fashion. This approach fits well into our requirement to maintain the blood pressure around a given set point. The impulse response approach to modeling the patient response to anesthesia is being used successfully in practice.

Suppose that we take a black box approach and obtain an impulse response for a patient. This response is shown in Fig. 3 (for a hypothetical patient---this is not actual data). Notice that the impulse response initially has a time-delay. This reflects the fact that it takes a finite amount of time for the patient MAP to respond to the infusion of anesthesia vapor. At this point in the book, we tell the students to ignore the time-delay, since in subsequent chapters they will learn to handle time-delays appropriately. A reasonable fit of the data is

$$y(t) = t\, e^{-pt} \quad \text{for } t \geq 0 ,$$

where p=2 and time (t) is measured in minutes. Different patients are associated with different values of p. The corresponding transfer function is

$$G(s) = \frac{1}{(s+p)^2}.$$

This simple model allows us to parameterize the patient with one parameter p. This provides a mechanism to study sensitivity of the closed-loop system to variations in p by looking at the sensitivity of the closed-loop transfer function to changes in p. This allows students to apply the theory that they learn in class to a problem in which they understand where the transfer function comes from, thus, understanding the limitation of the model.

V. Summary and Conclusions

In summary, the fluid flow problem introduces students to the process of developing a model beginning with basic physical principles, making simplifying assumptions, appropriately linearizing, and finally, obtaining a transfer function which can be used in the design process. The blood pressure regulation problem introduces students to the idea of obtaining models via experimental means using impulse responses. In both cases, the discussion may be considered overly simplified by some (especially practicing engineers). However, we feel it provides a good balance between teaching the basic concepts in controls and helping students connect the theory to the world around them.

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