MANAGEMENT IN THE PREVENTION OF MALPRACTICE IN ELECTRONIC REFEREEING SYSTEMS IN SPORTS

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PURPOSE

In the twenty-first century, the popularity of sports is growing day by day attracting an increasing number of people curiously watching their favorite players in all disciplines on all continents. With the increased share of sports on the global economic market, there is a growing interest in improving the game both in skills and in introducing new technologies. It is the new technologies that bring a novel long-awaited wave of attractiveness and opportunities for marketing and business.

The main feature of the existing systems is the extremely high financial cost of use, as well as the veil of secrecy with which the used technology is covered. Therefore, most sport events could not be covered by these systems for many years. The chance of potential new systems increases with possible multipurpose use. In the world of modern sports, where the stakes increase with each passing minute and where one wrong referee decision for the ball means a change in "sports luck", we rely on the modern technology ensuring that judges' decisions are impartial.

The component of human error in making important decisions is often decisive. There is a great need to implement technology that would reduce the chances of human errors in such important decisions. Furthermore, technological systems

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provide the analysis and improvement of the game. Systems based on such technology are used to collect a variety of data and use it for a number of purposes not restricted just to the sport area. Today, the most common applications of such systems are in tennis (Official Hawk-Eye Challenge System), football (*VAR*) and cricket, then for police and military purposes (Borović et al., 2018), as well as in the production, industrial branches of society such as the automotive industry. Apart from that, sport bet facilities certainly have impact on decisions of such electronic computer systems.

The aim of the authors of this paper was to discover potential malpractice in the use of these electronic systems and mark the points of potential malpractice, and also propose a new malpractice-prevention model on lowering the damage done by tampering the results.

EXISTING SYSTEMS OVERVIEW

The system that has attracted most attention so far and gained most popularity is the famous Hawk-Eye system, represented in almost every country in the world. At the same time, it is the adopted name of the first technology used to detect the position of objects in space, primarily in sports. It is a complex computer system that is officially used in making referee decisions in sports, such as: tennis, football, cricket, Gaelic football, bocce and basketball. This system graphically simulates the visual tracking of the path of a moving ball and shows the calculated record of the statistically most probable path in the form of a moving image, i.e. computer *3D* animation.

The Hawk-Eye system was developed in Great Britain by Dr. Paul Hawkins at the beginning of the 21st century, in 2001. At the beginning of 1999, he began research at the British company Roke Manor Research Ltd, founded in 1956, which already had more than 30 years of professional experience in the fields of image processing. The project was led by Dr. Paul Hawkins and funded by the Television Corporation, (Roke Manor Research Limited, 2019). The current owner of the Hawk-Eye system is Hawk-Eye Innovations Ltd. from the UK which has been part of the Japanese corporation Sony since March 2011. (BBC News, 2011)

The theoretical basis of the Hawk-Eye system is the principle of triangulation using visual images and weather data collected from a large number of high-speed video cameras that are placed at different predetermined places and angles around the observed terrain. Therefore, if we talk about tennis, there are ten cameras installed. The system quickly processes signals from video cameras. A predefined model of the control area with precise dimensions is given in the system before the start of signal collection, and includes important data on the basic rules of the observed game. Precisely, on each individual image from the video camera, the system identifies a group of pixels that correspond to the image and appearance of the ball. Then, using modern computer equipment, primarily high-speed personal computers, the *3D* position of the ball on each individual image is calculated while simultaneously comparing images in two physically separated video cameras at the same time. Thus, it is possible to make an accurate record of the exact path of the ball in space in a large series of images and mathematical calculations. It is also important to note that the system can predict the future trajectory of the ball using mathematical approximations and statistical calculations. In the end, based on the data recorded in the databases of the predefined game area and the video camera system, the exact place where the ball touches the observed terrain is calculated at the height of 0. This is also the final expert goal of all calculations. By simulating, system generates the *3D* animation - Automated Referee Decision, as seen in Figure 1.

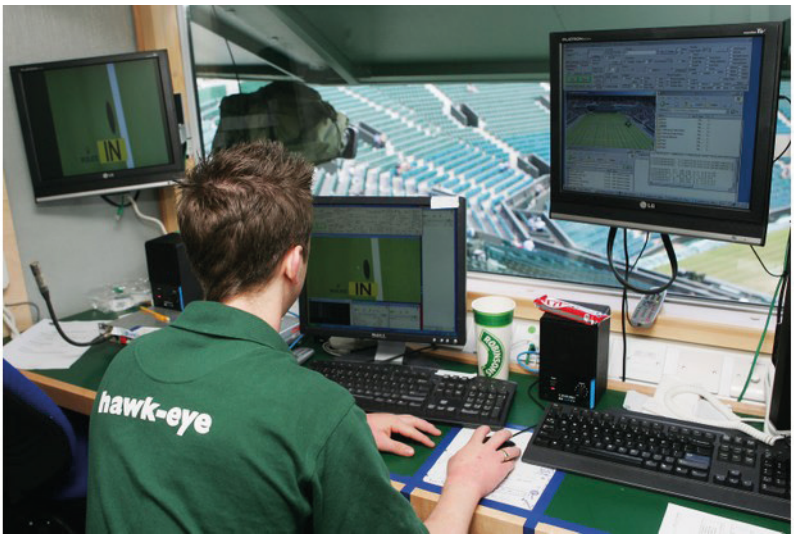

Figure 1 – *Hawk-Eye computer system, operator and 2 of 10 computers*

ORIGINAL OBJECT TRACKING SYSTEM

During 2010, a completely new advanced tracking system for moving objects in sports was designed by the authors of this research paper. (Borović, 2019)

The advanced tracking system has the following functional parts, independent subsystems, each of which has certain roles:

- Signal collection subsystem (video-cameras, computers and computer network)
- Subsystem for advanced detection of objects and positions in three-dimensional space
- System for *3D* simulation, animation and graphical display of calculation results

In the following years, 2015 and 2019, a number of professional experiments, thorough tests and comparative analysis have been done through these sequential phases:

- Simulation of the whole system
- Home system testing
- Testing the system in real conditions
- Preparation of documentation for official testing to gain the tennis federation certificate

The basis of the system are video cameras with appropriate technical characteristics placed in precisely defined and predefined places together with software applications for object detection and tracking of the ball. Up to six video cameras placed around the surveillance area were used at the locations where the experiments and tests were performed. As seen in the following figure, in Figure 2, we have 10 video cameras set up around the monitored play area together with separate units:

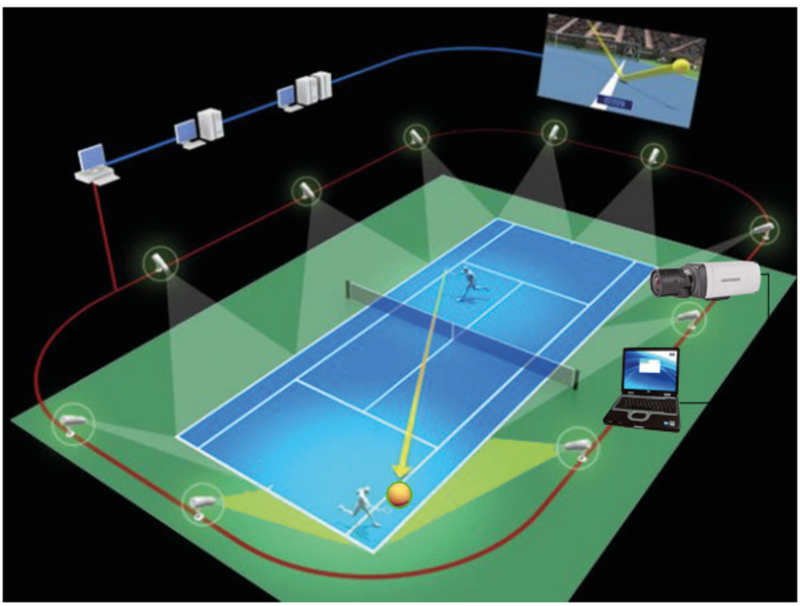

Figure 2 – *Video-cameras set around the game area*

The first subsystem, an independent unit, is a mandatory system of video cameras and technical equipment that monitors and records a sports match or training. It is possible to record other areas with different tasks. At the same time, this system collects signals in real time on a certain larger number of computers according to the following model:

1 camera = 1 associated computer.

The second part consists of a subsystem that determines the position based on the image from the camera (on-line) or on the image from the recorded video (off-line) and simulates the trajectory of the observed object in space, e.g. a ball in sports. The system consists of software developed in the Microsoft programming environment with program code written in *MS Visual Studio C ++* and *C #* 98, 2010, 2013 programming languages and uses the *AForge.NET* framework for ball detection and tracking, with the addition of the original author's algorithm. Testing and practical implementation was done for the system of detection and monitoring of objects based on the recorded video. By the way, the basis of this system for the detection and monitoring of moving objects in space are new, up-to-date improved publicly available mathematical algorithms with the application of mathematical principles. The original, designed system is shown in Figures 3 and 4 (Borović et al., 2019).

The third independent functional part consists of a system that, based on the calculation of the path of the object in space, performs a graphic simulation of *3D* animation in an attractive and visually appealing way. Software application for accurate, photorealistic *3D* visual animation was developed in *MS Visual C ++* programming language using *OpenGL* graphics library.

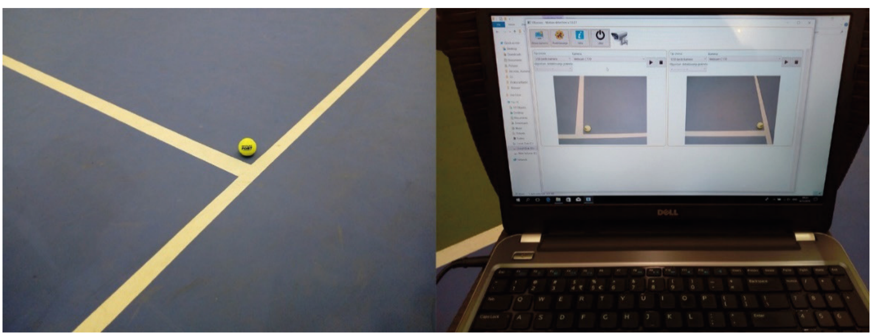

Figure 3 – *Ball view, camera test and the original application*

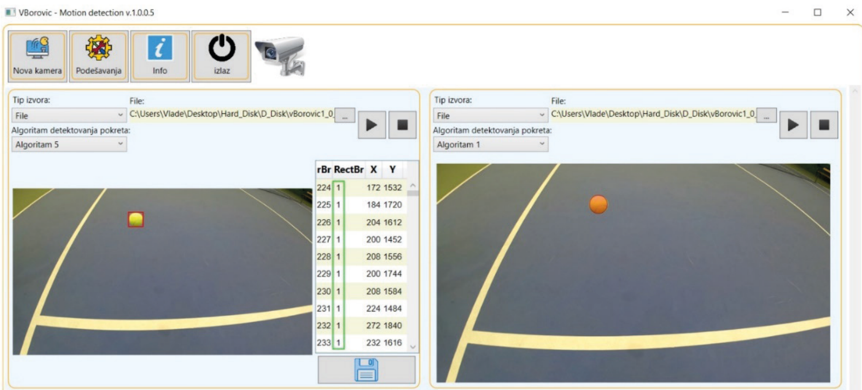

Figure 4 – *Ball detection in the tracking system*

DESIGN/METHODS/APPROACH

If a simple question is asked: *Are existing systems infallible?* The answer to this question is precise: *No!*

There are three dimensions to this issue:

- Technical
- Psychological
- Intentional

Based on numerous publicly published articles, expert debates, dedicated studies and statements of numerous actors, primarily in the world of tennis, football and cricket, the authors of this paper can say with certainty that all existing systems in the world have a certain margin of error and potential making the wrong electronic referee's decision accompanied with malpractice (Phys. Science X, 2008). As the authors above all know the process of functioning of this technology down to the smallest details, technical approach and procedures for detecting and tracking moving objects in space, it is clear that potentially and often detection errors occur, first of all positions of objects and graphical simulations of the path of their movement.

Perhaps these claims are best demonstrated by the public, written comment of one forum participant on one of the official websites of the manufacturer and owner of the Hawk-Eye system (pscaife3, 2016): "But none of Hawk-Eye's iterations show such a level of ground contact. Is this a design feature or the system is not able to show the actual level of contact with the terrain? Ten centimeters is a considerable distance and will vary depending on the type of tennis kick and the type of playing surface. The definition in Wikipedia also states projected (and predicted), but incorrect levels of contact." The comment was given on an accurate video recording of the functioning and explanation of the functioning of the mentioned system for position detection and tracking of moving objects which are frequent situations in the difficult detection of the exact contact and position of the observed object with the ground by the method of projection and prediction, and not entirely on the basis of images from video.

As clearly stated in an article from 2013 in a renowned magazine (Hawk-Eye at Wimbledon, 2013), the mentioned system is not infallible as spectators of sports events think. The question is how accurate the Hawk-Eye system really is. Back in 2008, a scientific paper entitled “Public Understanding of Science” (Collins & Evans, 2008) was published stating that the way in which the system presents its calculations and analyses in sports can easily lead people to mistakenly conclude that graphic, animated representations of results are a real picture of what actually happened. That system is an excellent opportunity to discuss uncertainty, reliability intervals of the detection process and mathematical-statistical visual delight.

It is also noted that public understanding of science, although approaching expertise only on rare occasions, can be improved in terms of science and technology processes. As the public understands and accepts measurement errors, the confidence interval can also be improved if electronic systems for referee decisions present the results of their calculations differently.

Psychologically, there is a great chance and danger that this system, in the way it is used, inadvertently leads technically insufficiently informed viewers to overestimate the ability of technical devices to resolve misunderstandings among people because measurement errors are not publicly highlighted. Thus, for example, virtual *3D* simulations and photorealistic animations can as reconstructions of events be easily used to show “what really happened”.

In the mentioned scientific paper (Collins & Evans, 2008), several real documented examples of controversial situations of using this system and the results of calculations with potential errors in international tennis tournaments are given. It has been mentioned several times that the way in which the results of this system are used and presented today can lead the public to the wrong conclusion about the degree of reliability of scientific measurements – it has been noticed for a long time, since the beginning of its application in sports. The authors of the mentioned paper believe that the lack of understanding of the possibilities and reliability of this system could be reduced by including information on the potential error of measurement and calculation that are presented graphically.

People and technical devices make two types of mistakes:

- Systematic errors
- Random errors.

The first are mistakes that are repeated and have a similar effect every time. The causes of such errors can often be technically understood and their negative impact on calculations can be predicted and compensated.

Other types of errors cannot be predicted except that their typical magnitude can be estimated mathematically using probability and statistics, the shape of the random distribution. They cannot be compensated, but can be taken into account when assigning confidence levels to the measurement and detection process.

Therefore, it is proposed to introduce the principle of automatic decision-making, which determines how computers, software and electronic decision-making systems should be used in sports with the obligatory mentioned types of errors. In the mentioned mathematical discipline, probability and statistics, error dispersion is usually present as a standard deviation, exception. Following these principles, it can be assumed that in 5% of the predictions of the trajectory and results of the Hawk-Eye system, which is 1 in 20, the error in the calculation could be greater than 9 millimetres, while in 1% the error may be even greater than 11.7 millimetres.

A series of publicly available articles on the Internet have raised a number of doubts and controversies about the accuracy and reliability of the Hawk-Eye system, with numerous errors in measurement, detection and *3D* graphical display of calculation results. Some estimates say that the system is accurate in only 60% of cases measured and used in tennis (Thomas, 2019) (Pugh, 2019) (Braun, 2012).

Even the company Hawk-Eye in its technical paper (Hawk-Eye Innovations, 2016) explains and specifies the following details with reference to errors in detecting the position of objects in space: "As shown in 2005 during ITF testing, Hawk-Eye was the first system to pass a series of rigorous tests and conditions, which means it was the first electronic system to be officially accredited. Practical results showed that the system had an average error of 3.6 mm compared to the high-speed camera located on the playing surface."

It is further claimed that, with the advancement of technology and software and their application, together with a decade of experience at major sporting events, their electronic refereeing technology has an average error of 2.6 mm.

The factors most affecting the errors in measurements and calculations in the conditions when the terrain is outside are also listed (i.e. sun, shadows, wind).

The paper (Collins & Evans, 2008) also suggests that more information should be published on the uncertain reliability and accuracy of measurements and calculations, primarily for television audiences and viewers, in order to more honestly show variations in the possible correct trajectories of the ball. They suggest, for example, that the predicted location of the ball contact with the court and the confidence intervals surrounding it be shown, both the location and the electronic referee's decision (if 95% it means there is only a 5% chance of error, i.e. the ball indeed fell outside this larger area of prediction).

In conclusion, the authors of this paper, without a subjective view, due to the potentially high probability of errors in tracking moving objects in existing systems in the world, can realistically agree with the need to show calculated graphical results and predicted paths together with the level of reliability, certainty and possible errors as seen in Figure 5. That would be quite fair to the public.

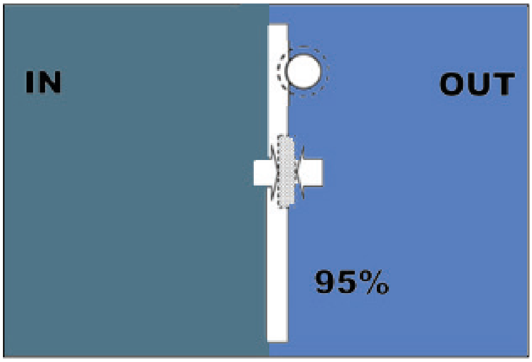

Figure 5 – *Indicated level of trust in e-referee system*

This would not only more accurately reflect the limitations of this technology but could potentially teach complex mathematical concepts and principles of statistics and probability to a large number of people. Hawk-Eye could still provide a "good ball" or "out" response to a request from the in-game referees, but the likelihood is correct, the right answer would also be clear to everyone, especially TV viewers and viewers around the field as they watch live match, which also form public opinion.

As for the testing of the original system in real conditions, first of all it included the preparation of the tracking system, then the demanding installation of all parts of the system in the agreed areas, courts for playing tennis. Basic, prearranged tests were performed. After a lot of negotiations, two physical locations in Belgrade were agreed upon for testing the system in real conditions. These are the following two sports fields:

- Professional tennis courts in Jajinci, Đoković tennis school, and
- Gemaks tennis courts in Belgrade, Challenger tennis tournament.

Specific practical testing was performed on video-recordings from web cameras with a resolution of 1 megapixel and a speed of 30 frames per second (*fps*), using authors' original system.

In one experiment, X and Y positions (in pixels) were calculated, the ball movement detection and contact with the field line were detected on the video camera images in the plane of that line. In a certain frame, the ball made contact with the field, which was documented in the image from the video camera. It shows the importance of the correct selection of the ball movement detection algorithm suitable for real game conditions.

Based on the obtained results, it can be concluded that:

- A new algorithm for the ball detection gives better results in tracking moving objects in tennis and
- Potential error in electronic decisions of the older version of the algorithms is significantly higher than in the new one.

The possibility of malpractice and errors in position calculations is high if the appropriate technical detection algorithm is not selected/used.

FINDINGS

In the following section, we give two examples where potential malpractice has been done, or could easily be done, stating parts of the system very vulnerable to malpractice actions and tampering the results.

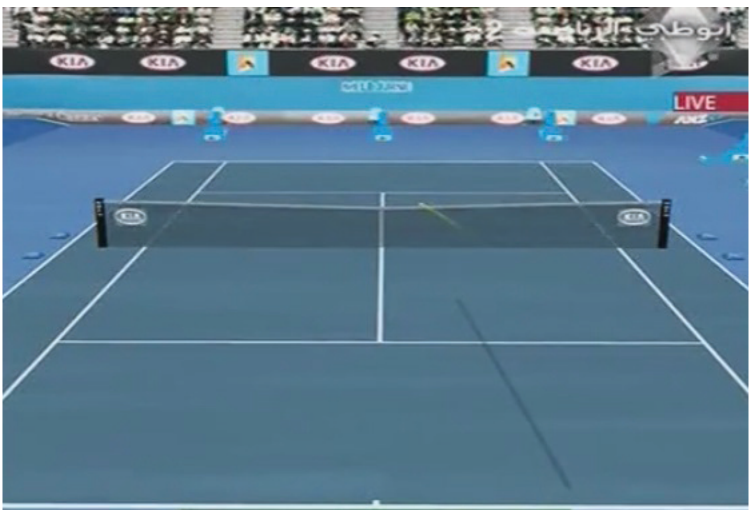

Figure 6 – *Example 1: Incorrect 3D animation and graphics*

As shown in Figure 6, an evident, probably intentional *3D* graphical error leads to a wrong electronic referee decision. It happened in Australia Open tennis tournament 2011. The calculation of the trajectory of object in space in the older

Hawk-Eye system from 2011 was tampered. The vague and potentially incorrect trajectory of the ball in the surveillance area is clearly visible. The inaccurate *3D* shadow that is rendered in real time and the so-called flickering within the net as well as low-resolution and quality textures, poor texture mapping in *OpenGL* and especially insufficiently clear border areas, a line on the tennis court in the space monitored by this system. Simply, the shadow does not follow the exact ball trajectory in *3D* space. The detected position and graphically presented ball are not correct. Thus, in almost every use of the system in making electronic refereeing, it was additionally possible to make a mistake in the decisions.

Insufficient precision of the field lines, graphic areas that are on the border, lead to possible minimal mistakes when presenting the referee decisions. By the way, the lines that mark the area of the game in all sports are the most important areas that are monitored in space by these systems. Simulation of calculation results through visual *3D* graphic presentation potentially shows the public and the professional public incorrect results of referee decision-making because errors in the detection of position and movement of objects in space are possible, although all mathematical calculations are correct. In other words, a graphical simulation misrepresents accurate results. A ball in sports, for example, that was not in the out, i.e. it was not out of line in the observed predefined area at the time of contact with the terrain, as described in the Hawk-Eye system, *3D* animation reproduces graphically incorrect result, as if it was out, i.e. outside the observed line in the field.

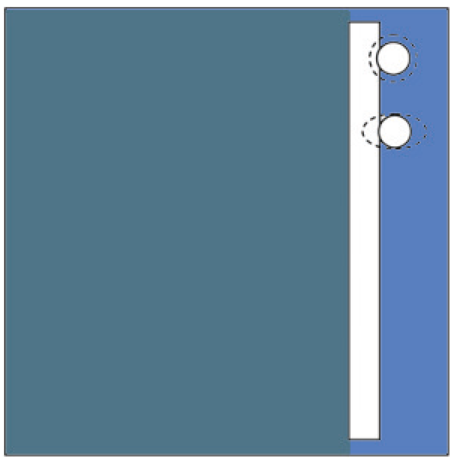

Figure 7 – *Example 2: Measurement and detection error*

It is clear in Figure 7 that the uncertainty of detection is shown by dashed lines so that the potential contact of the ball with the ground, i.e. tennis terrain can be anywhere within a dashed-line circle. The upper, slower ball falls on the field of almost 90^{o}. Trace detection can be with a big error in the case of the second lower ball in the picture due to fast movement and error in the direction of movement. The error can then be within a dashed ellipse, of arbitrary, highly dependent shape. Furthermore, the question is what the error limit in case of fast movement of the ball is.

Therefore, the database with the detected ball *3D* coordinates could be easily tampered and the results misused.

The scientific paper (Collins & Evans, 2008) stated that in direct contacts with the experts of the Hawk-Eye team and the *ITF* (International Tennis Federation) rather vague and incomplete tolerated error limits and percentage calculations of the possibility of measurement and calculation errors were obtained.

ORIGINALITY/VALUE

Numerous professional tests and research in modern sports are conducted every day (Bacvarevic Berjan et al., 2012) (Bozic, Pazin, Bacvarevic Berjan, 2019). Large number of collected data can be used to improve the game play, especially in tennis (Petkovic, Jonker, Zivkovic, 2001), and it is also subject to tampering, ending in false conclusions. Technical systems collect the information that can easily be changed intentionally or by a system error.

There are two vulnerable parts of the electronic tennis challenge system identified by the authors of this paper that can be used for intentional malpractice:

- *3D* animation, graphical display of a ball trajectory
- Database with calculated positions info (object x, y, z coordinates)

In the first case, the system operator, could easily change the graphical display of the calculated positions of the ball, therefore change the real trajectory to non-existent virtual path, causing the wrongful e-referee decision (in / out). This can be done in the *OpenGL* code.

The second part involves tampering with database, again by the system operator, changing the correct mathematically calculated positions. It also causes the wrongful e-referee decision. Both malpractice actions can be done unnoticeably.

If we speak about the management in the prevention of malpractice, the authors propose a management algorithm, a prevention model as shown in the following Figure 8, which can be applied to the electronic referee process.

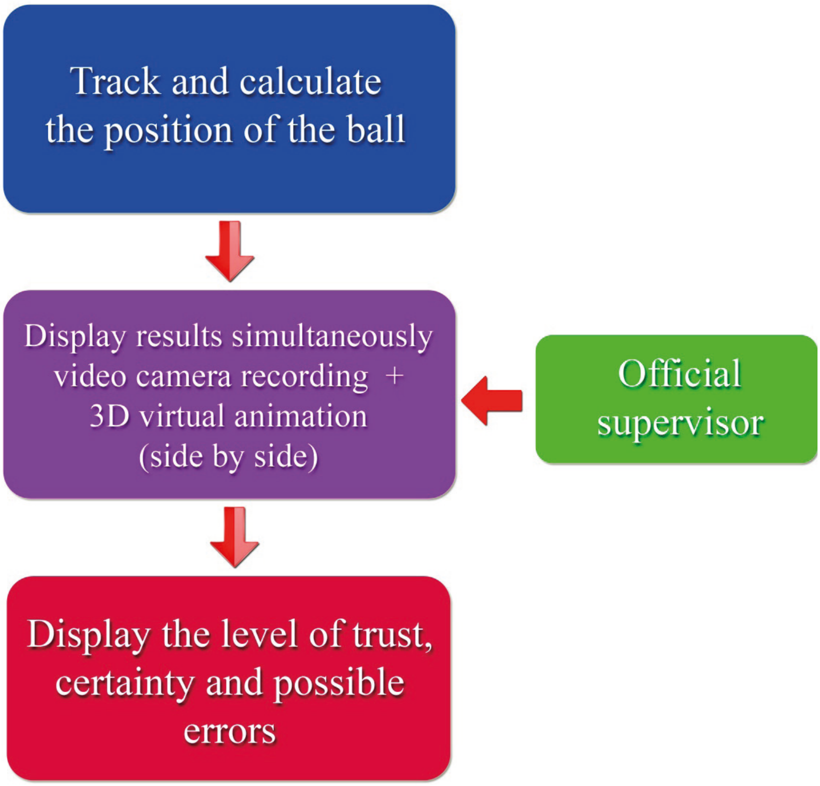

Figure 8 – A malpractice-prevention management model

Following these steps, we can assure higher trust in the system results, public objectivity feeling and lower the possibility of intentional malpractice:

- Track the ball in space, detect, measure and mathematically calculate all positions, in the video-camera images, predict the flight path and contact with ground. All data are stored in the system database.
- Official supervisor restricts database access and monitors the use of *3D* virtual graphics system with animation showing the ball trajectory. In the same time, both *3D* animation and a video recording from the independent high-speed *UHD* video-cameras are shown to the spectators, TV audience and public. It shows the electronic system flight trajectory and ground contact.
- When the e-referee decision is shown, it must be accompanied with the adequate level of trust, certainty and possible error margin numbers and in each and every challenge call and use of the system.

By using the proposed model, we lower the possibility for intentional malpractice, especially with data tampering in the database ball positions with predictions and misusing the *3D* animation results display.

CONCLUSION AND RECOMMENDATION

Modern technology electronic refereeing systems are used in almost every sport all over the world. The possibility of malpractice is very high. Errors are made by the technology or by a human, sometimes intentionally.

The authors described in this paper the used technology in every step, made the systems overview, additionally describing an original new system. The weak spots of systems are given, public doubts on the objectivity of electronic decisions with stated possible malpractice areas, actions, examples and places in the technology that can easily be used to tamper the results, so the end decision might be wrong.

We proposed a new management model for malpractice-prevention and gave strong recommendations for a tamper-proof, a safer and more objective use of electronic refereeing systems in sports.

The overall authors' recommendation is - when the decision is shown, adding a real-time video-camera recording also include adequate level of trust, certainty and possible error margin numbers in public display.

It would be quite fair to the public.

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