Establishing the Connection between Control Theory Education and Application: An Arduino Based Rapid Control Prototyping Approach

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***Abstract*—Automatic control theory is tightly related with other majors such as mechanical engineering and electrical engineering. Control theory education is an essential part of those majors and has significant effect on students' engineering practice and innovative ability. However, current control theory courses use the "teaching by telling" approach to teach students mathematical derivation centered knowledge, which cuts off the natural connection between the theory and application and leaves students ill-prepared for the engineering profession. This paper proposes to use a rapid control prototyping centered approach to fill the gap between theory and application and help to improve the learning quality. The main idea is to introduce digital simulation and hardware-in-loop simulation into the teaching practice. Digital simulation can accelerate the learning efficiency while the hardware-in-loop simulation can establish the connection between the theory and application.**

***Index Terms*—control theory education, rapid control prototyping, digital simulation, hardware-in-loop simulation**

I. Introduction

Control theory is a subject that focuses on how to analysis and regulate the behavior of non-autonomous dynamical systems. Although control cannot be seen as a visible object, it is widely existed in our daily environment. Therefore, the control theory is an elementary course for majors such as automation, electrical engineering, mechanical engineering, energy and power engineering, machinery, electrical information, instrumentation.

It is precisely because control theory is tightly related with engineering and mathematics; it requires rich background knowledge on mathematics, physics, mechanical, electrical, electronics, etc. Furthermore, the control theory itself covers a variety of subjects such as modeling, analysis and controller design, linear system, nonlinear system, continuous system, discrete system, time domain analysis and frequency domain analysis, etc. It is rich in content, wide in the knowledge, profound in theory and fast in update. Therefore, it is quite difficult to organize so much knowledge in very limited class hours. The control theory education has to be refined for students with different majors.

Like most of the courses, current control theory classes still use the "teaching by telling" approach [1] (i.e., teachers give lectures in class, students read books after class). Mostly the textbooks and teachers too much emphasize theories and mathematical derivations and ignore the application background of control theory. This teaching method brings two major problems: first, the students are passive recipients of knowledge instead of actively involved in the learning process. The knowledge they learned is far from what they learned in other engineering courses. The teaching process will become boring and cannot attract students' interests; second, this method will cuts off the natural connection between the theory and application. The problems students solved in classrooms do not fully reflect the real-world problems that they will encounter as engineers in the future, which leave engineering graduates ill-prepared for the engineering profession [2].

Yang identified this problem and studied the teaching reformation of the automatic control theory. He proposed to reform the course by optimizing the teaching content, improving the teaching methods, reforming the experimental teaching, innovation the assessment methods [2]. But he didn't discuss the particular methodology to achieve these goals.

Liu emphasis the use MATLAB simulation in modern control theory course teaching. However, the gap between theory and application is not filled [3]. Dixon proposed to develop Computer Aided Control System design (CACSD) tools to promote undergraduate controls laboratory development based on MATLAB. However, he didn't present how to embed such system into control theory education practice [4]. Grepl reviewed the Real-Time Control prototyping tools in MATLAB/Simulink and made detailed comparison. However, the listed tools are too professional or expensive [5]. They are not fit for general engineering major education scenario.

In this paper, the gaps between control theory and application are discussed and an Arduino based rapid control prototyping methodology is proposed to fill the gaps.

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II. Problem Ananysis

A. Content of Elementary Control Theory Course

As previously mentioned, control theory has very rich content. In the elementary control theory course, the content is mostly organized as shown in Fig. 1.

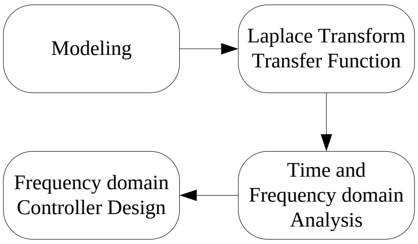

Figure 1. Content of elementary control theory course

The whole course usually takes 48 course hours and has the following content:

1) *Modeling*

Physical system modeling; linear differential equation;

2) *Model conversion*

Laplace transform; Inverse Laplace transform; Transfer Function

3) *Time and frequency domain analysis*

Pulse response, Step response; Nyquist Diagram, Bode diagram; Stability analysis; Root locus;

4) *Control*

Parallel compensation, Serial compensation;

The above contents form a comprehensive knowledge system of control theory for single input single output (SISO) time invariant system. However, all the contents are illustrated by mathematical derivation. And teachers commonly use confirmatory experiment; such method is hard to arouse students' enthusiasm to participate in experimental and learning activities.

B. Difficulties in Connecting Theory and Application

Connecting control theory and application is not a trivial thing. It requires hardware implement and software development and most of all, enough fund for preparing adequate experiment platforms. If the number of platforms is too small, the experiments have to be performed in turns, i.e., the teacher will spend much effort to accomplish those experiments.

Meanwhile, a good experimental platform should fit for the knowledge background of the students. Take students with mechanical engineering major as example, they might not be familiar with electrical circuit and embedded programming. Therefore, it is not easy for them to integrate and develop the whole control system.

Third, control theory is based on mathematics; hence most of the modeling, controller design and analysis are realized by mathematical derivations, which is an error-prone process. Even the students master how to program, without any doubt, they will spend much time on debugging the control system. Therefore, the experimental time can be very long and the students may lose interests during the long boring debug process.

To solve the above mentioned problems, an Arduino based rapid control prototyping approach is proposed to efficiently establishing the connection between control theory education and application.

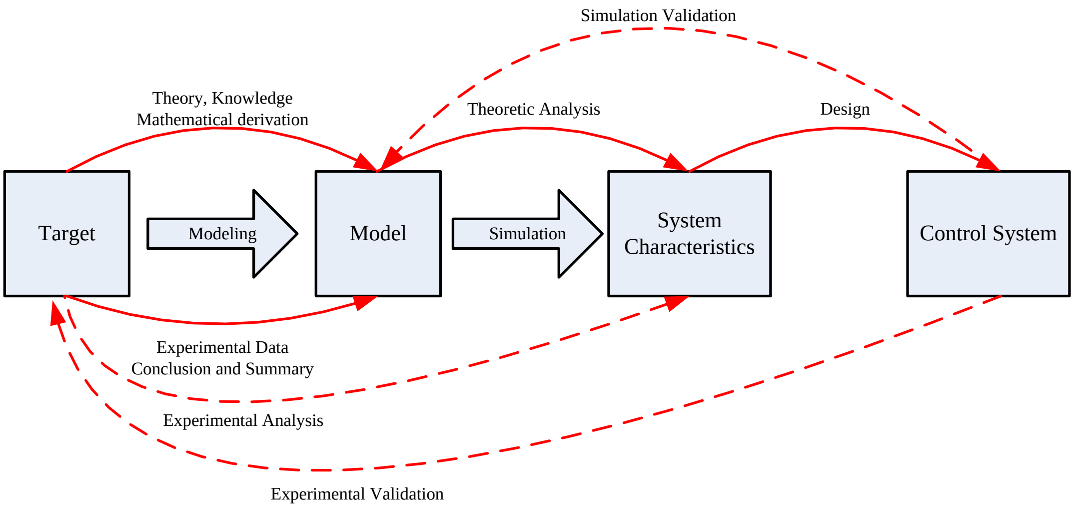

Figure 2. Flow chart of the control system MAD process

III. Proposed Solution

A. A Systematic View of Control Theory

Control theory can be seen as an application oriented technique. Its primary goal is to make the real physical system works as expected. Mathematics is just a tool for solving this problem. A systematic view of control theory application is shown in Fig. 2. It is consisted of Modeling, Analysis and Design processes, or MAD in short.

Modeling is the basis for the MAD process. It is closely related with application background. For students with mechanical engineering, physical laws such as Newton's Law, Lagrange Equations should be emphasized.

Usually analysis is done by theoretic calculation. However, nowadays, advanced digital simulation software such as Matlab is widely used in engineering and application fields. Therefore, how to analysis a system by using digital simulation should be introduced. Because simulation results can be demonstrated more intuitionist and vivid, it will brings benefits in two aspects: leading the students to master new tools for their future career and improving the learning efficiency and interests.

Controller design is the key point of control theory. In control theory courses, the controller design is mostly based on a given mathematical model instead of a physical system. The controller parameters are precisely calculated through Bode theorem or Root Locus method. However, because all the process are pure mathematical and there is no validation processes (neither experimental nor simulation), the students cannot sense the importance of the control theory. They may treat control theory is a mathematical trick instead of a very powerful tool. Therefore, it is very important to introduce simulation and experiments into the control theory education and form a complete MAD process.

B. Gaps between Control Theory and Application

In the traditional control theory education, as described in previous section, only the tasks shown with solid lines are taught. There is no experimental validation or simulation validation work. The students know nothing about how to implement a control system or how to evaluate performance of a real control system. The control theory education does not fully cover what an engineering student needs when he/she actually solves a real problem in the future.

Fig. 3 demonstrate the missing part between these the control theory education and real experiments.

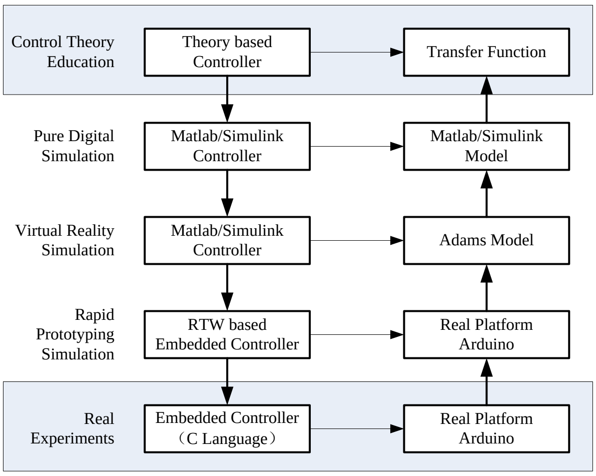

Figure 3. Establishing the connection between control theory education and application

There are three stages between pure theoretic courses and pure real applications.

1) Pure digital Simulation

Pure digital simulation is closely related with control theory. Based on control simulation software such as MATLAB/Simulink, it is very easy to build a control system by graphic programming instead of code programming. The digital simulation can provide students very quick and visual results and assist the learning process.

Because the programming language is quite similar with the block diagram in control theory, it is easy for students to learn the digital simulation programming language.

2) Virtual reality simulation

Virtual Reality simulation [6], [7] is a kind of digital simulation. The only difference is that the control target is build through specialized software instead of mathematical formulas.

For students of mechanical engineering, Solidworks, Adams are commonly used design tools. Virtual Reality simulation combines Matlab/Simulink with those specialized 3D software and can provide 3D animation showing the whole control process.

This technique not only increases the learning interest of the students, but also let them understand the inner connection between their major and automatic control theory.

3) Rapid control prototyping experiments

Rapid control prototyping [8] is a kind of hardware-in-loop simulation. It uses the simulated controller to control the physical target. It is a promising technique that can greatly accelerate the control system development efficiency.

The controller is constructed in Simulink environment, but automatically compiled and executed in external hardware to guarantee real-time performance. Because the program conversion is done automatically, it is easy to use even for students that do not master the embedded programming skill.

Rapid control prototyping provides the ability of validating the effectiveness and efficiency of the proposed controller on real platform instead of digital simulated target. Seeing believes, therefore, the results are convincing. Furthermore, controlling the real platform can let the student sense the controller's effect and understand the principle more deeply.

C. Filling the Gaps

To fill the existing gaps, the missing stages should be embedded in the control theory education process, not only in the controller design, but also in modeling and model analysis as shown in Fig. 2.

Fig. 4 is the proposed gap filling methodology.

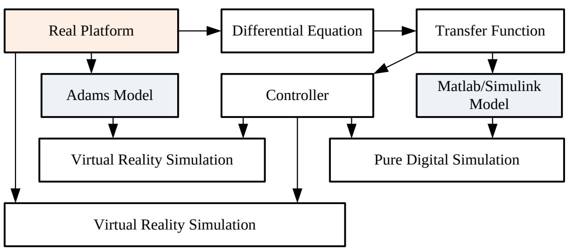

Figure 4. Gap filling methodology

A real platform should be chosen and setup first. The elements with dark background color are optional. According to the background knowledge of the students, the teachers decide whether to provide the students prebuilt model or not. If the students knows how to programming using Simulink, the "Matlab/Simulink Model" should be built by students themselves. If the students know how to use Adams or Solidworks, the "Adams Model" should be built by students themselves.

The elements with white background are the tasks done by the students, which cover the modeling, model transformation, analysis, controller design and simulation.

There are four main steps within this methodology.

STEP1: Modeling and Verification

When teaching how to derive the model of a physical system, besides demonstrating several benchmark examples, it is necessary to assign the modeling problem of the predefined real target platform as a quiz or homework. Let the students derive the corresponding differential equation and convert it into transfer function.

If necessary, Simulink programing language should be taught first. After deriving the model, the students can build their own simulation model and perform different experiments to verify the mathematical model.

This process has three functions: let the students practice the modeling skill; let the students master how to verify the derived mathematical model; let the students be familiar with simulation tools.

STEP2: Simulation and Analysis

In control theory courses, time domain analysis and frequency domain analysis techniques are both introduced. After teaching these methods, it is necessary to let the students use both theoretical analysis and simulation experiments to study the characters of the target platform.

Based on the Simulink model built in STEP1, the students can impose different kinds of input signals in the model and observe the outputs.

This process has two functions: enhance the understandings of analysis techniques by comparing the theoretical results with the simulation results; let the students to master the computer aided design tool.

STEP3: Controller Design and Validation

In elementary control theory courses, typically only the frequency domain controller design methods for SISO system are taught. The controller design process is based on stability criterions and frequency domain analysis methods such as Bode diagram. The performance of the closed loop control system is also given with several time domain or frequency domain indices.

This type of teaching and learning is too abstract and too boring for students with weak mathematical ability. In order to enhance the teaching quality, it is necessary to introduce digital simulation and virtual reality simulation experiments into the courses.

After teaching one kind of controller design method, students are encouraged to utilize it in the real target system. By adding controller programs into the Simulink model and forming a closed loop control system, the students can evaluate controller's performance immediately and directly by observing the time domain response oscillograph. Furthermore, the students can easily alternate the controller parameters and examine the relation between those parameters and the corresponding performance changes.

This process has two functions: Turn the abstract teaching and learning process into visible interactive experiments and increase the attractiveness of the control theory courses; Let the students become masters of the real control system and let them understand what they can do with a target system and how to achieve the desired performance.

STEP4: Rapid Control Prototyping and Accreditation

In the above steps, the students learn the theory and practice them using digital simulation methods. Although these methods are effective and visible, they still cannot replace the position of real target platform. Students can question whether the simulation is correct comparing with the real system. The model might be wrong or rough and the controller might be not fit for the real system. The digital results and even the virtual reality simulation results are just calculated numbers. Therefore, there is still a step far from the real application. That's why we introduce the 4th step: rapid control prototyping and accreditation. Until the students can use their controller to control the real physical system, their overall work can be accredited.

Rapid control prototyping use a simulated controller to control the real target platform. After the students tested and validated their controller using digital simulation methods, they can import their controller in the rapid control prototyping system and accredit the effectiveness of the proposed controller on real platform.

This process has three functions: Finally fill the gap between control theory and application; let the students understand how to implement a controller in a real platform and prepare for the future; Let the students practice how to debug and build a complete control system efficiently and correctly.

D. An Arduino Based Rapid Control Prototyping Soluction

In the proposed 4 STEPs gap filling methodology; the only obstacle happens in STEP4: **How to develop a complete and cost effective rapid control prototyping platform?** The commercial rapid control prototyping platforms, such as dSPACE and LABVIEW, are quite expensive and too powerful for teaching applications.

Recently, Arduino, an open-source computer hardware and software, is becoming extremely popular all around the world, both in geek fans community and academy [9], [10]. The company shares their specific design of hardware and provides free open source software to everyone. So anybody can contribute to this project. Consequently, Arduino and Arduino-compatible boards are becoming "standard" electronic building blocks and supported by many third party products, such as Matlab/Simulink.

Fig. 5 shows an Arduino UNO board. It is tiny, cheap and easy to hook up and use. It has 14 digital IOs, 6 analog inputs, 6 PWM pins and one serial communication port, which is quite enough for small projects.

Arduino is now supported by Matlab/Simulink. Using Real-time Workshop, the Simulink programs can be automatically converted into programs that can run on Arduino [10], i.e., setting up the controller on Arduino requires no Arduino programming skills. Therefore, it is quite fit for the rapid control prototyping task in the control theory education scenarios.

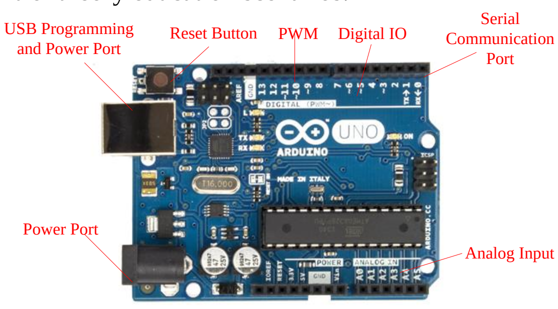

Figure 5. Arduino UNO board

Fig. 6 shows the flow chart of the Arduino based rapid control prototyping approach.

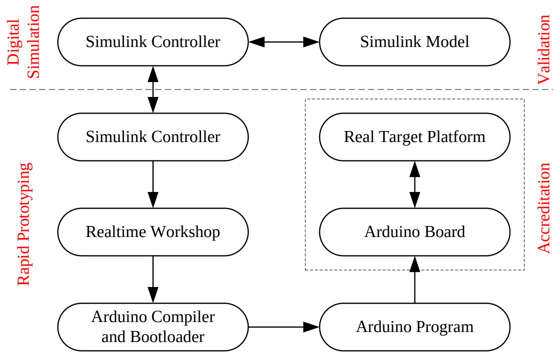

Figure 6. Flow chart of the Arduino based rapid control prototyping approach

After the students testing their controller using digital simulation methods, they can make a few modifications on their model and replace the mathematical model with Arduino-Simulink model. Then this model can be automatically converted and compiled into Arduino program and downloaded into Arduino.

After deploying the Arduino program, the real target platform can be controlled by the Arduino board with controller program composed by the students. The students can examine the performance through observation and measurements. If the performance does not meet the requirements, they can repeat STEP1 to STEP4 until everything works fine.

Notes: A complete real target platform is usually consisted of mechanical components and electrical components. For students which are not familiar with those components, it is necessary to give a brief introduction on those components and teach them how to derive the mathematical model in the modeling section.

E. Choosing Proper Platform

Real-world problems are complex, ill-structured, and sometime have conflicting goals. Therefore, the target platform should be chosen carefully according to the major of the students. The platform should also be interesting enough to capture the interests and attention of the students.

In control theory courses, there are a lot of benchmark platforms for demonstrating the control applications, such as DC motor drive system, linear pendulum, Acrobot, Pendubot, Ball-beam system. They are typically with large movement and occupy large volume, hence, in this paper, we propose to use the following two wheeled mobile robot (shown in Fig. 7) as the bench mark target platform.

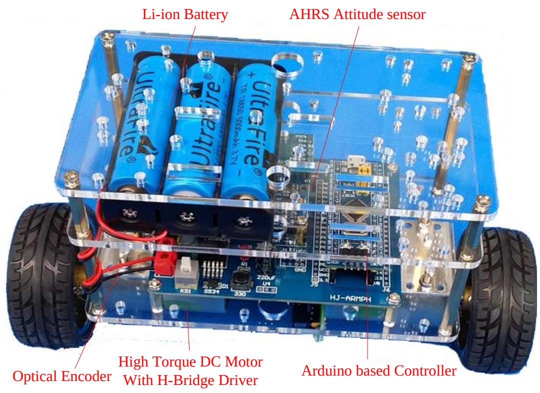

Figure 7. Real target platform: Two wheeled mobile robot

This Segway type robot has two DC motors directly driving its two wheels. Each motor has its own optical encoder which can measure the motor speed and position. There is an AHRS sensor board on the robot which provides the attitude information.

The robot can be bought in online store with a price of \$60 or DIY using 3D printers. Its dimensions are 220mm×80mm×50mm and it weighs less than 1Kg. Therefore, the students can even make their own robot.

Several experiments can be conducted on this platform:

- DC motor speed control experiment
  - ➢ Control of a typical second order system;
- DC motor position control experiment
  - ➢ Control of a high order system;
- Robot balance experiment
  - ➢ Model linearization and transformation;
  - ➢ Double Loop Control of a complex system;
- Robot speed control experiment
- Robot motion control experiment
  - ➢ Advanced tasks

The platform is complex and can be used in several chapters. In modeling section, teachers can let the students to model the DC motor, the driving circuits and the whole system. In controller design section, the above mentioned experiments can be arranged in different stages. This can let the students understand the platform gradually.

IV. Conclusion

This paper studies the problem of establishing the connection between control theory education and application. It is based on a Chinese old saying:

"what I hear I forget.
what I see I remember
what I do I understand"

This old saying precisely describes the central idea of this paper. We developed an Arduino based cost effective rapid control prototyping two wheeled mobile robot platform which can be closely integrated with commonly used control simulation software Simulink. Based on this, a 4STEP gap filling methodology is proposed. By utilizing digital simulation, virtual reality simulation and rapid control prototyping hardware-in-loop simulation, the abstract control theory learning process is turned into vivid and interesting gaming experience. This methodology let the students to see and manipulate the control system themselves and let them to remember and understand what control theory is and how to master control as a powerful tool in their future.

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REFERENCES

[1] A. Yadav, G. M. Shaver, and P. Meckl, "Lessons learned: Implementing the case teaching method in a mechanical engineering course," *Journal of Engineering Education*, vol. 99, no. 1, pp. 55-69, 2010.

[2] Y. Yang, "Discussion on the teaching reform of the automatic control theory," in *Proc. 3rd International Conference on Science and Social Research*, 2014.

[3] L. N. Liu and J. Hu, "The practice of MATLAB simulation in modern control theory course teaching," in *Proc. IEEE Fifth International Conference on Advanced Computational Intelligence*, Oct. 18-20, 2012, pp. 896-899.

[4] W. E. Dixon, D. M. Dawson, B. T. Costic, M. S. de Queiroz, "A MATLAB-Based control systems laboratory experience for undergraduate students: Toward standardization and shared resources," *IEEE Transactions on Education*, vol. 45, no. 3, pp. 218-226, Aug. 2002

[5] R. Grepl, "Real-Time control prototyping in MATLAB/Simulink: Review of tools for research and education in mechatronics," in *Proc. IEEE International Conference on Mechatronics*, April 13-15, 2011, pp. 881-886.

[6] C. Schmid and A. Ali, "A web-based system for control engineering education," in *Proc. American Control Conference*, 2000, vol. 5, pp. 3463-3467.

[7] T. Brezina, Z. Hadas, and J. Vetiska, "Using of co-simulation ADAMS-SIMULINK for development of mechatronic systems," in *Proc. 14th International Symposium on Mechatronika*, June 1-3, 2011, pp. 59-64.

[8] S. Choi and M. Saeedifard, "An educational laboratory for digital control and rapid prototyping of power electronic circuits," *IEEE Transactions on Education*, vol. 55, no. 2, pp. 263-270, May 2012.

[9] Arduino Website. [Online]. Available: http://www.arduino.cc/

[10] I. B. Gartseev, L. F. Lee, and V. N. Krovi, "A low-cost real-time mobile robot platform (ArEduBot) to support project-based learning in robotics & mechatronics," in *Proc. 2nd International Conference on Robotics in Education, INNOC Austrian Society for Innovative Computer Sciences*, 2011.

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