

Project-Based Teaching in the Digital Signal Processing Course: A Case Study of Competition

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Abstract: This study aims to enrich the case library for digital signal processing (DSP) courses. Taking the onboard balance ball control system from the National College Students' Electronic Design Competition as the research object, this paper analyzes key technical features of the competition device, including signal acquisition, noise reduction filtering, feature computation, and discrete control design. It discusses the mapping relationship between system implementation and DSP knowledge points and constructs a layered, progressive physical training scheme. This work explores a subject-competition-driven practical teaching mode for DSP courses and provides a feasible implementation path for DSP practical teaching reform under the background of emerging engineering education.

Keywords: DSP course; Disciplinary competition; Discrete signal; Case teaching

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1. Introduction

Disciplinary competitions can fully stimulate students' innovative consciousness and enhance their engineering practical skills in solving real-world problems^[1,2]. The problems of the National College Students' Electronic Design Competition are highly comprehensive, requiring not only hardware platform construction but also algorithm design and closed-loop control implementation. This can provide abundant practical examples for project-based teaching of the DSP course^[3,4]. This paper selects Question H of the 2026 National College Students' Electronic Design Competition in Guangdong Province, "Vehicle-mounted Balance Ball Control System," as a project example to analyze the practical application ideas of various digital signal processing (DSP) algorithms within the system. Converting competition problems into comprehensive practical training projects for the DSP course can expand the resources of the course's practical training case library and cultivate students' ability to disassemble and analyze complex engineering problems^[5,6].

2. Research background

At present, there is still a certain gap between DSP course teaching and the goals of emerging engineering talent cultivation. Course experiments mainly focus on basic verification content, with limited types of available teaching cases. Case updates are not timely, and practical teaching resources suitable for engineering practice are insufficient^[1,6]. Restricted by teaching resource conditions, students' understanding of course knowledge often remains at the textbook level, and their innovative consciousness and engineering application thinking cannot be fully trained. When facing practical project tasks, many students lack independent analysis and problem-solving ideas. In disciplinary competitions or course project design, they often feel at a loss, and their comprehensive engineering practical ability is difficult to substantially improve. Therefore, it is particularly important to build a diversified teaching case library for DSP applications so that teaching case resources can effectively support the competency training objectives of the course^[2,7].

3. Realization of DSP algorithm in vehicle balance ball control system

The onboard balanced rolling ball control system adopts a microcontroller and terminal vision module as its operating carrier. The system signal processing procedure includes multi-channel discrete sensor sampling, signal denoising, feature extraction, optimal estimation filtering, and discrete closed-loop control implementation, which corresponds to the core knowledge points of digital signal processing courses. The system is composed of a vehicle tracking unit and a steel ball balance control unit, with all algorithms executed under discrete sampling timing. Actual operation is affected by typical engineering disturbances, including ambient light interference, sensor measurement noise, and image pixel jitter.

3.1. Discrete signal processing of vehicle tracking unit

The vehicle utilizes eight grayscale sensors to acquire ground trajectory information and obtains discrete grayscale sampling sequences at fixed sampling intervals. Affected by ground reflection and ambient light fluctuations, the original sampling data contain random noise and cannot be directly applied for trajectory identification. The weighted centroid algorithm is employed to extract the center position of the black line from multi-channel discrete sampling values.

$$x = \frac{\sum (i \cdot g_i)}{\sum g_i}$$

In the formula, i represents the sensor number, and the trajectory position output is obtained through weighted summation and normalization operations. e is the deviation of the trajectory from the vehicle body.

In order to suppress trajectory position jumps caused by sampling noise, a first-order low-pass digital filter is adopted to smooth centroid output signals. Meanwhile, a soft dead zone and differential damping are introduced to reduce high-frequency jitter of the control system.

The system adopts a double closed-loop discrete PID control architecture. The outer loop takes trajectory offset as input and outputs the speed difference between the two driving wheels. The inner loop acquires discrete speed sampling data from the encoder and applies incremental digital PID to realize closed-loop speed adjustment. The control workflow completes signal acquisition, filtering calculation, and control output within a fixed interrupt cycle, achieving real-time regulation of the vehicle motion state. Competition constraints, including track parameters and driving speed, serve as engineering boundary conditions to

support practical algorithm parameter tuning.

3.2. Signal processing of steel ball balance control based on Kalman filtering

The steel ball balance platform is an open-loop unstable double-integral system. The system acquires the real-time position of the steel ball through vision feedback and calculates the tilt angle of the swing rod via a discrete closed-loop control algorithm. The vision module captures images to obtain pixel coordinates of the steel ball, and converts pixel coordinates into physical millimeter units after system calibration. The calibration procedure adopts 19-point least squares fitting, which corresponds to the engineering application of discrete data fitting^[8].

The swing rod control adopts the discrete form of the PI-D control law.

$$\theta_{cmd} = T_p e + K_I \sum e \Delta t - T_D v$$

In the formula, e is the position deviation of the steel ball, and v is the moving speed of the steel ball. The target tilt angle of the swing rod is output with amplitude-limiting processing and converted into motor position commands. To overcome static friction interference from the groove structure, a small square wave disturbance is added to improve low-speed control performance.

Obvious random jitter exists in the pixel coordinates of the steel ball acquired by the vision module. Direct input of these coordinates into the controller leads to frequent oscillation of the swing rod. The Kalman filter is adopted to perform optimal state estimation and filter the measured sequence of steel ball positions. The Kalman filter uses system process noise and measurement noise parameters to continuously correct the predicted and observed values of steel ball position and effectively suppress measurement noise generated by image detection. Meanwhile, a threshold for target loss protection is set to constrain the filter output during visual detection failure, and the operational stability of the system is improved.

3.3. Visual image signal acquisition and video stream processing

The system adopts a camera with a dual-channel image acquisition mode. Images captured by the camera are essentially two-dimensional discrete pixel signals. Image data from one channel is transmitted to the encoder for video compression coding, which realizes RTSP real-time streaming, two-dimensional digital video signal compression, and network transmission. Images from the other channel are sent to the KPU to execute the target detection model, identify the steel ball target, and output the pixel deviation of the steel ball center after confidence screening and target deduplication. The detected and filtered position information is transmitted to the back-end main controller in a custom serial communication frame format, and serves as observation input for the balance closed-loop control.

4. Mapping of cases and DSP course knowledge points

Analysis of the algorithms in this competition system shows that many technical implementations can be mapped to the core teaching content of the digital signal processing course. The specific correspondence is presented in **Figure 1**.

technology and knowledge points

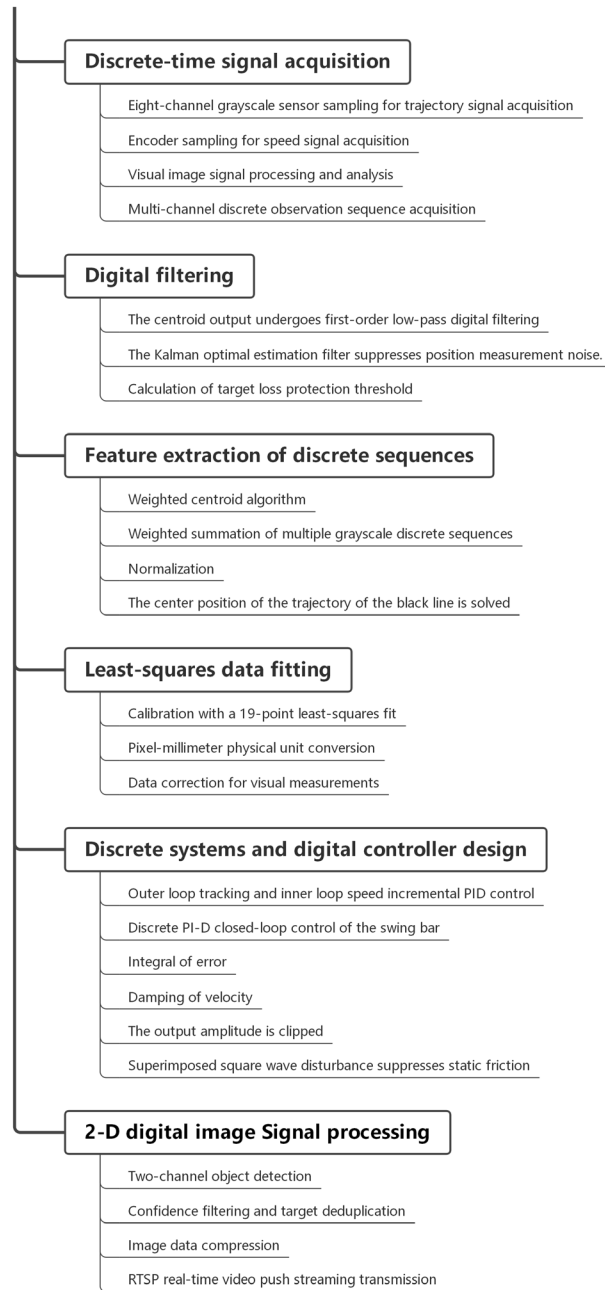


Figure 1. Correlation between technology and knowledge points

The above knowledge points have corresponding engineering implementations in the competition system. Most traditional DSP courses rely on simulation software for knowledge verification ^[9]. Idealized simulation environments usually neglect practical engineering noise. This physical case can directly reproduce signal interference caused by noise. Students can compare signal waveforms before and after filtering, tune controller parameters, and observe system response speed, overshoot, and steady-state error under different parameter settings. This bridges the gap between pure simulation experiments and practical engineering.

5. Case teaching design ideas

The on-board balance ball competition system covers several core knowledge points of digital signal processing. To convert the competition engineering case into classroom practical training resources, the complete competition project is reasonably disassembled, and teaching tasks are arranged progressively from simplicity to complexity. The teaching design adheres to the principles of knowledge point correspondence, hierarchical difficulty classification, and practical operability. The original competition tasks are decomposed into three training levels: basic level, improvement level, and comprehensive expansion level, as shown in **Table 1**. These levels correspond to diversified teaching scenarios, including in-class experiments, course design, and scientific and technological innovation expansion.

Table 1. Hierarchical task system

Level	Practical training task	Knowledge points of the DSP course	Teaching scenario
Basic layer	Multi-channel discrete signal acquisition and weighted centroid feature extraction; Observation of the effect of first-order low-pass digital filtering	Discrete time signal, sequence operation, FIR digital filtering	Classroom experiment
Improvement layer	Comparison of the suppression effect of Kalman filter on measurement noise; Parameter debugging of discrete PID digital controller	Stochastic signal processing, optimal estimation filtering, discrete systems and digital controllers	Course design
Comprehensive expansion layer	Image two-dimensional signal calibration, video stream compression principle analysis, multi-source signal fusion comprehensive debugging	Two-dimensional digital signal, data fitting, signal compression coding	Preparatory training for science and technology innovation and competition

The hierarchical task design eliminates the contents of complex mechanical assembly and low-level hardware driver development that are irrelevant to the DSP curriculum. Teaching emphasis is placed on signal processing algorithms. Students can carry out hierarchical practical training according to their own knowledge foundation, which realizes differentiated teaching and personalized talent cultivation ^[10,11].

6. Conclusion

Against the background of emerging engineering construction and industrial technological iteration, the experimental teaching of digital signal processing courses mainly focuses on simulation verification, while practical training resources oriented to real engineering scenarios are insufficient, resulting in the disconnection between students' theoretical learning and engineering application capabilities. This paper takes the vehicle-mounted balance ball control system of the National College Students' Electronic Design Competition as the research object, analyzes various digital signal processing algorithms adopted in the system, and reconstructs the competition project to form a comprehensive practical training case applicable to classroom teaching. By designing hierarchical and progressive training tasks, core knowledge points, including discrete signal sampling, digital filtering, and discrete controller design, are integrated into the practical training process. The adopted case reproduces real engineering conditions such as light interference and measurement noise, enriches the engineering practical teaching resources of DSP courses, and helps cultivate students' ability to analyze complex engineering problems. It also provides an effective reference for the practical teaching reform of DSP courses.

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