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Research on the Architecture of an Intelligent Tennis Training System Integrating Computer Vision and Big Data Analytics

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Abstract: *To address issues such as reliance on subjective experience and weak data processing capabilities in traditional tennis training systems, this study constructs an intelligent tennis training system architecture integrating computer vision and big data analytics. In terms of technical implementation, the computer vision module employs YOLO series object detection algorithms to achieve rapid and accurate positioning of tennis balls and athletes in complex court environments. Combined with a human skeletal keypoint detection model, it captures core motion features such as hitting and movement, quantitatively assessing action standardization through comparison with standard templates. The big data analytics module establishes a multi-dimensional data collection system, utilizing algorithms like clustering analysis, association rule mining, and predictive modeling to classify athletes, develop personalized training plans, evaluate training effectiveness, and predict performance. The system adopts a four-tier architecture of "data acquisition layer-data processing layer-data analysis layer-application layer," enabling end-to-end collaborative data processing and offering functions such as personalized plan recommendations, real-time feedback, and motion correction. Research findings indicate that this system overcomes the limitations of traditional training, achieving precise quantitative measurement and scientific analysis of training data, effectively enhancing the intelligence and specificity of tennis training, and providing objective scientific support for athletes' technical improvement.*

Keywords: *Intelligent Tennis Training System, Computer Vision, Big Data Analytics, System Architecture*

1. Introduction

In recent years, tennis has continued to gain popularity worldwide. According to the "Basic Data on the Development of Tennis in China," by the end of August 2024, the number of tennis players in China had exceeded 25 million, marking a significant increase compared to 2021 with a growth rate of 28.03%. The number of tennis courts has also grown in tandem. Globally, in 2024, the number of tennis participants surpassed 1.06 billion, representing a 21.6% increase from 2021. Tennis is now expanding from its traditional strongholds in Europe and America to emerging markets.

With the widespread popularity of tennis, there is an increasing demand for training effectiveness and player performance improvement. Traditional tennis training systems rely on coaches' subjective judgment and experience-based guidance, which come with numerous limitations. For instance, in technical movement analysis, coaches' visual observation alone struggles to accurately detect subtle deviations in players' hitting actions—such as inconsistent toss heights during serves or improper wrist movements during strikes [1]. These issues are often overlooked, leading to slow technical progress. Moreover, conventional training methods fail to comprehensively quantify key performance metrics like swing speed, power, angle, movement velocity, and reaction time. This lack of objective data makes it difficult to develop personalized training plans, resulting in inefficient, one-size-fits-all approaches.

To address these issues, an intelligent tennis training system has emerged. This system integrates computer vision and big data analytics, offering significant advantages. Through computer vision technology, utilizing high-definition cameras and advanced image recognition algorithms, it can capture every movement detail of the player in real time and with precision—from footwork and body posture to racket swing trajectories—providing a comprehensive and accurate data foundation for subsequent

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analysis. Big data analytics, in turn, enables deep mining and analysis of vast training datasets, identifying not only technical weaknesses in players' performance but also allowing the development of personalized training plans based on their physical condition, technical strengths, and training objectives [2]. This achieves precise and efficient training. For instance, by analyzing a player's historical training data and identifying a low success rate in backhand returns, the system can provide targeted backhand-specific training plans, including backhand practice exercises under various scenarios, strength and coordination training, effectively enhancing the player's technical proficiency. Therefore, researching the architecture of an intelligent tennis training system that combines computer vision and big data analytics holds important practical significance for advancing the scientific and intelligent development of tennis training, improving player training efficiency, and elevating competitive performance.

2. Theoretical basis of related technologies

2.1 Principles and applications of computer vision technology

Computer vision technology is the core support of intelligent tennis training systems, which simulates human visual mechanisms and relies on algorithms and models to achieve object detection, recognition, tracking, and feature extraction, laying the foundation for accurate collection and analysis of training data [3]. In tennis training scenarios, object detection and recognition are based on the YOLO algorithm, which transforms the detection task into a regression problem and directly predicts the target category and position through a single forward propagation. The training video image is first divided into S × S grids, and B bounding boxes and confidence levels (including the probability of target existence and the accuracy of bounding boxes) are predicted from the grid containing the target center. At the same time, C category probabilities (such as tennis and athlete posture) are output, which can complete multi-target detection in a very short time and meet the real-time training requirements. In practical applications, it can quickly locate tennis balls and track their trajectories, obtaining information such as serving speed and hitting landing points; At the same time, this study can identify the position and posture of athletes, accurately detect deviations in serving and throwing height, throwing amplitude, and other movements by comparing with standard templates, and provide guidance for technical improvement.

The SIFT algorithm is key in the image feature extraction process, which can extract local feature points with scale invariance, rotation invariance, and illumination robustness. The process includes four steps: firstly, scale space extremum detection, which compares pixels with 26 neighboring points (8 at the same scale and 9 at each upper and lower scale) using Gaussian pyramids and DoG images to screen candidate feature points; The second is key point positioning, fitting a three-dimensional quadratic function to optimize the position and scale, removing low contrast points and unstable edge points (based on the Hessian matrix principal curvature ratio); The third is direction assignment, which involves calculating the gradient direction histogram of key point neighborhoods (360 degrees divided into 36 intervals), taking peak values and more than 80% of secondary peaks as directions to achieve rotation invariance; The fourth step is to generate 128 dimensional descriptors (16 × 16 neighborhoods divided into 4 × 4 subregions, each subregion with an 8-dimensional gradient vector), which can be normalized to suppress the influence of lighting and accurately identify the movement characteristics of athletes such as hitting and moving, assisting in the standardized judgment of movements.

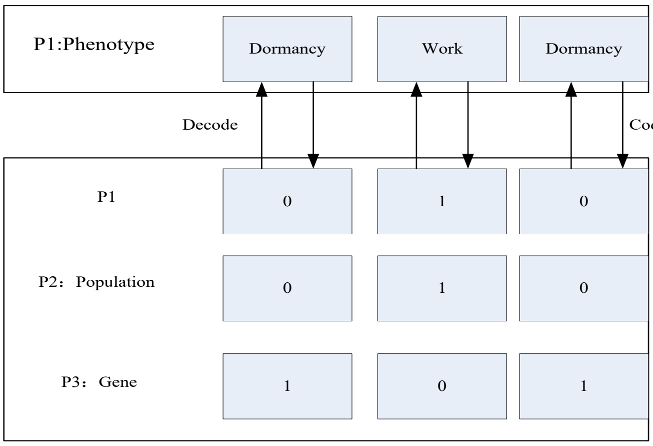

Figure 1 Eagle Eye System

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The Eagle Eye system, as a typical application, consists of multiple high-speed cameras, computers, and large screens. Based on computer vision and triangulation technology, the multi position camera captures the court at a high frame rate, locates the tennis ball through algorithms, and combines triangulation to calculate the three-dimensional motion trajectory (including speed, rotation, and landing point), achieving millimeter level inside and outside judgments in competitions to ensure fairness; The recorded game data, such as the success rate of hitting at different positions and movement routes, can also provide reference for training and assist coaches in developing targeted training plans, as shown in Figure 1.

2.2 Principles and applications of big data analysis technology

Big data analysis technology is the core support of intelligent tennis training systems, which can efficiently process and deeply mine the massive and complex data generated during training, extract valuable information to support training decisions, and assist in personalized and accurate training. Its application begins with data collection, with sources covering four aspects: firstly, sensor data, which collects hitting parameters, movement data, and physiological indicators through rackets (acceleration, gyroscope sensors), sports shoes (pressure sensors), and sports clothing (biosensors); The second is video data, which relies on high-definition cameras on the field to record movements and ball trajectories, providing materials for visual analysis; The third is competition data, including results, technical statistics (such as serving success rate); The fourth is the basic information of athletes (age, physical function, etc.), which lays the foundation for personalized training.

The raw data needs to be preprocessed: data cleaning removes noise through threshold setting and filtering algorithms, identifies and processes outliers; The processing of missing values adopts deletion or mean/regression filling according to the amount of missing data; Data standardization (Z-Score, Min Max method) eliminates dimensional influence and improves analysis reliability.

Data analysis relies on three core algorithms: clustering analysis (unsupervised learning) to classify athletes based on technical characteristics, physical fitness, etc., such as distinguishing between "strong serve bottom line attack type" and "strong defense front type", to assist coaches in developing targeted plans; Association rule mining reveals data associations, such as increasing the success rate of backhand training when the intensity reaches a threshold, which helps optimize training content and intensity; Classification algorithms (supervised learning) are based on historical data modeling to predict game outcomes or error types, providing a basis for strategy adjustments.

In practical applications, a training case of a professional athlete highlights its value: through cluster analysis and comparison with athletes of the same type, it is found that their backhand stability is insufficient. Based on this, personalized plans are formulated to increase backhand specific training and dynamically adjust the intensity; Real time analysis of hitting parameters and evaluation of action standardization during training. If there is no improvement in serving speed, association rules are used to mine positioning problems (such as action details and training methods) and adjust the plan, ultimately significantly improving backhand ability and game winning rate.

3. Requirement analysis of intelligent tennis training system

3.1 System functional requirements

This function is the core of the system, relying on computer vision technology to achieve: capturing hitting and moving movements through multi view high-definition cameras on the court, and combining YOLO and other object detection algorithms to recognize athlete posture, racket position, and ball trajectory, extracting key parameters such as hitting point, swing speed/angle, movement speed/step frequency, etc. After comparing with the standard action database, the regularity of the action can be accurately determined - such as real-time reminders for adjusting the plan when the hitting point deviates, and providing strength training suggestions when the swing speed is insufficient; In mobile analysis, by evaluating the efficiency of movement and the rationality of routes, special training and landing point prediction strategies such as fast start, emergency stop and direction change are pushed for slow and unreasonable route problems.

As a scientific training support, the system first comprehensively collects training data, including hitting (frequency, success rate, proportion of types, speed/rotation), movement (distance, area frequency), physical fitness (heart rate, calorie consumption) and other indicators, and generates intuitive

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reports. The analysis process is divided into two categories: longitudinal comparison of data from athletes at different stages, and identification of changes in positioning techniques/physical fitness (such as investigating movement or strength factors when the success rate of serving decreases); Horizontally compare data of athletes of the same level/excellence to identify gaps (such as developing acceleration plans if the forehand speed is low). At the same time, algorithms such as association rule mining and cluster analysis are used to explore the correlation between training methods and technological advancements, or to classify athlete training needs based on data.

The system customizes a plan based on individual characteristics and data of athletes: first collect basic information (age, physical function, training years), and combine training/competition data to analyze technical strengths and weaknesses, physical condition (endurance/explosiveness), and competition style. Design specialized training for weak areas (such as arranging hitting and motion correction exercises if the backhand error rate is high); Allocate training based on physical weakness (lack of endurance to increase running, weak explosiveness to deepen squatting). At the same time, based on the competition objectives and time, simulation training will be added before the competition to enhance adaptability, and a recovery plan and next stage goals will be formulated after the competition.

3.2 System performance requirements

Accuracy is the core performance indicator of the system, which runs through the entire process of data collection, analysis, and solution development, directly determining the application value. In the data collection stage, the system uses high-precision equipment: high stability acceleration sensors, gyroscopes, and high-definition cameras are selected to accurately obtain hitting parameters, motion details, and ball trajectories, with errors controlled within a very small range; Combining multi-sensor fusion and image calibration algorithms to eliminate device errors and environmental interference, ensuring data authenticity. In the data analysis stage, the accuracy is improved by optimizing algorithm parameters. For example, after a large amount of training data optimization, the YOLO algorithm achieved a tennis recognition accuracy of over 95% in complex court environments; Using cross validation, model evaluation, and other methods to screen adaptation algorithms, such as selecting high-precision classification algorithms when predicting competition performance, to ensure reliable analysis results. In the planning stage, based on accurate analysis results and combined with professional training knowledge, the training content, intensity and other parameters are determined. For example, the physical fitness plan refers to the precise calculation of exercise volume based on physical fitness data, taking into account both effectiveness and safety.

Real time performance is the key to meeting real-time training guidance and can help adjust strategies in real-time. The system relies on high-performance hardware and parallel computing technology to improve processing speed, such as GPU acceleration technology to achieve real-time analysis of video data and quickly identify actions and ball trajectories; Reduce data read and write time through efficient storage and retrieval technology. The data transmission adopts 5G network and optimized protocols to reduce latency and avoid data loss. The system can complete a single action analysis within 0.1 seconds and push results and suggestions to the display screen or mobile device; Continuously monitor the status during training, adjust the plan in real time, and ensure targeted training.

Scalability support system adapts to future development and meets diverse needs. The architecture adopts a modular layered design, dividing the data acquisition layer, processing layer, analysis layer, and application layer. The functional interfaces of each module are clear, and expanding new functions (such as adding new sensors and algorithms) only requires modifying the corresponding module without affecting system stability. The system has good compatibility and can seamlessly integrate future new technologies such as advanced biosensors and VR/AR technology, enriching the training experience. Simultaneously supporting flexible configuration, providing high-precision analysis and customized solutions for professional athletes, simplifying the interface and adding entertainment modes for amateur enthusiasts, and adapting to different user needs.

3.3 User requirements analysis

Professional athletes require a system that focuses on high-precision technical analysis, personalized tactical guidance, and comprehensive physical fitness monitoring. At the technical analysis level, it is necessary for the system to accurately capture complex motion details, such as serving and throwing parameters, and the characteristics of the force exerted at the moment of hitting. After comparing with the standard movements of top players, improvement suggestions should be output to optimize the

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serving speed, rotation, and landing point control. At the same time, the success rate and error reasons of different hitting methods in the competition scene should be analyzed to enhance the ability to respond. In terms of tactical guidance, the system needs to mine opponents' technical weaknesses and tactical preferences based on their data, develop special strategies such as serving and receiving before the game, adjust the rhythm and attack and defense plan in real time during the game, and provide psychological guidance for key points. In terms of physical fitness monitoring, the system needs to collect real-time physiological indicators such as heart rate and blood oxygen, evaluate fatigue, and develop specialized training plans for endurance, strength, etc. based on this, balance intensity and rest, and avoid injury risks.

Amateur enthusiasts focus on usability, fun, and basic technology improvement. In terms of usability, the system needs to simplify the operation process, lower the threshold for use with a graphical interface and guidance, and use convenient devices such as mobile phones and cameras to collect data, eliminating complex debugging. On the level of fun, gamified design such as level tasks and virtual battles can stimulate training enthusiasm, establish personalized growth profiles to record progress, and enhance a sense of achievement. In terms of improving basic skills, the system needs to recognize basic movements such as grip and serve, compare them with standard movements, provide improvement suggestions through animated demonstrations and textual explanations, and provide real-time feedback on hitting strength, accuracy, and other information to assist in gradually improving skills.

Coach needs revolve around auxiliary teaching, team management, and training effectiveness evaluation. When assisting teaching, the system needs to integrate teaching videos, animated demonstrations and other resources, support coaches to play teaching content, decompose actions, and combine real-time demonstration functions to provide on-site guidance. In terms of team management, the system needs to centrally store athletes' personal information, training and competition data, making it easy for coaches to view individual progress and physical fitness status, while providing team data analysis to support team training and tactical development. In the training effectiveness evaluation stage, the system needs to generate evaluation reports on technical improvement, physical fitness improvement, etc. by comparing data from different stages, to assist the coach in optimizing the training plan.

4. System architecture design that integrates computer vision and big data analysis

4.1 Overall system architecture design

The architecture design of the intelligent tennis training system follows three core principles: high-performance principle. By using multi-core CPUs, high-performance GPU hardware, and parallel computing technology, it optimizes the computation speed of object detection and action recognition algorithms, ensuring real-time processing of massive video and sensor data to meet the real-time training requirements; The principle of scalability adopts modular and layered design, dividing the system into independent modules and setting standard interfaces. When adding new functions (such as connecting new sensors) or expanding data processing capabilities, only the corresponding modules need to be upgraded, without affecting the overall stability of the system; The principle of reliability relies on redundant design, distributed storage, and fault detection and recovery technology. For example, a multi node distributed storage architecture can be serviced by other nodes when a node fails, and real-time monitoring and automatic diagnosis and recovery functions can reduce system downtime. The system adopts a four-layer architecture consisting of a data acquisition layer, a data processing layer, a data analysis layer, and an application layer, with each layer working together to form a "data acquisition processing analysis application" closed loop. The data acquisition layer serves as the bottom layer, ensuring comprehensive and accurate data through high-definition cameras arranged in multiple locations (capturing tennis trajectories, athlete movement details) and sensors such as heart rate and acceleration (collecting physiological indicators and exercise parameters); The data processing layer is responsible for preprocessing and feature extraction tasks, cleaning the data through threshold setting and filtering algorithms, normalizing and unifying dimensions, and extracting feature points using SIFT algorithm after decoding the video data; The data analysis layer is the core, using clustering analysis (classifying athletes), association rule mining (revealing the relationship between training and technology), and classification algorithms (predicting competition performance) to mine the value of data; The application layer serves as an interactive interface, providing coaches with training reports and opponent analysis tools, pushing personalized solutions and real-time error correction suggestions to athletes, and supporting data query and statistics to assist in technical improvement.

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4.2 Computer vision module design

The computer vision module of the intelligent tennis training system adopts a multi position layered strategy in camera deployment: high-definition cameras with wide-angle function are installed at the four corners of the tennis court to cover the boundary area and capture the trajectory of the tennis boundary and the athlete's corner movements; This study installed a camera at each end near the net to monitor the serving/receiving area and obtain data on serving actions, ball trajectories, and receiving times; The aerial deployment of bird's-eye cameras provides panoramic images, supporting the analysis of athletes' overall movement routes. Some cameras are equipped with adjustable brackets to meet the requirements, and key scene cameras have high-speed continuous shooting function to ensure that critical moments are not missed. In the process of image acquisition and transmission, the resolution of the high-definition camera is set to 1920×1080 pixels or above, the frame rate is ≥ 60 frames per second, and the automatic exposure and white balance functions are enabled to ensure clear images and adapt to different lighting conditions; The transmission adopts a mixed mode of "wired+wireless", and the cameras in the processing center achieve high-speed transmission of hundreds of megabytes per second through Gigabit Ethernet. For difficult to wire or mobile cameras, the delay is controlled in milliseconds using 5G network. At the same time, H.264/H.265 encoding is used to compress data, combined with verification and retransmission mechanism to ensure data integrity. Object detection adopts the YOLOv5 algorithm optimized with massive training data, which quickly identifies tennis balls and athletes and predicts bounding boxes through image grid partitioning, feature extraction, and classification; The target tracking adopts the "SORT algorithm+appearance feature matching" scheme. The SORT algorithm is based on Kalman filtering and Hungarian algorithm to predict the target motion state and match the new frame detection results. It introduces color histogram and HOG features to assist in solving occlusion or temporary loss problems, improve tracking accuracy and robustness, and ensure continuous tracking of tennis trajectories.

4.3 Design of big data analysis module

In the design of the big data analysis module of the intelligent tennis training system, the data storage adopts a collaborative architecture of "relational database+distributed file system": the relational database (such as MySQL) stores structured data such as athlete basic information and training plans, and relies on clear data structures and SQL operations to achieve efficient addition, deletion, modification, and query, such as quickly filtering data through tables containing fields such as "athlete number, physical fitness indicators"; Distributed file systems (such as HDFS) store unstructured data such as video images and sensor raw data. With high fault tolerance and parallel read-write capabilities, large files are stored in blocks on multiple nodes, improving data reliability and read speed; At the same time, the file path and associated information (such as athletes and scenes corresponding to videos) of HDFS data are stored in a relational database through an index table, achieving fast association access between the two types of data. The data analysis process is divided into four stages of closed-loop processing: the data extraction stage uses SQL to filter target structured data from MySQL (such as training records of a certain athlete during a specified period), and locates unstructured data in HDFS based on the index table; In the data conversion stage, structured data is cleaned, denoised, and normalized, while unstructured data is decoded and features (such as action feature points) are extracted; Data analysis, as the core process, selects clustering analysis (to classify athlete types), association rule mining (to analyze the relationship between training parameters and competition results), classification algorithms (to predict competition performance), and other methods to mine data patterns according to the objectives; In the data visualization stage, tools such as Echarts and Tableau are used to visually display the results through line charts (showing trends in technological advancements) and heat maps (presenting active areas on the field). In terms of data mining and machine learning algorithm applications, clustering analysis (such as K-Means) is combined with multidimensional data to divide athlete clusters (such as "strong serve bottom line attack type"), assisting in the development of targeted training plans; Neural networks (such as MLP and CNN) rely on nonlinear mapping capabilities to construct models and input multiple types of data to predict game performance (such as win rate); Association rule mining (such as Apriori) has discovered patterns such as "when the intensity of backhand training reaches a threshold, the success rate of backhand in matches increases", optimizing training content and intensity to reduce injury risks.

5. Conclusion

This study successfully constructed an intelligent tennis training system architecture that integrates

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computer vision and big data analysis, achieving research results with practical and theoretical value. At the application level of computer vision technology, precise tracking of tennis trajectory and efficient recognition and analysis of athlete movements are achieved: YOLO series object detection algorithms are used to quickly and accurately locate the position of tennis and athletes in complex court environments, providing reliable data support for action analysis; Build a human skeleton keypoint detection model to capture core features such as hitting movements and moving steps in real-time.

In terms of the application of big data analysis technology, establish a multidimensional collection system that covers athlete basic information, training data, competition data, and physical function data; This study utilizes data mining and machine learning algorithms to conduct in-depth analysis of massive data, achieves athlete classification through clustering analysis, and develops personalized training plans based on category features to enhance training targeting; This study utilizes association rule mining to reveal the intrinsic correlation between technical movements and competition results, providing a scientific basis for optimizing training plans; It constructs an evaluation index system and prediction model to achieve real-time evaluation of training effectiveness and future performance prediction, supporting scientific training decision-making.

The system adopts a four-layer architecture of "data acquisition layer data processing layer data analysis layer application layer", which achieves collaborative processing of data throughout the entire process through technological integration, providing personalized scheme recommendation, real-time training feedback, action error correction and other functions, significantly improving the level of intelligent training. Compared to traditional systems, it breaks through the limitations of relying on coaches' subjective experience, achieves precise quantification and scientific analysis of training data, objectively guides and meets the personalized needs of different athletes, and real-time feedback function helps athletes dynamically adjust training strategies, accelerating the improvement of technical level.

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