# Marine Systems Identification, Modeling, and Control

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# Preface

This book has evolved over many years of teaching dynamics and control to undergraduate and postgraduate students following marine technology programs. A key realization by the authors was that although most marine technology degree courses teach an introduction to dynamic systems and control theory, for the majority of students this will be the only engagement they have with this subject. Nevertheless, the teaching and learning materials available and used in such courses are usually written to prepare the student for further advanced studies in the subject, and very often not described in a marine context.

The book therefore aims to explain key topics while referring to marine-related systems and components and cover the dynamics and control in a practical manner, while keeping the theoretical and mathematical level which is expected in a degree-level course. Having extensive experience with distance-learning courses, one particular objective has been to make the text suitable for independent self-study. For this reason the authors demonstrate theory and system analysis using examples written not only in Matlab, which is the industrial standard simulation software for control engineering, but also in Scilab which is open source and freely available.

# Contents

**Chapter | One**

# Introduction

**CHAPTER POINTS**

- Introduction to control systems.
- History and background.
- Open- and closed-loop systems.
- System dynamics.
- Software tools.

## 1.1 INTRODUCTION TO CONTROL SYSTEMS

Control engineering is the science of altering the behavior of a dynamic process in a beneficial way. By dynamic process, we mean a process whose output(s) change as a continuous, time-varying function of the input(s). A simple example is the temperature of a room controlled by a boiler and radiator. The input to the system is the desired room temperature and the manner in which the actual room temperature responds is a dynamic function dependent on the physical parameters associated with the boiler, room, and the external conditions.

Control systems are key components in a range of industrial areas and applications, including marine and mechanical engineering, industrial manufacturing, chemical and process engineering, aviation, space flight, and electrical systems. Control systems also surround us in everyday life, in applications such as thermostats (in, e.g., hot water tanks and refrigerators), washing machines, consumer electronics, traffic lights, car cruise controls, etc.

The use of a control system in a mechanism, device, or process may have many different objectives. Of highest importance is to ensure *system stability*, for example controlling the reaction rate in a chemical process to prevent it going out of control. Control systems may also be used to optimize the operation of a plant, such as the adjusting of fuel and air flow rates to an engine to maximize fuel efficiency and minimize emissions. The use of active roll stabilization in ships modifies the dynamic behavior of the vessel in order to improve passenger comfort. Control systems may also be used to improve inherent performance limitations of a system, for example, to speed up the dynamic response. An example of the latter is the control of modern fighter jets,



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where advanced control is used to stabilize the aircraft and provide improved high-speed manoeuvrability.

In addition to a controller, control systems also usually include other elements:

- *Sensors* are used to measure some physical property of the process or plant and thus provide information for the controller, e.g., a thermo-couple device to provide temperature data or an optical encoder to measure the rotation of a motor.
- *Actuators* transduce signals from the controller to provide the input to and cause a change in behavior of the process or plant, e.g., a hydraulic ram to rotate the rudder in a steering gear system, a heater, or an electric motor transmission to drive a link of a robotic arm.

It is important to keep in mind that these components may also influence the behavior of the overall control system, for example, if they have a slow response or provide inaccurate or noisy data.

## 1.2 HISTORY OF CONTROL ENGINEERING

The field of control engineering has developed alongside the industrial revolution. The steam engine centrifugal governor, used by among others James Watt and illustrated in Figure 1.1, is often considered to be one of the first automatic controllers. The governor adjusts the steam supply to the engine according to the engine speed, ensuring stable operation under varying load conditions. (If the speed drops due to a load increase, the steam supply is increased, and vice versa.) These early control systems were developed by engineers in the mid-nineteenth century and were followed by a more formal mathematical analysis of dynamic systems by scientists such as James C. Maxwell and Oliver Heaviside.

What is currently considered to be standard techniques in feedback control systems design, including proportional-integral-derivative (PID) feedback control, root locus, and frequency response methods, were developed around

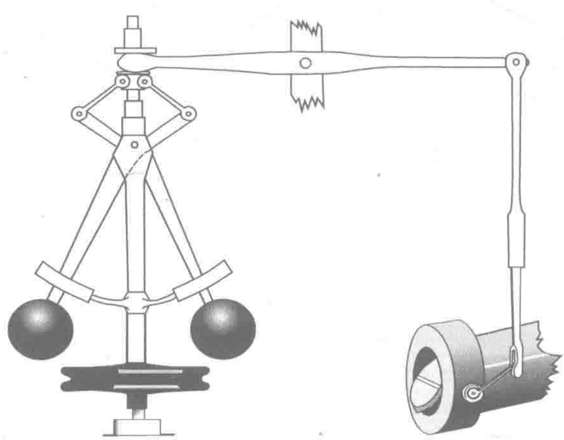

**FIGURE 1.1** Centrifugal engine governor.

1920-1950 by engineers and scientists such as Walter R. Evans, Hendrik W. Bode, and Harry Nyquist. Evans developed the root locus method, a graphical method to determine the behavior of a system for variations in some design parameter, such as controller gain. Bode and Nyquist developed techniques to study the time-domain stability and behavior of a system based on its frequency-domain characteristics. We will use these tools later.

## 1.3 CONTROL SYSTEM STRUCTURE

Control systems can, in general, be classified as either open loop or closed loop. Let us look at what these terms mean, and what the structure of a control system looks like.

### 1.3.1 Open-loop systems

In open-loop systems, the output of a plant or process may be controlled by varying the input, but the actual output has no influence upon that input. This can be illustrated with a simple block diagram as shown in Figure 1.2.

An example of an open-loop control system is a room with a simple electric fire, illustrated in Figure 1.3. In this case, given an input (the mains supply switched on), the output (the room temperature) will eventually arrive at some constant level, i.e., the room temperature will become constant with time. The value of the output is dependent on the prevailing conditions or plant behavior, in this case the size of the heater and the heat losses from the room. If the rate of

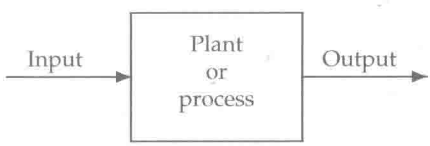


**FIGURE 1.2** Open-loop control system.

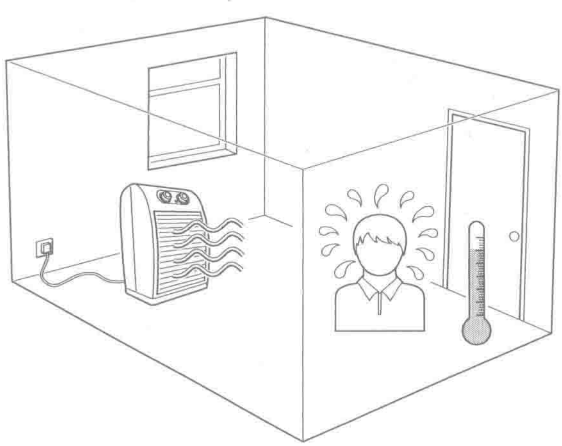

**FIGURE 1.3** Room with electric fire example.

heat loss changes, for example, due to a change in outside temperature (external disturbance) or if someone opens a window (change in the plant), the room temperature will eventually settle at a new and different steady-state value. The open-loop control system does not know about the change in temperature and is therefore unable to correct for these external disturbances; when switched on the electric fire output is constant for all cases.

### 1.3.2 Closed-loop systems

In order for the system to be able to respond to external disturbances, variations in the input, or plant changes, and to achieve a desired output value, a *closed loop* (also known as feedback) system is required. Using a closed-loop control system, the actual output is continuously compared with the desired output value, in order that the controller can compensate for these system changes.

Consider the electric fire example from above: in a well-insulated room the temperature might rise to an uncomfortable level and the fire would have been switched off by someone sensing the room temperature. This situation is illustrated in Figure 1.4. Based on the "sensor signal" (the felt temperature), the person determines the action to be taken, i.e., acts as a controller, and switches the supply on or off. The actuator in this system is the heater, which is the component providing the heat energy input to the room. The controller adjusts the heater state, thereby modifying the flow of heat energy to the room. This type of control system is known as a closed-loop control system, or sometimes an error-actuated feedback control system.

### 1.3.3 System structure

In all closed-loop control systems, the output is measured and compared to the *desired* output (the setpoint). Any difference between the two (called an "error

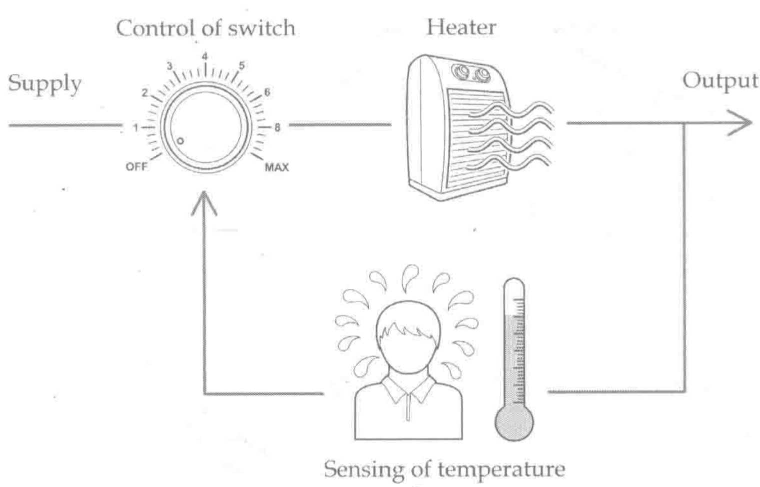


**FIGURE 1.4** Room with electric fire and "manual" control.

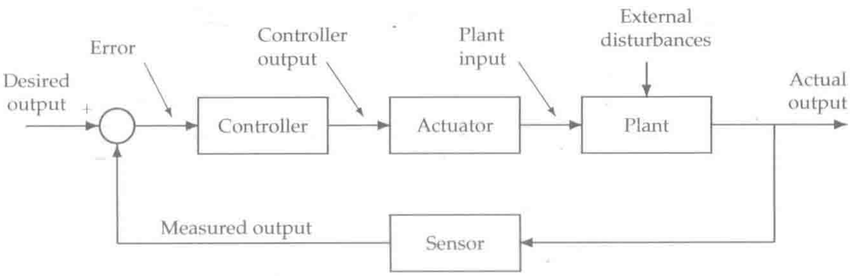


**FIGURE 1.5** Feedback control system.

signal") forms the input to the controller. Open-loop control systems do not have this feedback loop, and can therefore not compensate for errors resulting from changes in the plant, variations in the setpoint, or disturbances acting on the system in the way that closed-loop systems can.

The standard block diagram representation of a feedback control system is shown in Figure 1.5. In many cases, the actuator and the plant are represented by one block, since they are often closely integrated.

In the block diagram, the blocks represent components of the system, whereas the connecting vectors represent some system state or signal. In the room temperature example, if controlled by a thermostat, the room is the plant, with the output being the physical room temperature and the setpoint is an electronic signal representing the desired output temperature. The sensor, a component of the system, converts the actual temperature to a measured temperature signal. The difference between the setpoint and the actual output value, the error signal, is fed to the controller. The controller output signal operates the actuator, the heater. The output from the actuator, which is the input to the plant, is the physical variable that we influence to achieve the desired output. (In this case, the heat flow to the room.)

In most modern control systems, the setpoint, sensor, error, and controller output signals are electronic signals. This is, however, not always the case; for example, the centrifugal governor discussed above is a purely mechanical controller. Such systems can also be fitted into the general structure above.

### 1.3.4 Marine control system examples

Control systems play an essential part in modern marine systems. There are numerous examples of maritime control systems; we will look at several of these later. A couple of introductory examples are included here.

#### Tank level control

Figure 1.6 illustrates a day tank where the supply line flow is automatically controlled with a valve to maintained a suitable tank level. The level sensor provides a measurement of the actual tank level to the controller, which again controls the fuel supply valve to maintain a desired tank level. Through the level

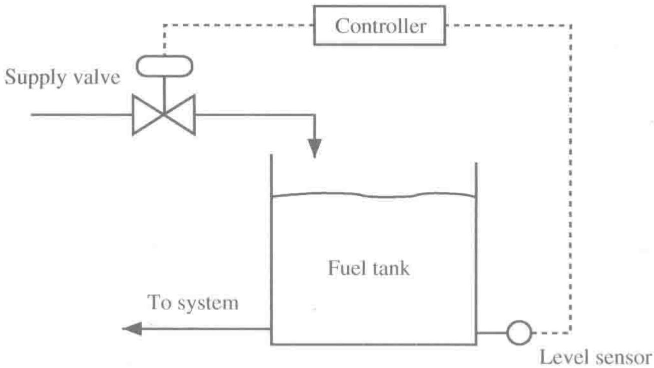


**FIGURE 1.6** Fuel tank level control.

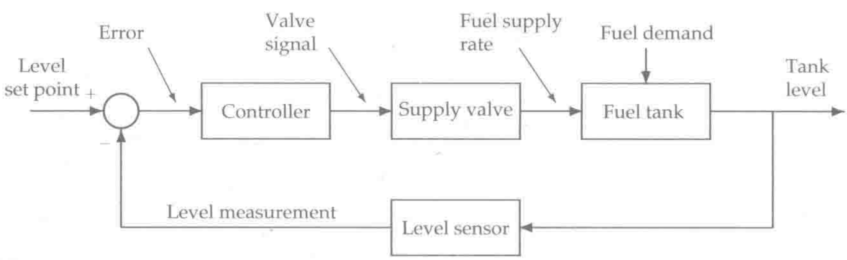


**FIGURE 1.7** Tank level control block diagram.

measurement, the controller can respond to changes in fuel demand, hence this is a closed-loop control system.

Fitting this into the standard block diagram feedback control-loop structure, we get a system as shown in Figure 1.7. The level setpoint is provided in the controller, either programmed in or as an input that can be varied by an operator. The main external disturbance in this case are variations in the fuel demand, i.e., the output flow from the tank, which is what the control system should compensate for.

## Fuel viscosity control

Controlling the viscosity of the fuel supplied to the propulsion engine(s) is essential and in order to achieve this, temperature control by electric or steam heating is typically used.

Figure 1.8 shows a common setup. The fuel is supplied through a fuel heater, through which a steam flow is controlled in order to provide the appropriate heating power. A feedback signal is provided by a viscosity meter downstream of the heater, which provides a information to the controller about the actual viscosity, in order that the opening of the steam supply valve can be regulated to produce the desired viscosity. Figure 1.9 shows the feedback system block diagram of this system.

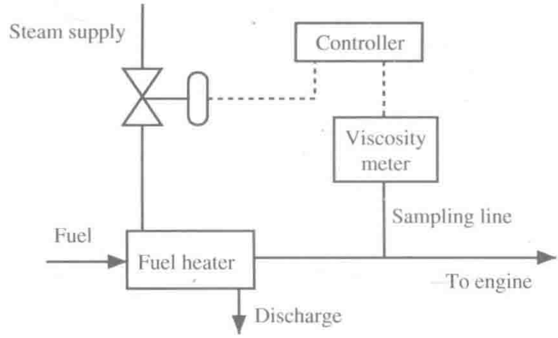


**FIGURE 1.8** Fuel viscosity control.

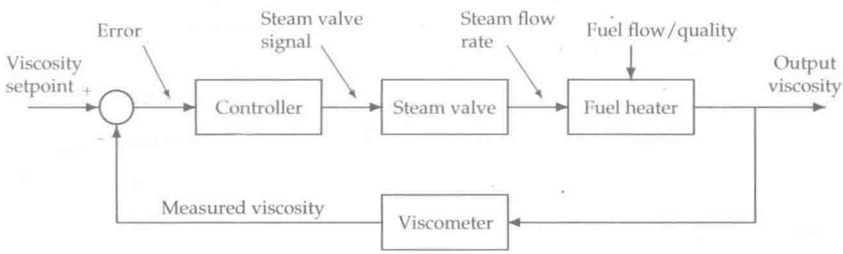


**FIGURE 1.9** Fuel viscosity control block diagram.

### Fin roll stabilization

Fin roll stabilization, as shown in Figure 1.10, is commonly used to improve the behavior of a ship under the impact of wave loads. By measuring the actual roll angle, a righting moment can be produced by controlling the angle of the fins.

Figure 1.11 shows the feedback block diagram representing this system. In this case, the controller demands a certain fin angle output, whereas the fin system, which could even be a feedback control system in its own right, will respond and produce a righting moment on the vessel.

## 1.4 SYSTEM DYNAMICS

A key concept in control engineering is system dynamics. The dynamics of the system determines how quickly it responds to controller outputs and to external disturbances. For the control system designer, the plant or process is often given; e.g., the design of a ship or a room of a given size. However, one may well be able to choose the actuator(s) and/or sensor(s) used in the control system.

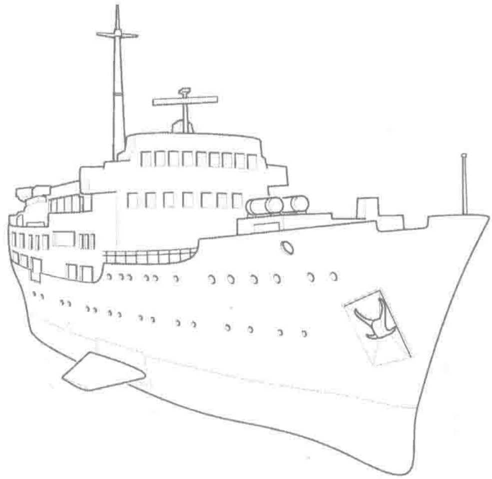

**FIGURE 1.10** Fin roll stabilization.

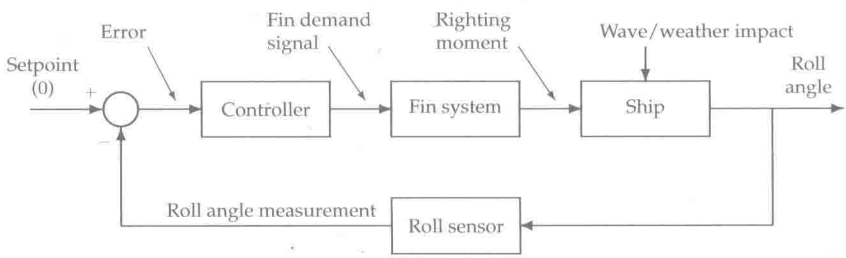


**FIGURE 1.11** Fin roll stabilization control block diagram.

Choosing an appropriate actuator is important. If a ship steering gear does not have a powerful enough actuator it will only be able to move the rudder slowly under rough conditions. In the case of temperature control, if a boiler cannot supply sufficient heat, the room will remain cold for a long period of time; the system will be "sluggish."

Often we apply a control system to a process or plant to speed up the response time, although ultimately the process limits the performance. This is an important point to bear in mind; for example, we could easily over-specify a control system for a slowly changing process, spending a lot more money for a fast-acting control system that does not provide any gain in speed or accuracy of response.

### 1.4.1 Dynamic response examples

Consider the fuel tank level control example above; probably the simplest controller we can use on this plant is one that switches on the supply if the

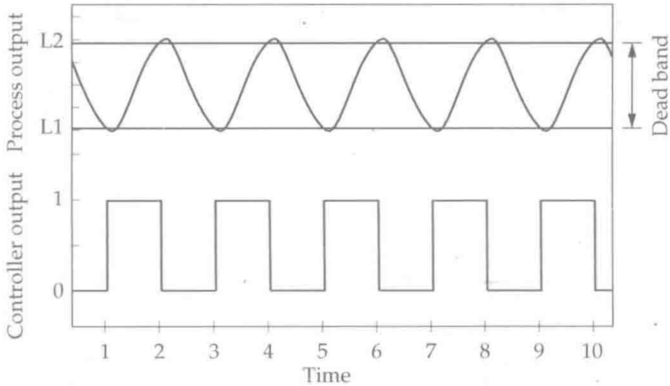


**FIGURE 1.12** Controller output and plant response for on/off control.

tank level falls below a predetermined value, and switches the supply off when the level reaches a higher, second value. This is know as on/off, or bang-bang, control.

The response may look something like that shown in Figure 1.12. The two levels L1 and L2 are the setpoints for switching on or off the supply. Hence, the tank level will fluctuate between these levels (known as the dead band), and the supply will be either fully on or switched off. This system may be satisfactory for the tank control, where the main objective probably is to avoid the tank going empty, but for many systems, e.g., the viscosity controller and roll stabilization above, an oscillating response like this may not be acceptable.

If we consider the viscosity controller example from Figures 1.8 and 1.9, the control objective will be to maintain close to constant output viscosity (at some setpoint value) even in the case of varying fuel input conditions. A critical event in this system may be the change of fuel supply tank, after which a fuel with a different quality and temperature may be supplied.

Figure 1.13 illustrates some possible system responses following from such an event. We assume that at time zero the system is in a stable condition and the input conditions suddenly change. (Hence, our dynamic problem starts at $t = 0$.)

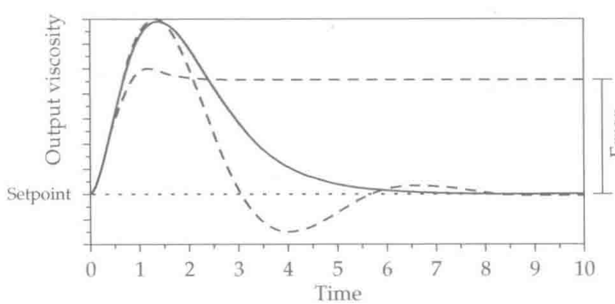


**FIGURE 1.13** Dynamic response plots for viscosity control system.

In a typical case, shown by the solid line, the output viscosity may temporarily increase until the controller has time to correct the fuel heating power. How quickly this occurs may depend on many factors, e.g., the speed of response of the controller and steam supply, or the thermal mass and heat transfer properties in the heat exchanger.

One could also imagine a case where the control system over-compensates slightly and drives the output viscosity below the setpoint, before settling at the desired value. This may give a quicker response away from the high-viscosity output, at the cost of some oscillation around the setpoint before the output settles. A third alternative response could be that the control system is unable to fully compensate for the change in input viscosity; this is shown by the second dotted line. In this case, the output viscosity will remain at some value different from the setpoint; there will be a *steady-state error*. This may be the case, e.g., if the heater is unable to supply enough heat for the new fuel, or if the controller is wrongly tuned.

We will see numerous further examples of system dynamic response later.

## 1.5 ADVANCED CONTROL ENGINEERING TOPICS

Control engineering is a vast subject area and this text presents only an introduction to control engineering and control systems design. To give the reader an idea of the "bigger picture," this section presents some important topics for potential further study and their relevance.

### NONLINEAR CONTROL

All real-world systems have some degree of nonlinearity due to, for example, time delays, hysteresis, or simply that the system has inherent nonlinear characteristics. (We cover some of these aspects in Section 2.4.) Sometimes, the system can be approximated as a linear system, but in many cases it is critical to take the nonlinear characteristics of a system into account in order to achieve acceptable controller performance.

### DIGITAL CONTROL

Advances in computer technology in recent years have opened up the way for high-performance digital controllers. There are a number of advantages of using a digital system to apply a control algorithm: (a) Digital controllers are software-based so they can be reprogrammed. (b) They can be interfaced to modern IT systems, giving data robustness and data security. This offers flexibility in terms of changing the controller design, and it also enables the implementation of advanced control strategies, e.g., knowledge-based techniques.

### OPTIMAL CONTROL

Optimal control is concerned with optimizing the operation of a system to minimize some cost function. For example, how to get from state A to state

B using the least possible amount of energy. Using mathematical optimization techniques, the controller can be designed to meet such criteria.

### ROBUST CONTROL

Robust control is important in systems which are not well defined, such as highly complex plants with internal feedback mechanisms or systems with time-varying properties. A robust controller seeks to employ stability margins in order to maintain system performance for varying conditions.

### INTELLIGENT CONTROL

Intelligent controllers are those which use knowledge-based techniques to improve controller performance. This allows the utilization of knowledge of the system or operator experience, and can include using such techniques to tune standard (e.g., PID) controllers, or by employing an intelligent controller. Common techniques used include fuzzy logic and artificial neural networks. One major advantage is that such controllers can be highly nonlinear, giving superior performance in nonlinear plants.

### ADAPTIVE CONTROL

As the name suggests, adaptive control techniques seek to adjust the controller performance to the plant behavior. For example, the behavior of ship will depend heavily on the loading, and an adaptive controller will take this into account when determining the controller response. Adaptive controllers can be pretuned, but can also be combined with intelligent control to make the controller self-tuning. The latter can be useful in plant whose properties vary with time, for example, due to wear in the system.

## 1.6 SOFTWARE FOR CONTROL SYSTEM ANALYSIS AND DESIGN

Software tools are today invaluable in the analysis and design of control systems. Extremely powerful tools exist and these programs are under constant development. The market-leading tool for system analysis and simulation is Matlab/Simulink [1] offered by The Mathworks, Inc. Matlab/Simulink allows both analytic and numerical analysis of dynamic systems and very useful design tools exist in the range of toolboxes (e.g., the control system, robust control, and nonlinear control toolboxes) available for the software.

A free, open-source alternative to Matlab is Scilab [2], developed by a consortium of academic and industrial users. Although Scilab does not contain the same number of sophisticated and specialized features as Matlab, it does have very powerful tools for control engineering. Octave [3] is another open-source software package which also has a range of control-related tools. Its syntax is very similar to Matlab's, however it is predominantly command