21 Century 21世纪高等院校电气信息类系列教材

Experiment Handout of Automatic Control Theory and Application

自动控制理论与应用实验指导

戴亚平 编著

机械工业出版社
CHINA MACHINE PRESS

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本书采用中英文对照的方式编写，通过理论与实例结合的方式，深入浅出地介绍了自动控制实验中的控制系统设计与实现方法，可供相关专业采用双语教学的高等院校使用。

全书共分10章，介绍了自动控制系统的建模及各种控制器的设计与实现，包括根轨迹校正、频率法校正、PID控制器设计、LQR控制器设计、模糊控制器设计、神经网络PID控制器设计、遗传算法控制器设计等实验系统。每个章节中都配有必要的实例，让读者能快速掌握控制器设计与实现方法。

本书面向高等院校的学习自动控制理论课程师生以及对自动控制理论有一定认识的工程技术人员，旨在帮助读者用较短的时间掌握控制器设计的技巧和方法，并提高读者的实践与动手能力。

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前　言
PREFACE

“自动控制原理”是工程类学科的一门重要的专业基础学位课程，在电气工程、机械工程、航天工程等工科专业都会设置。该课程既包含数学与工程科学相结合的理论知识，又包含理论与工程设计实践紧密结合的实验内容。本书是为了配合自动控制理论实验课程的教学而撰写的。

编者经过多年的教学实践获得如下体会：针对“自动控制原理”的实验课程，如果有一套与多媒体教学、网络教学、实物实验教学相结合的新型设备，允许教师拿到课堂进行实验教学、学生课后自己进行实验训练、科研人员针对自己设计的控制算法进行反复实验，会极大地提高“自动控制原理”这门课程的教学效果。

为了实现“课堂教学实验、课后网络化实验、学习者自创实验”的工作目标，我们开发了一套“便携式单自由度机械臂”实验系统，该系统构成了自动控制原理的实验硬件基础；在这样的硬件基础上，又开发了一套软件系统与硬件系统配套使用。我们设计的这套实验系统适合初学者使用，也允许使用者自己开发相应的实验项目。此外本书针对高校常用的“球杆实验系统”和“倒立摆实验系统”也进行了智能控制实验设计方面的讲解。

我们所期望的实验教学不再是学生在规定的时间，在座位有限的实验室进行的自控实验课程。而是将实验教学做到与学生、教师随时随地在一起，使得实验过程也能够如同教科书一般时刻伴随着读者。基于这样的实验教学思想，我们编写了这本涵盖了经典控制理论中多个基本实验的教材，在此基础上也想抛砖引玉，能够为激发高校开发出更多适合于培养工程型人才的实验教学教程出一点力。

全书共分 10 章，针对数学建模、超前滞后校正、PID 控制、智能控制等方面进行设计与实验，每章都有具体的实例与实验模板，目的在于让读者结合实例更加快捷地掌握控制系统的设计与实现方法。

本书主要面向工科院校学习自动控制原理课程师生，可作为大、中专院校相关专业的教学和参考用书，也可供有关工程技术人员和软件工程师参考。为了方便广大读者更加形象直观地使用此书，每一章都给出了实例操作过程的 Matlab 程序的源文件，供学习者参考使用。全文采用中英文对照的方式撰写，以适应当前大专院校双语教学的需求，也可以作为培养留学生的参考教材。

本书由北京理工大学自动化学院的戴亚平编著，刘向东，姜增如，许向阳等也为

本书的编写提供了大量帮助。日本东京工科大学的大山恭弘教授与佘锦华教授于2006年向编者的研究室赠送了最初版本的单自由度机械臂系统，此后北京理工大学自动化学院的多届研究生参与了“便携式单自由度机械臂系统”的开发，目前已经是第4代产品。在此对他们的大力帮助与辛勤工作一并表示感谢。

由于时间仓促，加上编者水平有限，书中不足之处在所难免，欢迎读者联系1282892958@qq.com批评指正，编者将不胜感激。

编者

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目　录

Chapter 1 Introduction

"Automatic Control Theory", "Modern Control Theory" and "Intelligent Contro" are very important, but hard to understand courses for automation major's students. There are many abstract concepts in these courses, such as the system's stability, controllability, convergence speed and anti - interference performance, etc. Currently, many universities have carried out some education innovation, trying to improve the students' interest through varieties of teaching methods. The goal is raising the quality of theory teaching. The main steps of education innovation include the following aspects:

(1) The Demo experiments are added in class teaching via multimedia equipment

Teachers modify the PPT courseware, insert video, photos, animations etc., by means of multimedia technology, to stimulate students' interest by visual, auditory, tactile, etc. The vivid teaching in classroom will attract students to attend the teaching activity, and improve the quality of classroom teaching effectively.

(2) Add computer - assisted instruction

By means of simulation software and other compute tools, a lot of deduction, graphics rendering, etc., will be replaced by only one or two "instractions" in program. It will save teaching period effectively. Through observation and analysis of simulation output

第1章 概 述

自动控制原理、现代控制理论以及智能控制对于自动化专业的学生而言，是非常重要的课程，也是比较难以理解的几门课。课程中一些概念比较抽象，如系统的稳定性、可控性、收敛速度和抗干扰能力等。目前，各个高校都进行了不同程度的教学改革，力图通过多样的教学方式提高学生的学习兴趣，提升理论教学的教学质量。各高校的教学改革主要从以下几个方面进行：

(1) 课堂教学借助多媒体设备加入演示实验

教师通过修改教学课件，在课件中插入视频、图片、动画等，恰当地应用多媒体技术，从视觉、听觉、触觉等多方面提升课程的可理解程度，激发学生的学习兴趣，鼓励学生积极参与课堂知识的学习，从而提高课堂的教学质量。

(2) 引入计算机辅助教学

利用计算机仿真软件等教学工具，可以把大量的计算推导、图形绘制等工作仅用一两条指令代替，从而有效地节省教学时间。通过对仿真数据的观察和对输出图形的分析，加深了学生对基础理论的认识和理解。

data and graphics, it will enhance the students' understanding to basic theory.

(3) Offer experimental curriculum to aid theory teaching

The using of multimedia and computer aided instruction often cannot satisfy the requirements of engineering courses, because these experiments do not combine the physical plants. In recent years, due to the demand of "Engineer Accreditation", "Major Degree Certification" in universities to, a large number of experiments course are carried out in undergraduate and postgraduate education for assisting the theory teaching, so that the major knowledge will link the practical application closely. These curriculums which combined with the practice should not only make students verify the theoretical knowledge, but also improve the ability of engineering application.

According to all above mentioned, multimedia based experiment, networked experiments and so on are the hotspots currently. Developing a suitable experimental course is an important task in universities' in and after class experiment teaching innovation. With years of teaching practice, if there is a new set of device combining multimedia teaching, online teaching, and physical experiment to aim at we find that the control curriculum, will greatly improve the teaching and studying quality. The device will be taken by teacher to classroom, will be exercised by students after class, will be used by researchers to test their own controller algorithm repeatedly.

(3) 开设实验课程辅助理论教学

多媒体与计算机仿真类的辅助教学，因为不能结合实物的对象进行实验，所以不能满足工程类课程的学习需求。许多高校因为有了类似于“工程师认证”、“专业学位认证”等教育教学需求，近年来在本科与研究生的教学中增设了大量的实验课课程用于辅助理论教学，将专业知识与实际应用紧密联系起来。这种能够结合实践的课程，可以使学生验证已经学过的理论知识，还可以在实验的过程中提高学生的工程应用能力。

综上所述，多媒体、网络化等多种类型的实验教学目前正处于发展的热点，如何开发出适合课堂与课后的实验教学课程，是目前高校实验教学改革的重要任务。经过多年的教学实践，我们发现，针对控制类的课程，如果有一套与多媒体教学、网络教学、实物实验教学相结合的新型设备，允许教师拿到课堂进行实验教学、学生课后自己进行实验训练、科研人员可以自己设计控制算法进行反复实验的实验设备，会极大地提高教学效果。

Based on the idea, we designed an experimental system, which is the set of motion control system with a simple model, and is not only suitable for beginners, but also allows users to develop their own experimental program. In order to achieve such teaching ideas, we prepared the experiments handout which covers all the experiments of classical control theory. We would like to test firstly, and believe there will be more universities to develop more suitable experimental teaching tutorial for the cultivation of engineering talents.

我们正是基于这样的思想，设计出一套实验系统，该系统具有简单的运动控制模型，适合初学者使用，也允许使用者自己开发相应的实验项目。我们还编写了这本涵盖了经典自动控制理论中所有实验的讲义，在此基础上也想抛砖引玉，激发高校开发出更多适合培养工程型人才的实验教学教程。

In order to complete the goal of "experiments in teaching class, networked experiment after class, creative experiments by user", we designed and implemented a set of experimental system named "Portable One Freedom Robot Arm" (POFR - Arm), which constitutes the hardware of automatic control experiment. In POF - Robot system, we use DC motor as actuator, the position of the motor moved as a controlled object. In order to observe the experimental results more conveniently, an "arm" is connected to the DC motor as position indicator. Single Chip Micro computer (SCM) is used as the logical control unit to control the POFR - Arm position.

为了达到"课堂教学实验、课后网络化实验、学习者自创实验"的工作目标，我们首先设计并实现了一套"便携式单自由度机械臂"实验系统，该系统构成了自动控制实验的硬件基础。在该系统中，使用直流减速电动机作为实验装置的执行机构，减速电动机的位置作为系统的被控对象。为了更直观地观察实验结果，在电动机的出轴上接一个机械手臂，作为电动机位置的指示标志。使用单片机作为逻辑控制单元，对机械臂进行位置控制。

System hardware structure of POFR - Arm is shown in Figure 1.1.

机械臂硬件系统结构如图 1.1 所示：

Taking the POFR - Arm system as controlled object, we designed corresponding experiments course for "Automatic Control Theory": Mathematical modeling experiments, the root locus method correction experiments, frequency method correction experiments, pole

将该套单自由度机械臂系统作为被控对象，本书设计了对应"自动控制原理"课程的实验教程内容：系统的数学建模实验，根轨迹法校正实验，频率法校正实验，极点配置实验，PID 控制器设计实验，线性二次型最优控制器设计实验

configuration experiments, PID controller design experiments, linear quadratic optimal controller design experiments, etc. After the training of above experiments, students have a clear acknowledge and understanding for classical control theory, both the principles and the applications.

等。通过以上实验的训练后，学生对经典控制理论中的主要理论方法与应用都会有明确的认识与理解。

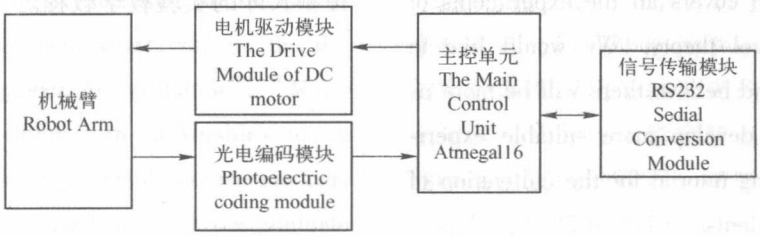

Figure 1.1 System Hardware Structure of POFR – Arm

图 1.1 便携式单自由度机械臂硬件系统结构图

Note that the experimental device in Figure 1.1, The POFR – Arm can be replaced completely by other experimental device, and the experimental method designed can also be used for other controlled objects. Here we just take the POFR – Arm shown in Figure 1.1 as an example to illustrate the use of the experimental teaching tutorials.

需要说明的是，图 1.1 的实验装置完全可以被其他的实验装置所替代，本书所设计的实验方法同样可以用于其他被控对象的使用。这里只是将图 1.1 所示的单自由度机械臂作为一个例子，来说明该套实验教学教程的使用。

Similarly, the designed system in Figure 1.1 just only solved the experiment problem of being in the laboratory, limited by the time and space; it cannot meet the user's requirements of "anytime, anywhere". So, we design a set of networked device shown in Figure 1.2. With the appearance of this device, the experimental object in Figure 1.1 was posted online, which allows students to use all types of internet tools in hands (computer, mobile phone, iPad, etc.) to do the experimental learning "anytime and anywhere".

同样，图 1.1 设计的系统仅仅是解决了实验者亲临现场的实验问题，受时间、地点的限制，并不能满足实验者"随时、随地"的要求。为此，我们设计了一套网络化装置如图 1.2 所示。在增加了这套装置后，图 1.1 的实验对象就被放到了网上，该套系统能够允许学生利用手中的各类上网工具（计算机、手机、iPad 等），进行"随时、随地"的实验性学习。

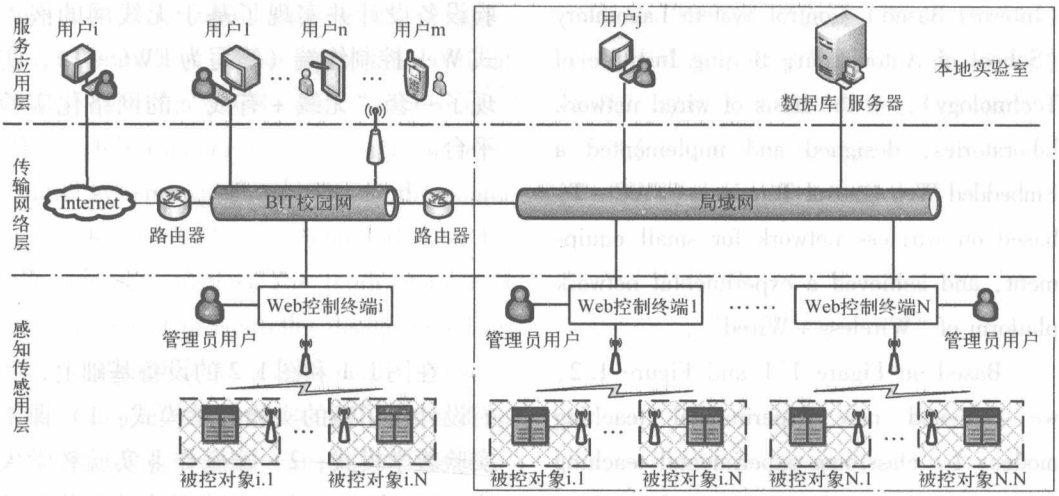

Figure 1.2 Hardware Structure of Network Experimental System

图 1.2 实验系统的硬件结构图

By the POFR – Arm, students can not only verify the theoretical knowledge taught by teachers in class, but also design their own experimental steps to verify control algorithms. The final results will be transmitted to PC or mobile terminals via the Internet, so that both the efficiency of the laboratory equipment and students study will be improved.

The laboratory equipment's connecting with "the Internet" is supported with more mature technology, which has a familiar name called "Internet of things". With the prosperity of intelligent mobile terminal market, we began to enter the mobile Internet era.

As an extension of the mobile Internet, Internet of things has begun to walk into and change our life step by step. People began to connect traditional devices to the Internet to achieve the "objects" of the network, through the ubiquitous mobile network, then to achieve the remote monitoring and operation on a variety of devices anywhere and anytime. Remote

运用单自由度机械臂，学生们除了实验验证在课堂上老师教的理论知识，也可以自己设计实验步骤，来验证其他控制理论与控制算法的控制效果。最终的实验结果通过互联网传送回学生的个人电脑或手机终端上，实验设备的使用效率和学生的实践效率都大大提高了。

允许实验设备“上网”，有较为成熟的技术支持，这个技术有一个耳熟能详的名字称为“物联网”。随着移动智能终端市场的走向繁荣，我们开始进入移动互联网的时代。

作为移动互联网的延伸，物联网一步步地走进并改变我们的生活。人们开始将传统的设备接入互联网，以实物联网也开始实现“物”的网络化。通过无处不在的移动互联网，实现对各种设备随时随地的远程监控与操作。（北京理工大学自动化学院）远程控制实验室，在有线网络化实验室的基础上，针对小型实

(Internet Based) Control System Laboratory (School of Automation, Beijing Institute of Technology), on the basis of wired network laboratories, designed and implemented a Embedded Web Control Terminal (EWC - T) based on wireless network for small equipment, and achieved a experimental network platform of "Wireless + Wired".

Based on Figure 1.1 and Figure 1.2, we designed new experimental teaching modes: 1) classroom experimental teaching mode; 2) homework experimental teaching mode; 3) multi - people interactive and discuss experimental teaching mode.

These new modes are profoundly changing the way of talents training in engineering disciplines, and with the further application of Internet technology, there will be more experimental mode appear in college education.

The purpose of this book is to provide students a new experimental platform, in which students can complete the task of teaching experiment originally done only in the laboratory. Now the experimental courses can be done by students and teachers anywhere anytime, which like your "carried - on" textbook in your learning career.

The main contents of this book are: The second chapter is the experimental modeling of second - order system; The third chapter is the root locus lead - lag compensation experiment; The fourth chapter introduces the frequency method lead - lag compensation experiment; The fifth chapter introduces the state space Pole assignment test; Chapter six

验设备设计并实现了基于无线网的嵌入式 Web 控制终端（缩写为 EWC - T），实现了一套“无线 + 有线”的网络化实验平台。

在图 1.1 和图 1.2 的设备基础上，我们设计出了新的实验教学模式：1）课堂实验教学模式；2）家庭作业实验教学模式；3）多人互动、讨论形式的实验教学模式。

这些新的实验模式都在深刻改变着工程学科的人才培养方式，并且随着互联网技术的进一步应用，可能还会有更多的实验教学模式在高等教育中涌现出来。

我们这本书的目的，就是提供给大家一个新的实验平台，在这个平台上可以完成原先只能在实验室里完成的实验教学任务。现在的实验课程可以做到与学生、教师随时随地在一起，如同你的教科书一般“时刻”伴随在你的学习过程中。

本书主要内容有：第 2 章讲述二阶系统的建模实验；第 3 章讲述根轨迹超前 - 滞后校正实验；第 4 章是频率法超前 - 滞后校正实验；第 5 章是状态空间极点配置实验；第 6 章是 PID 控制实验；第 7 章是线性二次型最优控制算法（LQR）控制实验；第 8 章讲述模糊控制系统的设计实验；第 9 章讲述基于 BP 神经元

introduces PID control experiments; Chapter seven introduces linear quadratic optimal control algorithm (LQR) control experiment; The eighth Chapter is the design of fuzzy control system experiment. The ninth chapter is the design of PID controller based on BP neuralnetwork method. The tenrh chapter is the experiment of controller design based on genetic algorithm. After learning the course of these experiments; students will have a deep understanding of control theory in engineering applications.

The born of this book benefits from the years of work by many post graduate students, and thanks to the support of 985 project funds. During the 985 construction equipment at the support of equipment department of Beijing Institute of Technology, we re - develop our purchased equipments, so that these experimental equipments could better serve teachers and students.

Moreover, through the development of these experimental equipments, students' practical and research abilities are improved effectively.

方法的 PID 控制器设计；第 10 章讲述基于遗传算法的控制器设计实验。通过这些实验课程的学习，学生可以加深对控制理论在工程应用的理解。

本书最终能够形成是得益于多届研究生的工作结果，并且得益于 985 工程经费的支持。在北京理工大学设备处支持下所进行的 985 工程建设中，我们对购置的实验器材进行了二次开发，使得这些实验器材能够更好地为教学服务。

通过开发这些实验设备，也培养了学生的动手与科研能力。