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Comprehensive Study on Sports Technology

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Abstract

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The aim of this thesis is to explore the technologies used in major sports, from the beginning to their present time. The idea is to understand the science behind the technologies used in sports and hardware implementation and software implementation with the use of algorithms. This research also looks at the utilization of Artificial Intelligence in modern sports prediction, the essential role of wearable technologies for professional teams and the simulation technology emulating the sports has emerged as training and recreational platform.

Although the accuracy of the technologies used in sports has improved drastically compared to last decade, problems still arise with the complexity of the technology.

Keywords: Technology, Innovation, System, Data

Contents

List of Abbreviations

AI:	Artificial Intelligence
COVID:	Coronavirus disease
DRS:	Decision Review System
DRS:	Drag Reduction System
EEG:	Electroencephalogram
F1:	Formula One
FIFA:	Fédération Internationale de Football Association
GPS:	Global Positioning System
LBW:	Leg Before Wicket
LED:	Light Emitting Diode
LiDAR:	Light Detection and Ranging
OERT:	Optically Enhanced Radar Tracking
RFID:	Radio-frequency identification
VAR:	Video Assistant Referee

1 Introduction

Sports are not just a game, they are a vital part of people lives offering a much-needed escape from daily stress, providing a sense of release and relaxation. People are brought together in sports and lifelong friendships are created providing a sense of belonging to a community. Sports require discipline, dedication, and hard work, teaching the value of perseverance and teamwork, skills that can be applied to all aspects of life.

The rapid evolution of technology has significantly impacted the world of sports, resulting in a more immersive, analytical, and enjoyable experience for fans. However, some followers remain sceptical of these advancements, preferring traditional methods.

The aim of this thesis is to explore the various technologies used in sports, from the beginning to their present time. This includes an overview of how sports were played prior to the development of technology, and how every innovation in technology has facilitated the elimination of errors and inaccuracies. This thesis explores the technologies used in football, cricket, tennis, athletics, swimming, Formula One etc.

The idea is to understand the science behind the technologies used in sports and hardware implementation including electronic components, cables, and sensors and software implementation with the use of algorithms.

In addition, the intention of this research is to learn the utilization of artificial intelligence in modern sports prediction and the essential role of wearable technologies for professional teams. The thesis will look at the major sports technologies along with their application in different sports.

2 Background

In the beginning, before the invention of radio and television, fans of sports team could only watch the game in the stadium with limited capacity of thousands of people. Followers missing the game could only find out the results from the words of spectator after the game or from the sport column written in the newspaper next day.

Prior to the development of modern technologies in sports, decision-making was largely dependent on subjective assessments of officials, which frequently resulted in controversial and sometimes incorrect calls.

In athletics, for example, a false start was determined entirely on the subjective view of the starter. Line judges made conclusions in tennis based on their view of the ball, which can be challenging to see when considering the speed and compression of the ball on ground.

Similarly, referees made key decisions in football based on their own judgment which varied in comparison with other referees, which was frequently questioned by players and fans. There was little consistency in foul decisions as one referee would call a foul for a small contact in the penalty box awarding a penalty and other referee did not even consider it calling a foul.

Sports has become more reachable around the world with invention of radio and television in which both can broadcast the sports instantaneously with commentary. With more viewings, all the mistakes made in the game has been greatly criticized.

All these past incidents resulted in the need for a more unbiased and precise decision-making method, which eventually led to the implementation of technology in sports. The introduction of technology in sports has been a significant development in the way decisions are made. It has brought a more objective and accurate approach to decision-making, reducing the potential for controversy, and ensuring fair outcomes in sporting events.

3 Technology in game

3.1 Football Goal-line technology

The development and implementation of goal line technology in football originated from a highly controversial match between Germany and England during the 2010 FIFA World Cup. During the match between Germany and England, Germany held a 2-1 lead when England player Frank Lampard hit a shot from outside of the penalty box that bounced off the crossbar and over the line as seen in Figure 1, before rebounding back into play, but the goal was not awarded as the assistant referee failed to signal for it.

This incident occurred just 53 seconds after England had scored a goal, and had the goal been awarded, it would have given England significant momentum. Despite Lampard's non-awarded goal, Germany went on to win the match 4-1, resulting in England's exit from the World Cup. The incident fueled further calls for the use of technology in football, which FIFA had previously rejected. [1]

Figure 1. Ball crossed the line, but no goal was awarded.[1]

Responding to the several refereeing errors at the 2010 FIFA World Cup, FIFA initiated a series of authorized tests in July 2011, which ultimately led to the adoption of the current game systems.

During the initial testing phase, various goal-line technology systems were evaluated, and the primary criterion for approval was that the match referee must be informed within one second of the incident if a goal has been scored, as mandated by FIFA regulations. This information is transmitted through both a vibration and visual signal to the referee's watch. It is essential that the referee receives this indication, regardless of their position on the field of play or within the technical areas.[2]

After the initial testing, two out of the eight proposed goal line systems - Hawk-Eye and GoalRef - were selected for the second stage of testing. In 2013, GoalControl received a license for professional matches and was selected for use in the FIFA Confederations Cup of the same year. In the following sections, these goal line technologies will be explored in more detail.

3.1.1 GoalRef

The GoalRef system uses electromagnetic fields and RFID technology to detect when a ball has fully crossed the goal line. The system consists of a reader with an exciter loop antenna and receiving antennas around the goal frame. The ball contains loop antennas that reflect back a portion of the electromagnetic field, which is received by the receiving antennas around the goal frame as seen in Figure 2.

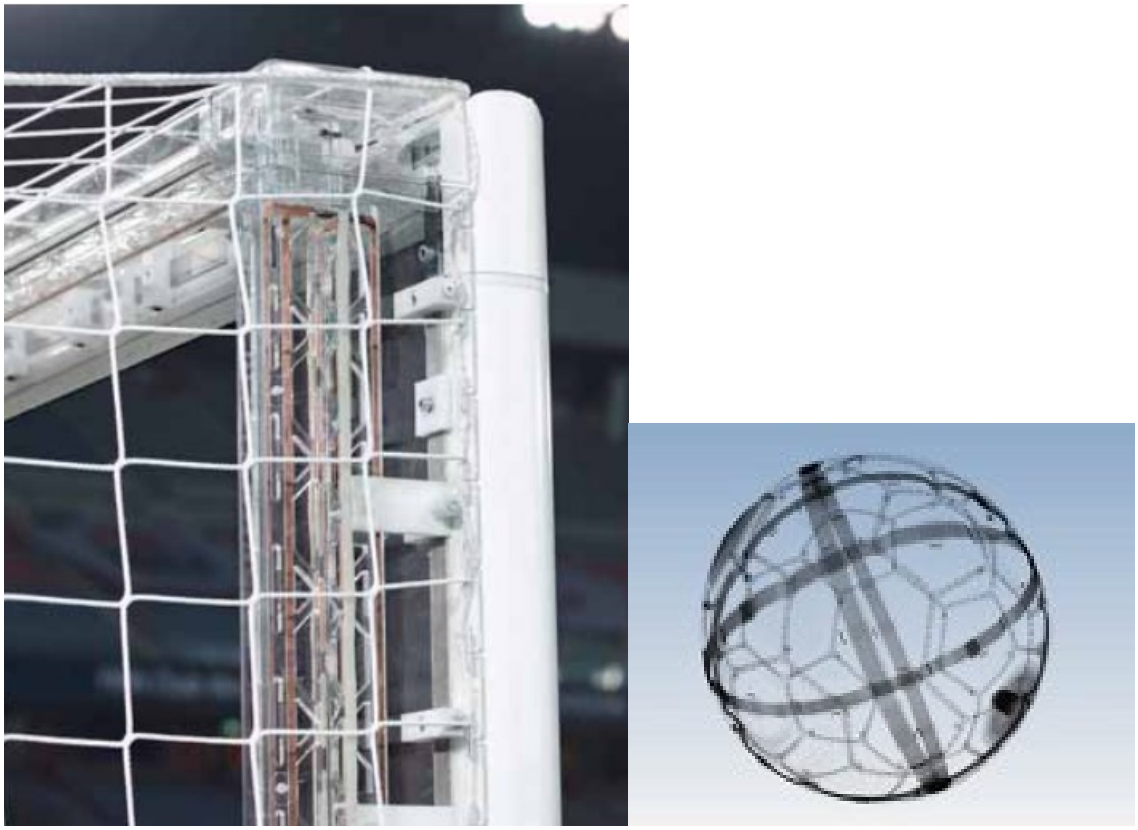

Figure 2. Goal frame with GoalRef antennas and X-ray vision showing 3 coils inside ball. [3,4]

The system can determine whether the ball has crossed the line inside or outside the goal frame based on the amplitude of the frame-antenna component. The receiver stage in the reader analyzes the signal and triggers a communication link to the referee watch. The ball contains three orthogonally arranged loop antennas as shown in Figure 2, to achieve detection properties that are rotationally invariant.[5]

3.1.2 GoalControl-4D

All stadiums use the same principle: seven cameras are positioned around each goal to create the sensory system of GoalControl-4D goal line technology. Each end of the field is covered by a line of cameras that provide complete coverage of the penalty area. When the ball enters the penalty area, it is automatically picked up by the seven cameras at that end of the field and tracked continuously

in three dimensions in real time as can be seen in Figure 3. Up to 500 image sequences are captured per second by each camera during action situations.

Two high-performance computer stacks located in the server room receive the image sequences in real-time via fiber-optic cable. Using specialized detection software, the evaluation unit processes the image sequences individually. The software separates the ball from the image sequences and determines its real-time position by calculating its x-, y-, and z-coordinates, as well as its speed which makes it 4D.

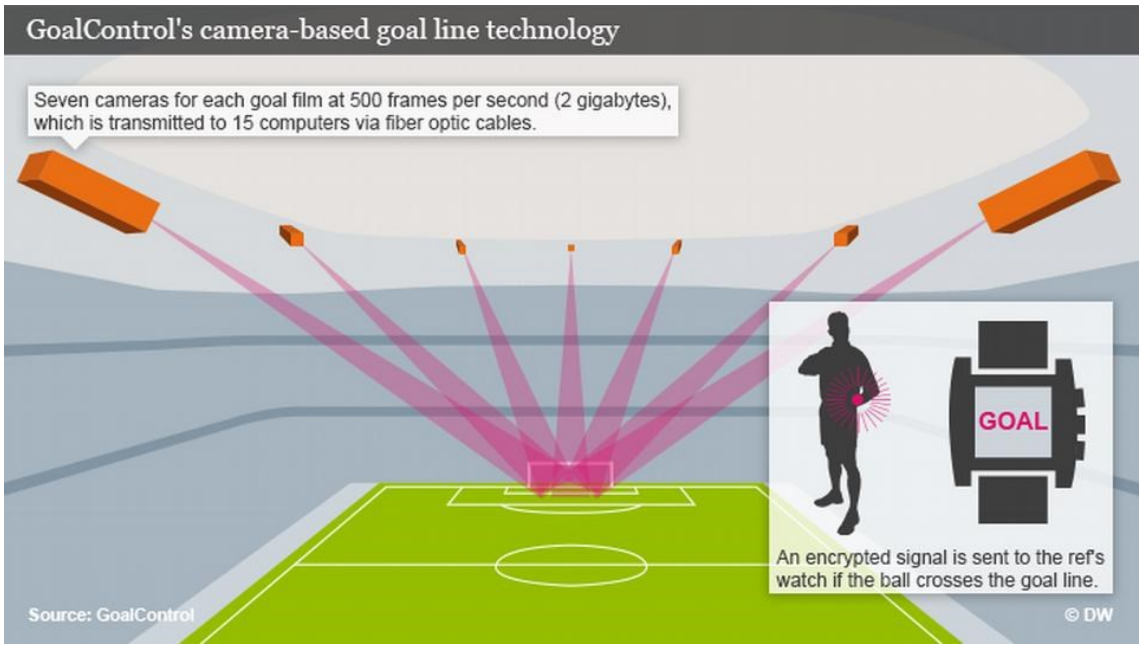

Figure 3. GoalControl Goal Line Technology [6]

This system is fully automated, and the functionality of the system can be overseen occasionally by the technician. An encrypted signal is pinged to referee's GoalControl-4D watch from the central evaluation unit within seconds, if the goal line is completely crossed by the ball.[7]

3.1.3 Hawk-Eye goal line technology

Hawk-Eye invented in 2001 for cricket ball tracking and later implemented in tennis is widely known technology as it is presently used in almost all major sports

including football. Triangulation is the basis of Hawk-eye technology. Instead of measuring distances to a point directly, triangulation involves measuring angles to it from known points at either end of a fixed baseline as seen in Figure 4. As a result, the point can be fixed as the third point of a triangle with a known side and angle.

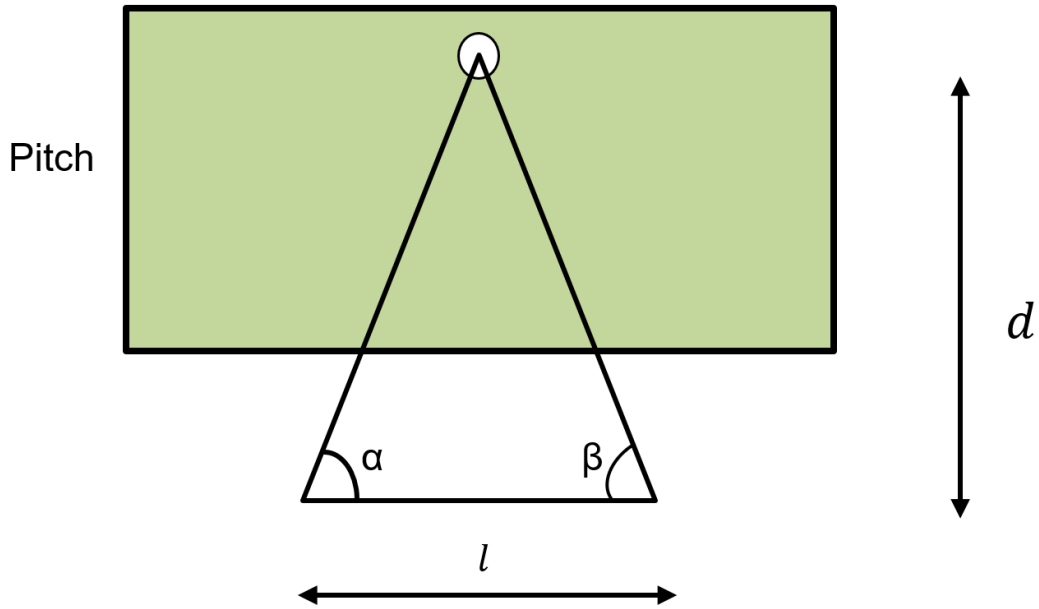

Figure 4. Triangulation formed using 2 cameras angles.

The equation below shows how triangulation is used to calculate the distance, d with the two camera angles α and β the from fixed baseline and the distance length between 2 cameras, L. [8]

$$l = \frac{d}{tan\alpha} + \frac{d}{tan\beta}$$

$$d = \frac{l}{\frac{1}{\tan\alpha} + \frac{1}{tan\beta}}$$

In football, 7 Hawk-Eye cameras are installed around the goal area. The most common location for the camera is on the roof of the stadium but there is flexibility on the camera positioning. The cameras are designed to track balls at high speed, with the images from the cameras being processed to locate the ball. Triangulation is used by two of the seven cameras to be able to track the ball. The system is accurate up to 3.6 millimetres according to Hawk-Eye.

Software combines the information from the cameras and tracks the ball in relation to the goal once the cameras start tracking the ball. In the event the ball crosses the goal line, the system instantly sends a signal to all match officials via their watches and earpieces.

Figure 5. 3D graphic replay showing no goal.[9]

By displaying the 3D graphic replay like in Figure 5, broadcasters show where the ball is in relation to the goal line, determining whether the goal was scored.

3.2 Football Offside technology

The offside rule in football states that during play in opposition half, an attacking player must be behind at least two opposition players which in most play including the goalkeeper, between him and the opposition goal when a pass is being played to him.

Offsides are generally signalled by the linesmen – two assistants of the referee observing the play from outside the playing area line in each half of the pitch. Offside offences are signalled by flags held over or in front of the linesmen. The difference between a player being offside or onside is very small in a lot of offside calls. Offside calls have historically been subject to human error due to millimetres separating them. In modern days with the implementation of technology, a correct decision can be made in football.[10]

3.2.1 VAR Offside technology

The Video Assistant Referee (VAR) was introduced in 2016 to assist the on-field match referee with decisions regarding goal, penalty, red card for serious foul play or violent conduct and eradicating error in showing foul cards to mistaken identity. VAR officials monitor the game live in front of screen from video operations room and will check any incident according to the procedure and communicate to on-field referee to stay with the original decision or overturn the decision taken by referee when necessary. The on-field referee has also the choice to also review any decision for the incident by going to the sideline monitor showing slow motion footage of the incident with as many cameras angle as possible; the referee can either change his or her mind and overturn his or her decision or stay with the original decision. VAR has the advantage of seeing the incident from 33 camera angles surrounded in the stadium.

There has been a second check on offside calls leading to goals since VAR came into play and this has made the offside decision conclusively accurate. Linesman withhold raising the flag for offside call if the play leads to goal-scoring potential, the flag is only raised when a goal is scored or the ball in possession of opposition team. The VAR checks the linesman’s call in the background using video footage and after multiple reviews with different camera angles, VAR can overturn the offside call decision and re-award the goal if incorrect call was made by linesman in replay. In football matches every goal scored by a team is checked by VAR for

offsides and a goal is disallowed if any offside offence missed by the linesman is detected by the VAR during a re-check.

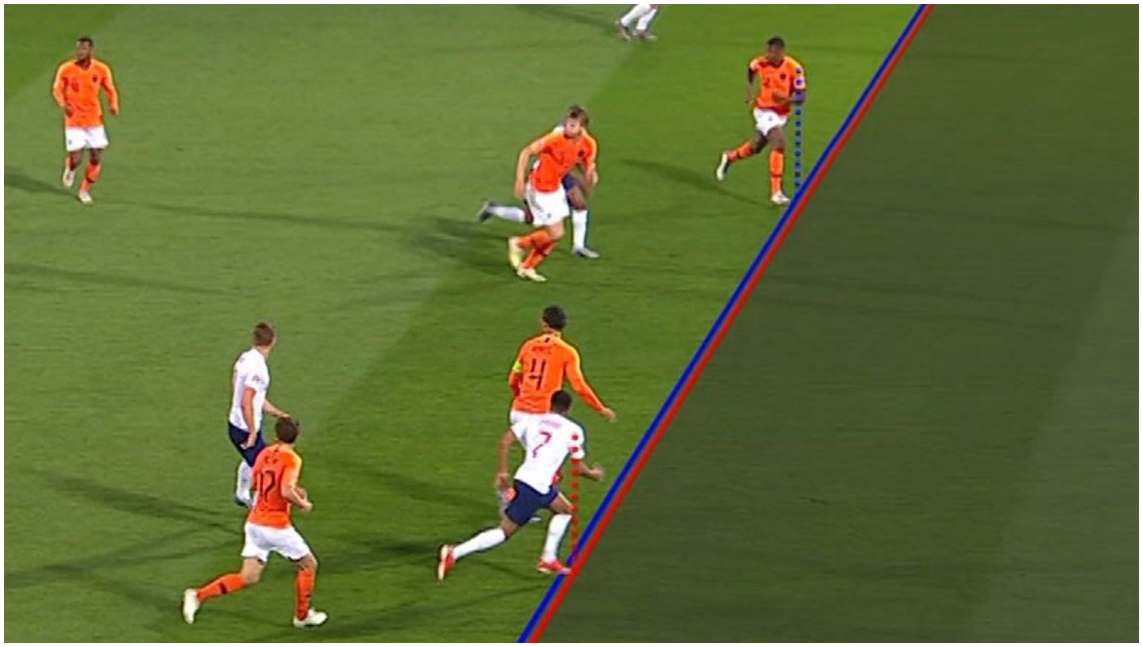

Figure 6. Offside line drawn by VAR.[11]

A Virtual Offside Line is a line added on top of a video replay as seen above in Figure 6, in football matches to help officials decide if an attacking player is in an offside position. The line is drawn across the field at the point where the ball is played by a teammate of the attacking player, and it is used to compare the position of the attacking player to the position of the second-last defender the moment the ball is being played. If any part of the attacking player's body is closer to the goal than the second-last defender, the player is considered to be in an offside position and play is stopped. The virtual offside line is used by officials in conjunction with the Video Assistant Referee (VAR) system to make more accurate offside calls. [12]

3.2.2 Semi-Automated Offside Technology

Semi-Automated Offside Technology is introduced in 2022 and used in FIFA World Cup 2022 alongside with Al Rihla ball which is based on connected ball technology. This technology has been in development for some period as the

VAR offside checks usually takes too long to make final decision on offside incidents when the incidents are very difficult to assess and most the offside incidents reviewed by VAR are marginal. Upon monitoring not only FIFA tournaments but also the leagues around the world who are applying VAR, the aim of new technology was improving the setup and workflow for offside decisions.

The most obvious problem was the offside decision-making process because after conducting studies with providers, FIFA found out that in average on a global level it takes 70 seconds until the decision for an offside incident is made. The momentum of the game can be disrupted with a long wait of 70 seconds as it can affect the players, referee, and fans on the pitch. There are also cases of human error in imprecise drawings of line and in line placement which led to incorrect decision by VAR.

Figure 7. All 29 Data Points in Player body [13]

12 motion cameras mounted underneath the roof of stadiums use advanced image processing and machine learning techniques to triangulate players body

positions on the field. This data can be used to create a 3D visualization of a play that can be viewed from any angle. Each player has up to 29 data points as seen in Figure 7 and these data will be sent to 50 times per second so the position of the player will be determined very accurately on the field of play particularly limbs as well as all the part of the body relevant to the offside rule.

Figure 8. Al Rihla, connected ball with integrated IMU sensor.[14]

The connected ball technology used with offside technology is developed in close collaboration with FIFA, Adidas and KINEXON. The ball with a 500Hz inertial measurement unit (IMU) sensor positioned in the centre of it as previewed above in Figure 8 is integrated with a suspension system developed by Adidas. The sensor is used to collect very accurate ball movement data, which is transmitted to the Video Match Officials within seconds. The connected ball with a sensor inside sends data up to 500 times per second to the operations room, and it is tracked by 12 cameras along with the position of the player. This data is crucial in determining the kicking point and the position of the player at that particular moment, which requires the highest accuracy.[14]

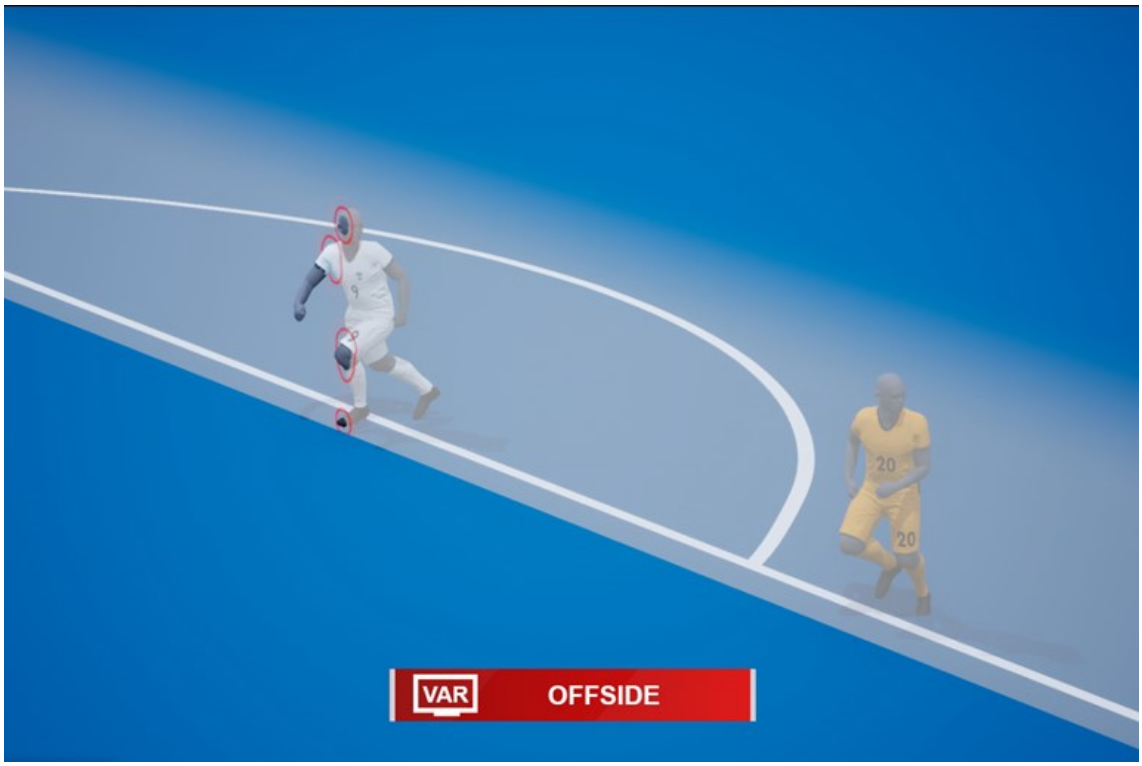

Figure 9. 3D animation generated using data points.[15]

The same data point which was used to determine the players position will be generated into a 3D animation as can be seen in Figure 9 and this animation will be shown on the giant screen at the stadiums and will be provided to TV broadcasters and the TV viewers will be able to see them on their screen.

Based on results, this offside technology is deemed very reliable compared to the previous offside technology. This technology is not fully automated as the final decision is still taken by video match official. [15]

3.3 Cricket technology

Cricket technology has come a long way in recent years, transforming the way the game is played and officiated. From the use of instant replays to make more accurate decisions, to advanced analytics and tracking systems that provide deeper insights into player performance, technology has become an integral part of the modern game of cricket. This section will provide a brief overview of some of the key technologies that have been developed in cricket and how they have

impacted the game. Cricket is very influential in paving ways for many technological innovations like Hawk-Eye and Virtual Eye as these have also spread on to other major sports.

3.3.1 Ball tracking technology

Hawk-eye from England and Virtual eye from New Zealand are the main ball tracking technology providers in cricket and assisting in 3D ball trajectory projection to TV broadcasters. Hawk-Eye considered the most popular one as it is used widely around the world is deemed expensive compared to Virtual Eye as it offers more frames per second.

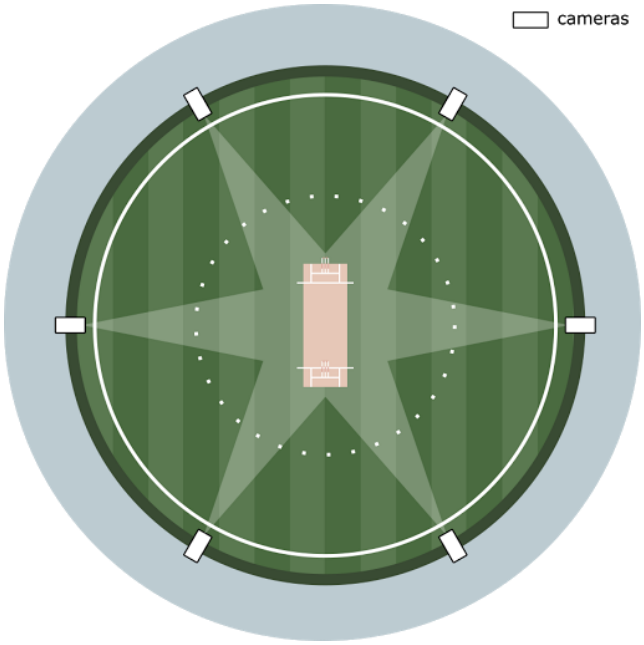

Figure 10. Six Hawk-Eye ball tracking cameras

As seen in the above Figure 10, there are six locked off Hawk-Eye cameras in cricket stadium often with a resolution as high as 300 frames a second which produces composite picture. A path is generated by the composite picture using the triangulation geometric algorithm as discussed before. The ball trajectory is computer generated using ball tracking frames including speed and bounce of the ball as well as other variables.

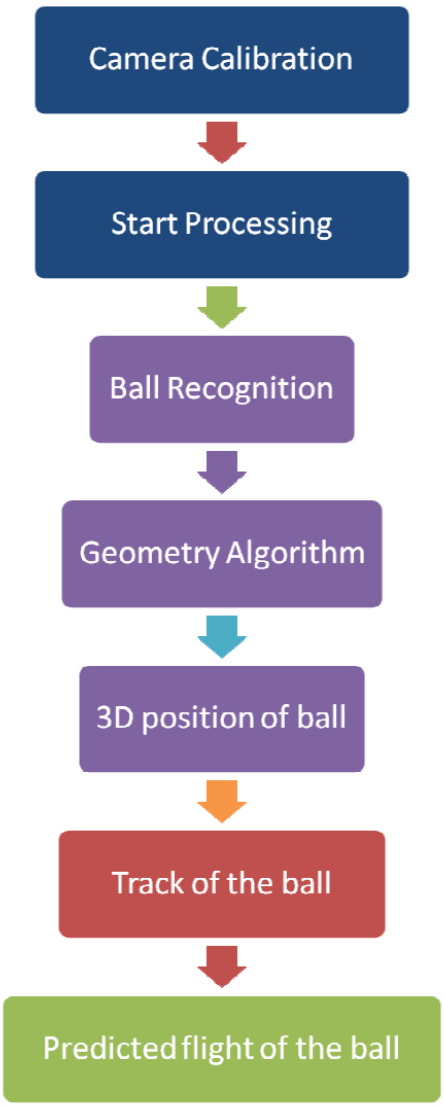

Figure 11. Hawk eye system in cricket [16]

Figure 11 shown above shows all the steps of Hawk-Eye system. The system is mainly divided into two parts: identifying the pixels representing the cricket ball in every image by using an algorithm that identifies the size and shape of the ball, and a geometric algorithm that obtains data from each camera to determine the exact position of the ball by using the coordinates of the ball in multiple images and the positions of the cameras.

Ball tracking in cricket has many applications which can be used to give out wicket decisions with the assistance of TV umpire as well as illustration of team or player performance statistics by broadcasters to TV viewers and commentators.

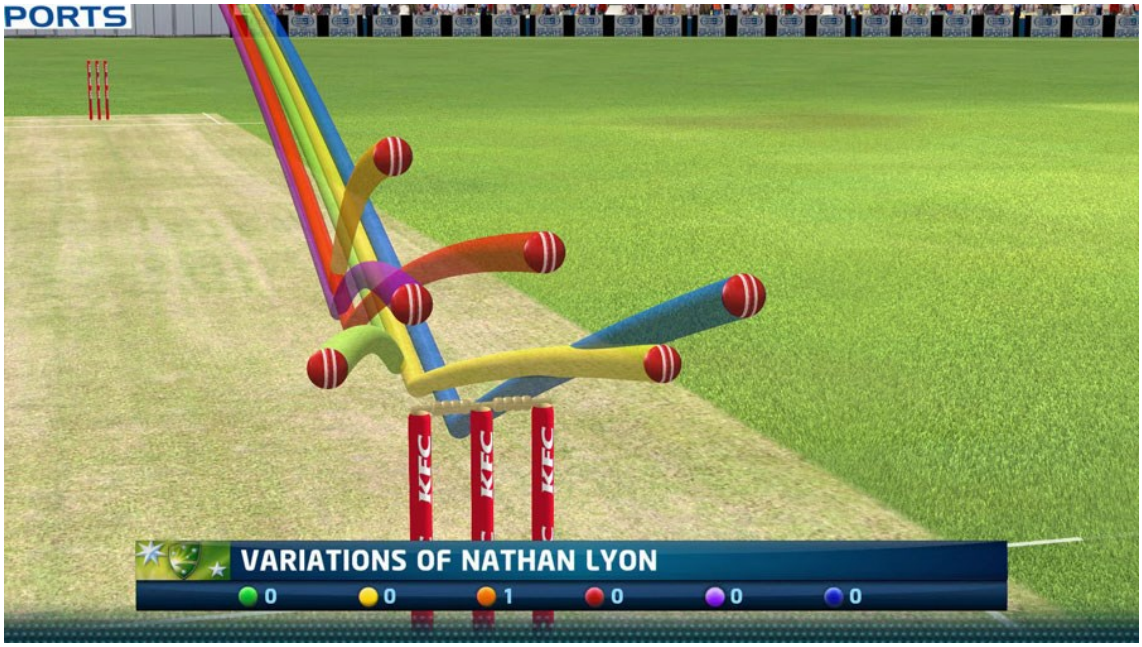

Figure 12. Ball trajectory using Virtual Eye ball tracking.[17]

A computer-generated 3D ball projection is created using Virtual Eye ball tracking system as seen in Figure 12, that illustrates the balls bowled in an over which can be used to demonstrate the performance of a bowler.

The speed of the ball bowled in cricket can go up to 150 kilometres per hour and it can a difficult job for umpires to give an out or not out decision within a few seconds while also considering height and the angle the ball is going in whether it is going to hit the stumps or not. The LBW, Leg Before Wicket is an out decision given by on field umpire if the batsman misses the ball as it was going to hit the stumps, but it is obstructed by player legs. Before the emergence of ball tracking technology, the final decision on LBW out by on-field umpire would have stood as there were no methods to track the ball trajectory.

With Hawk-Eye, the path of the ball is computer-generated because once the ball hits the pad, there is nothing else for the cameras to track as the game is over because of an obstruction. However, in the absence of an obstruction, the computer generates a simulation based on the composite picture captured by the six cameras. The accuracy of the generated curve depends on the number of

points obtained, which increases with the resolution of the cameras used. Thus, the higher the resolution, the greater the number of points captured, resulting in a more accurate ball trajectory curve.

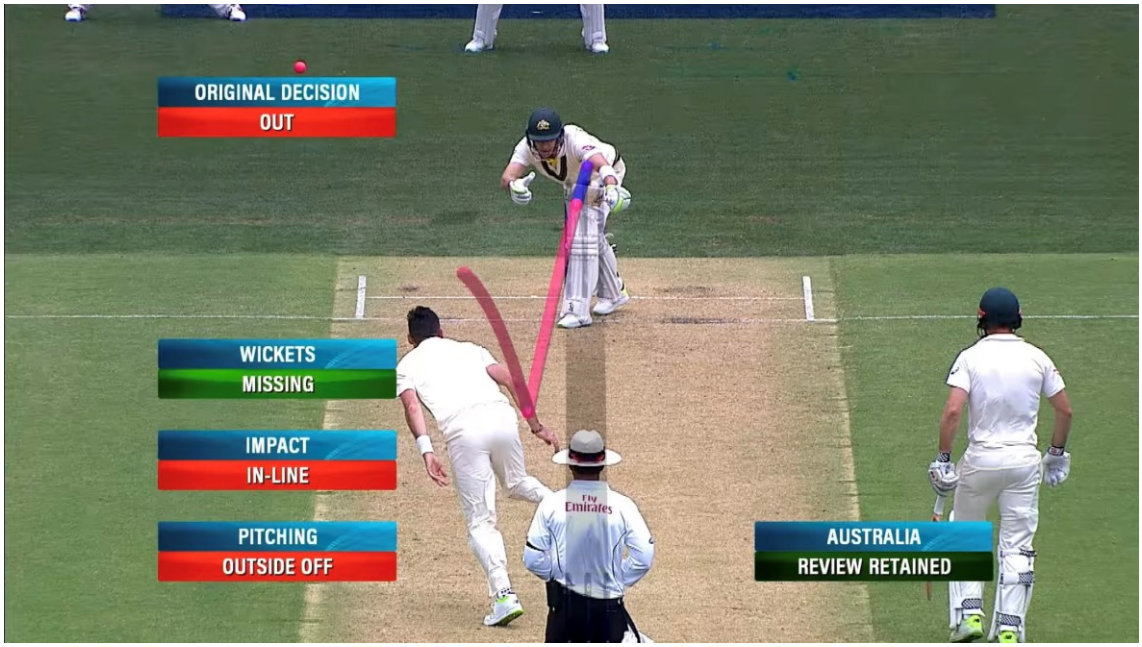

Figure 13: Ball tracking used by DRS to make decision on LBW.[17]

The introduction of Decision Review System (DRS) has the given option for player to challenge an umpire final decision during an incident. DRS can check legality of delivery and go through step-by-step procedures for example if the ball has come in contact with bat and where the ball has pitched.

Figure 13 demonstrates how a batsman has taken a DRS review after umpire has given out for LBW and the ball tracking has shown as projection that the ball is missing the wicket. Third umpire in video room would ask the on-field umpire to overturn the decision and the review is a success for the batsman. If the ball had hit the stump, umpire will overturn the original decision to out if it was given not out.

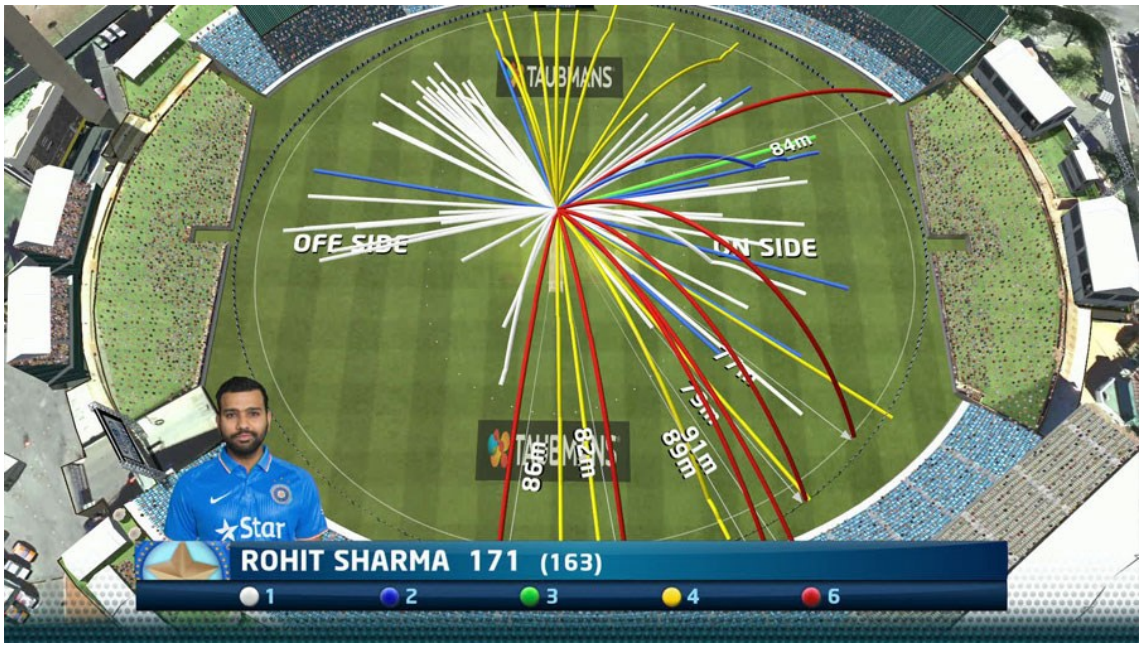

Figure 14. Wagon wheel shows a whole field view of runs scored by a batsman.[17]

Wagon Wheel demonstrates the area of field used to score runs by the batsman using ball trajectories which are recorded in the system. A graphic is then generated, showing different colours for 1s, 2s, 3s, 4s, and 6s runs as seen in Figure 14.

This information enables commentators, spectators, and opposition teams to analyse the areas where the batsman scores, as well as determine whether they hit more shots along the ground or in the air. This information is essential for a fielding captain, who may change the field placement in present and future matches to adapt to the batting tendencies of a particular player.

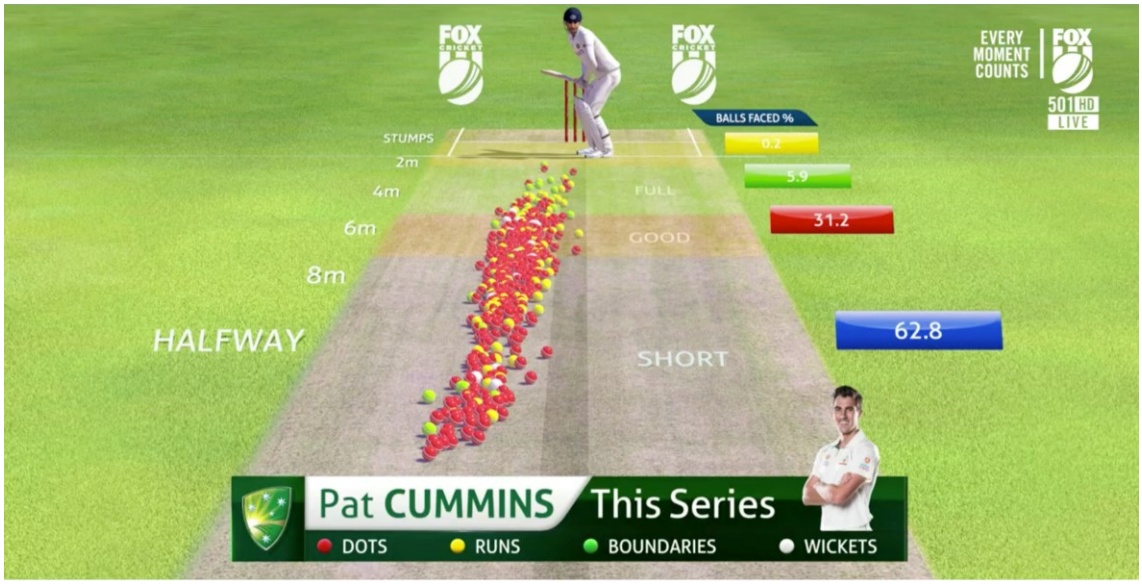

Figure 15. Pitch map shows the pitches of every ball bowled.

In Figure 15, Pitch maps shows where the bowler has ball bounced or pitched on the pitch. The pitch in cricket is divided into various zones which shows where the bowler primarily pitches the ball. Pitch maps can help identify general characteristics of bowlers, such as being taken for many runs. Using the ball tracking system, bowlers can see where they landed the balls, allowing them to adjust their strategy. These graphics are used by opposition players to study the pattern of the bowlers and plan their gameplay accordingly.

Batsman typically finds it difficult to score runs against the balls bowled in good length and these ball pitches are mainly shown for analysis by commentators and experts.

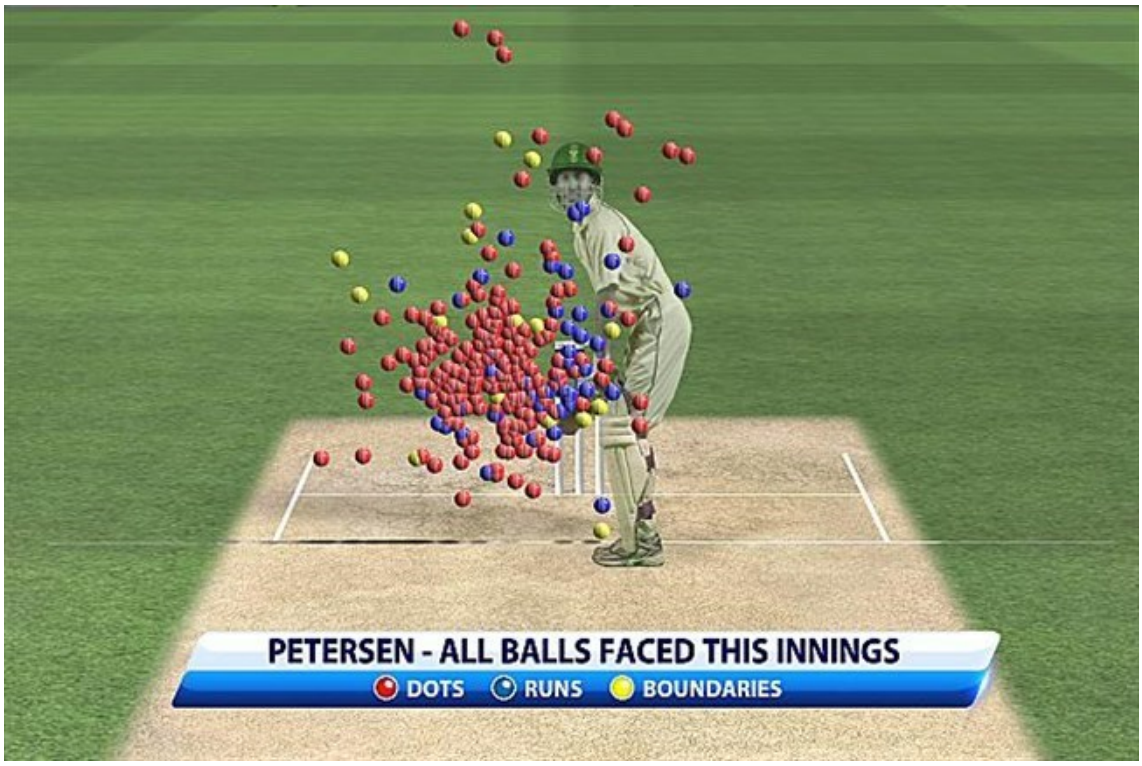

Figure 16. Beehives demonstrate the batsman point of view.

Beehives illustrates a graphic generated by the system that shows the position of balls in the plane of the batsman as shown in Figure 16. The system places a mark on the plane showing where the ball passed or would have passed the batsman, regardless of whether the batsman played a shot or not. The system can also categorize the balls on which the batsman scored run in one colour and the ones which he did not score run in another colour. This helps to identify the strengths and weaknesses of a batsman and his scoring zones. The bowler can use this information to decide where to bowl, such as whether to bowl away from or into the body of the batsman or to pitch it up or bounce it hard into the deck.[16]

3.3.2 Hotspot

Hotspot is a technology that was invented by BBG Sports in 2012, which uses infrared sensitive cameras to detect the spot of contact between the ball and bat. Infrared energy lies in the non-visual spectrum, which is not visible to the human eye, and as a result, infrared cameras are used to pick up the energy.[18] Hotspot technology is an essential part of the Decision Review System (DRS), and it

requires two cameras to be positioned on opposite sides and above the field of play to record images continuously. The friction between the ball and bat raises the temperature on the contact surface, which is picked up by the infrared sensitive camera. The heat generated by the collision of the ball and bat is recorded by the cameras, and the recorded measurement information is sent to a computer, which generates a series of black-and-white negative frames using a subtraction technique. The system then reveals the contact of the ball with the bright spot, indicating where the ball has hit the bat.

Hotspot technology's initial accuracy was 85%, which has improved to 90-95% over time. However, this technology has its exceptions and controversies. Hotspot has failed several times when reviewing for out decision by DRS, and the use of tape hinders its accuracy. Protective coatings on the bat can also diminish the Hotspot marks. Batsmen have tried to minimize the heat signature by using silicon coatings on their bats, which is why new regulations have been set for the placement of stickers and logos on the bat.[19]

Figure 17. Edge detection using infra-red camera.[20]

When bowling team asks for DRS review in case of a bat and ball contact for not out decision given by on-field umpire, TV umpires take a slow, frame-by-frame

approach to review the incident as seen in Figure 17 and sends the final decision and asks the on-field umpire to overturn their decision after seeing the bright spot on the bat of batsman using Hotspot infrared cameras.

3.3.3 Snickometer or UltraEdge

The Snickometer or the upgraded version UltraEdge is used to pick up sound waves of any small ball touch with the bat for LBW and catch out decisions. A sensitive microphone is set up behind the stumps and is used for capturing specific frequency of audio. Different frequencies of sound are produced when the ball hits the bat or any of the leg pads. The sound of the bat nicking the ball with the help of resonance filter is picked up by the microphone connected to the stump. An oscilloscope is shown in the form of graph as seen in Figure 18, is shown to spectators in stadium or TV audience. If there is spike or variation in graph, then there is contact with the bat and no contact if no graph has flat line.

Figure 18. Sound frequency detected from contact.[20]

The Snickometer or UltraEdge is used checking together in sync with slow motion video capture, for TV umpires to determine if the ball has touched the bat or not.

By using it, the third umpire can make a correct decision in case of an uncertain hit on the bat or pad on the way to the wicketkeeper.[21]

3.3.4 Speed Gun

Bowling speed is an important factor in cricket, as it can affect the effectiveness of the delivery and the ability of the batsman to respond to it. Speed Gun also known as Radar Gun can accurately determine the speed of ball with the help of Doppler effect. This Speed Gun consists of a transmitter and a receiver. It emits invisible waves known as microwave. Microwaves are used because they have a large wavelength and can penetrate the air with less deviation than waves with shorter wavelengths. It can read speed instantaneously. The Speed Gun sends microwaves toward pitch direction to calculate speed of moving ball on pitch which is placed on a high pillar near the Sight screen.[22]

Sports operator uses a combination of cameras from Hawk-Eye and radar technology to track the ball's movement from the bowler's release point to the batsman or stumps. The speed of the ball can be calculated using this combination at various points during its trajectory, including the release point from the bowler's hand. In Figure 19, a picture is shown below to demonstrate the measurement of bowling speed using Doppler effect.

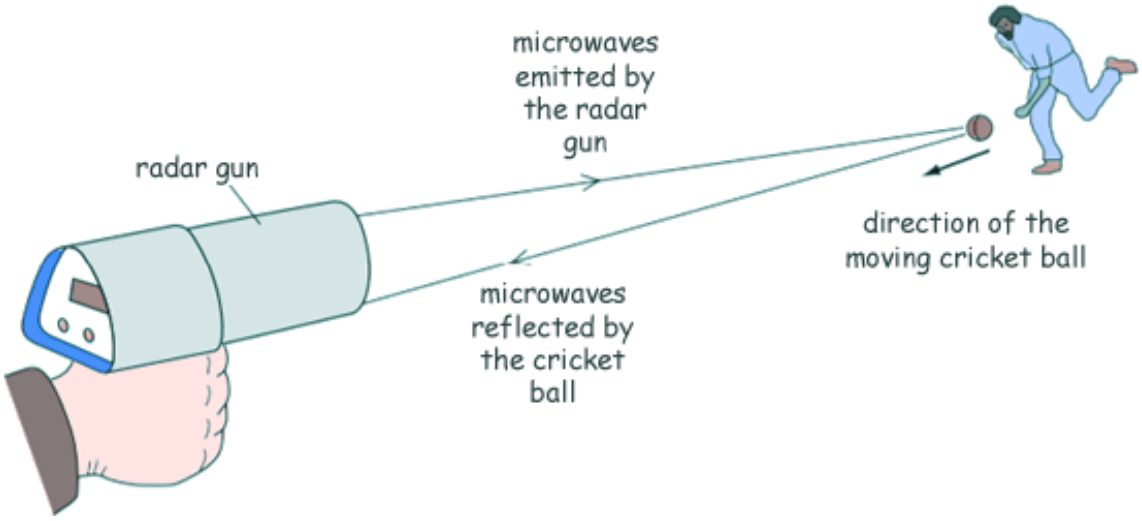

Figure 19. Bowling speed is read using Doppler effect.

$$v = \frac{\Delta f}{f} \times \frac{c}{2}$$

Speed of the ball, v is measured with the formula above where ∆f is the frequency difference between the microwaves emitted by the gun and reflected waves back to the gun, f is the frequency of emitted wave and c is the speed of light.[23]

3.3.5 LED Wicket

A wicket consists of 3 stumps and 2 bails, and an out is given when bowled, stumped, or run out. Runouts and stumping are very difficult decisions to make for an umpire as they must be precisely determined whether the bails left the stumps before a batsman places the bat on the crease line. There are cases in cricket where the player is given out when he should have not been and given not-out when he should have been because of difficulty in determining the exact point at which bails are dislodged from the stumps during stumping and run-out.

LED Wickets are introduced by Zing International in cricket as they are more visible than traditional wooden stumps and bails, making it easier for umpires to make accurate decisions. They are made with Plastic Composite material and the circuit is embedded into this material. The bail powered by low voltage batteries has a microprocessor that illuminates within a millisecond after detection of the separation between bails and stumps.

Each bail consists of an inductive loop and the bail assembly contains an inductive sensor which detects any change of inductance. Inductors in the circuit produce a strong electromagnetic field and eddy current flows when the bails are on stump. When the bail moves, the metal pellet in each bail causes a change in inductance which is detected by the inductive sensor and the amplitude of the electromagnetic field changes. Each inductive loop is inductively coupled to an inductor coil which is connected in series with the LED lights. When the circuit is initially powered, the LED lights glow due to the high resistance provided by the inductor coils. Once the magnetic field is built up in the inductor coils, current can

flow normally through the wire, and the inductor coils provide less resistance, taking current away from the LED lights.

Inductive sensors are better than other methods as they have some advantages. They are not easily affected by external factors such as rain, vibration, dirt, or grass on the stump saddle. The sensitivity of the sensors can be adjusted to avoid false readings caused by vibrations from wind or footsteps.

Figure 20. LED stumps and bails in action when wicket is broken.[24]

When there is a displacement of the bail between the support arm and the metallic saddle, a change in inductance is detected, which results in illumination of the LEDs to provide an indication as seen in Figure 20. The assembly also includes a signal transmitter that can transmit a signal indicating a separation between the bail and the stump to a remote receiving device, such as a television receiver. The signal can be transmitted via various means, such as hard wire, radio wave, infrared, or wireless standard for exchanging data over short distances using short wavelengths. [25,26]

LED stumps have been praised for their accuracy and reliability, as they eliminate the need for the umpire to make a subjective decision about whether the ball hit the stumps or not.

3.4 Tennis Electronic line judge

In tennis, line judges are responsible for calling if the ball has gone out play or bounced inside the line by communicating to the chair umpire and player. It is difficult job for line judges to make the in or out call, as it can be the difference of few millimetres of the ball bouncing inside or outside the line. That is because if observed closely, a tennis balls bounce mark is not a circle, it is an oval because the tennis ball compresses while hitting the ground in force. The length of the oval bounce mark can be many times the size of the diameter of the ball, and it depends on the surface of court.[27]

Figure 21: Mylar Sensor checked by inventors Geoffrey Grant and Robert Nicks [28]

The first successful public demonstration of an electronic line judge device for tennis was in 1974, invented by Geoffrey Grant and Robert Nicks. It used mylar pressure sensors as seen in Figure 21 beneath the court surface to distinguish

between a ball and a player's foot and was able to make calls on whether the ball landed in or out of bounds, foot faults, net cords, and legal serves. It was successfully used at the Men's World Championships of Tennis in 1974. This electronic line judge system was not commercialized.[28]

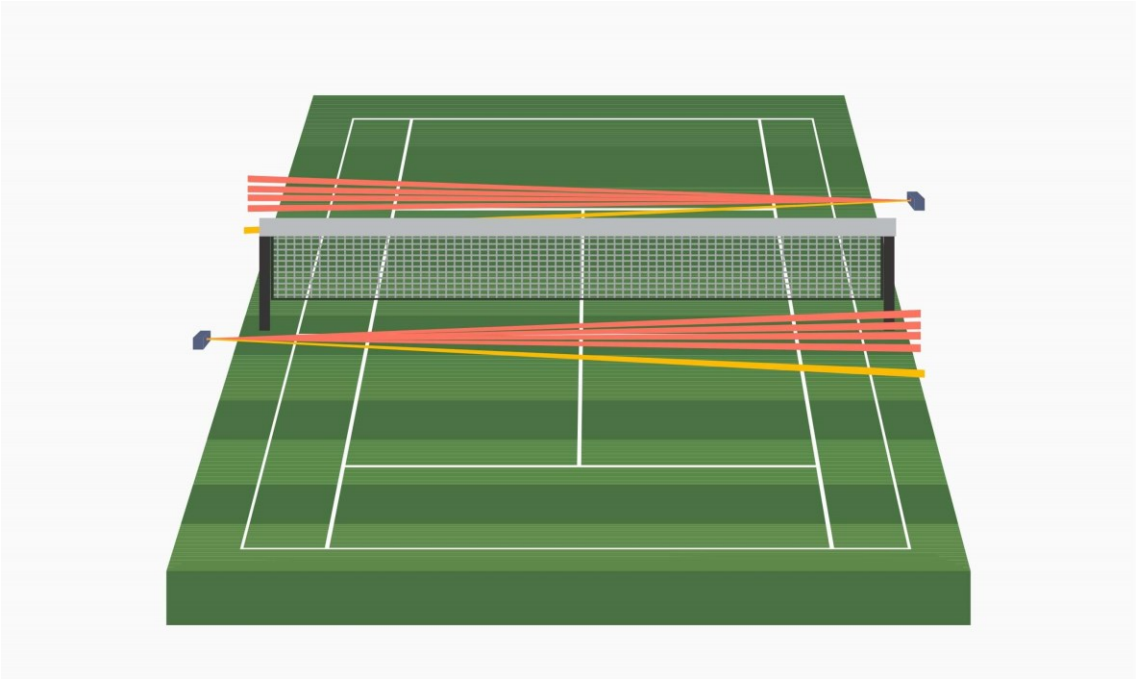

Figure 22. Cyclops system emitting five infrared beams across the court.[29]

The Cyclops system was introduced commercially in 1980 and the system was successful as it was reliable. The Cyclops system was installed beside the court to determine if a tennis serve was in or out. It worked by emitting five infrared beams across the court, with one beam running along the service box line and the other four running outside the line as seen in Figure 22. When a ball hit the good side of the service box line, it broke the first beam and turned off the others, signaling with a green light that the serve was good. A red light and a loud beep were produced if the ball broke any of the other four beams without breaking the first beam. The system was only used for close calls and was limited to serves, as foreign objects could cause phantom beeps. The system had to be deactivated by the umpire after each good service to prevent further beams from being tripped.[30]

Figure 23. Hawk-Eye ball projection and top-down view of ball-ground impact [27]

Hawk-Eye was introduced in tennis in 2006 to help making accurate line calls. It was initially used for television broadcasts to show viewers where the ball landed on close line calls as seen in Figure 23.

Hawk-Eye Challenge system enabled players to challenge line calls by line judge or chair umpire asking for a review of the call. The system uses the data from 10 camera surrounding tennis court to generate a 3D model of the ball's flight path, which can be used to determine if the ball landed inside or outside the lines. Once the challenge is made, the referee will initiate the review process, which typically involves reviewing the footage from multiple camera angles to determine the correct call.

Players can have a certain number of challenges per set usually two or three, which they could use to challenge line calls they felt were incorrect. If the challenge was successful, the player retained the challenge and could use it again later in the set. If the challenge was unsuccessful, the player lost the challenge for the remainder of the set.[31]

3.5 Timing Systems

Timing systems are used widely in time based sports completition to accurately measure and record the performance of athletes during a competition or training.

Timing systems play a critical role in determining the winners and rankings of athletes in a race or event, and can also be used to track the progress and improvement of athletes over time. These systems typically use technologies such as cameras, sensors, and GPS to provide precise data on an athlete's speed, distance, and time. This valuable information can be used by coaches to optimize training, equipment, and strategy of the athletes.

3.5.1 Athletics and Swimming

In Olympics, OMEGA are responsible in timekeeping for athletics and swimming events for long time using camera technology together with timing systems. In modern athletics event, the timing system consists of the electronic starting gun, starting block and false start detection system at the starting line and photo finish camera, pairs of photocell and scoreboard showing time on the finish line as seen in Figure 24.

Starting block enables athletes to take body position which allow them to reach to maximum speed with use of proper technique. The starting block has false start pressure sensors to prevent athletes to start sprinting before the start of the race by measuring force exerted and their reaction times which must be within 100 milliseconds after the start signal. A false start is declared if the pressure is different for any sprinter within one tenth of a second after the start gun and possibly can disqualify the athlete in major event.

There is a speaker behind the starting block which signals the start of race by sending a pulse from electronic starting gun when the trigger is pressed. The starting electronic gun is connected to the timing system by cable and the false start system is also connected to it by another cable. Timer starts when starting electronic gun trigger is pressed which replicates a loud gun sound for the spectators.

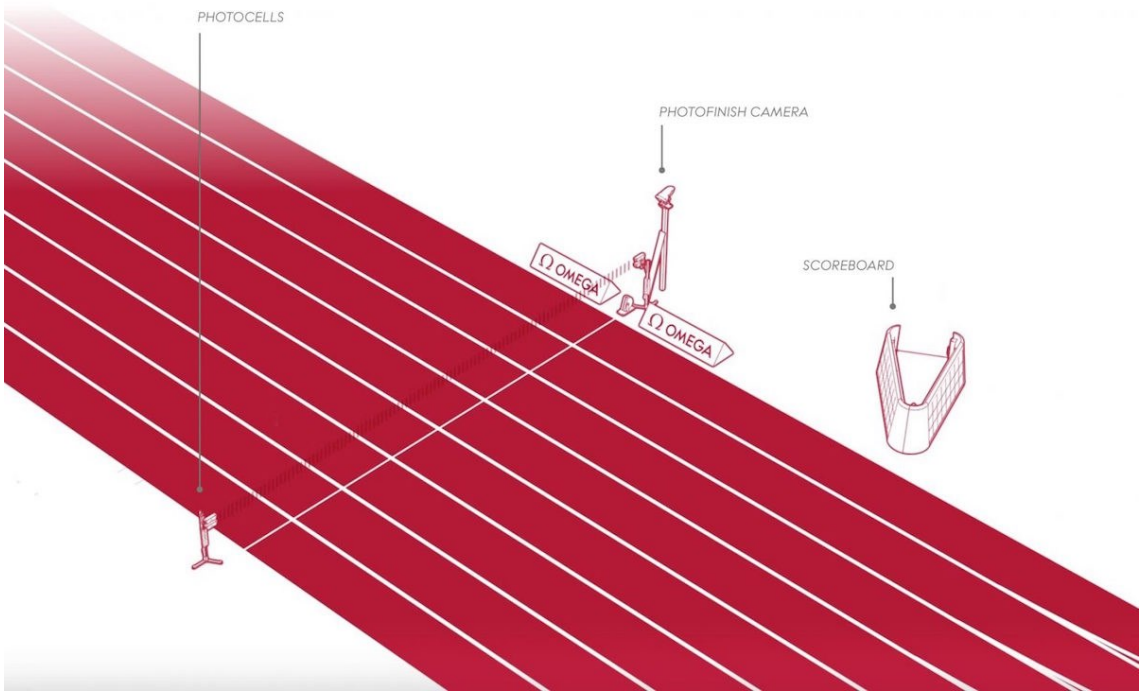

Figure 24: Equipment in Finish line of race[32]

OMEGA uses Scan'O'Vision MYRIA camera as photo finish camera which uses a combination of a time detector and a chronograph. The camera capture 10000 pictures every second of the finish line to generate the photo finish picture of runners crossing the line. Photocells placed in two sides of finishing line stops the running time of athletes which is displayed on TVs and scoreboard.[32]

In swimming, Quantum aquatic timing system is used together with sensors for measuring the swimmer's reaction times following the start signal. Similarly, like athletics, swimmers start from the starting block with adjustable footrest angle for an ideal dive in to water.

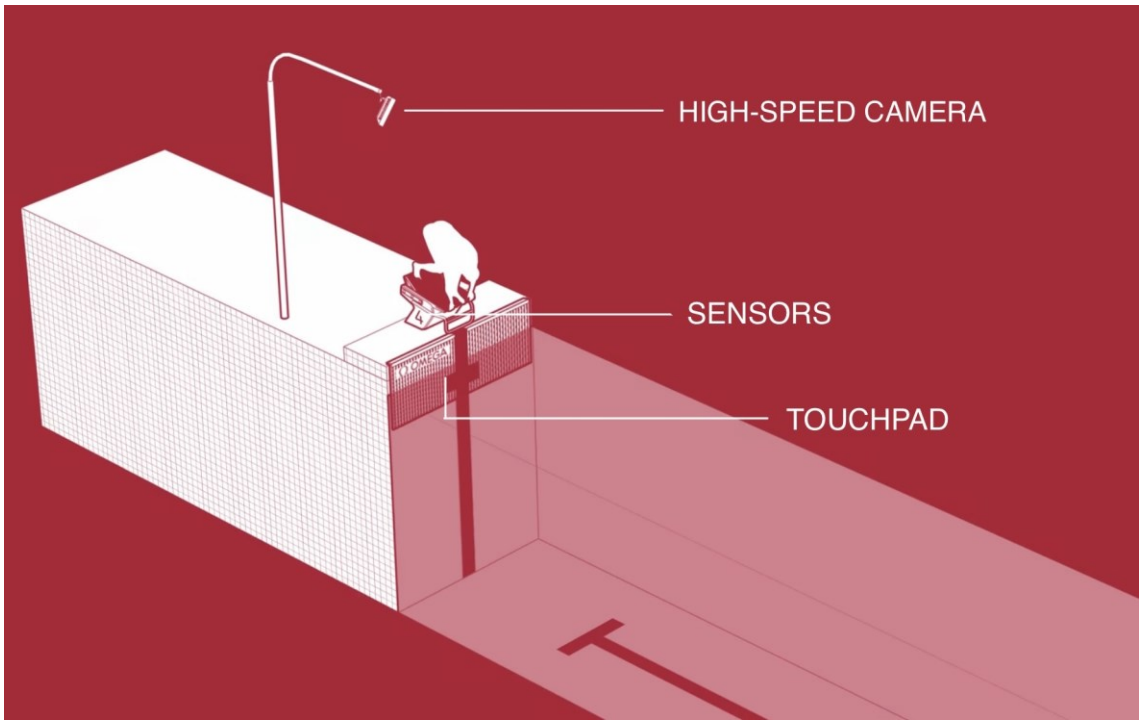

Figure 25: Camera, Sensors and Touchpad used in Swimming competition.[33]

In Olympic events before technology advancements, competitive swimmers started their races reacting on the sound of a starting pistol and depended mechanical stopwatches to record their times at the end of a race.

Loudspeakers are integrated on each starting block and the starting signal is emitted simultaneously. A microphone device is used to send a start pulse to the timing system and speaker in starting block when the button is pushed.

Touchpad, a pressure sensor is set in the underwater wall acts as finishing line which need to be touched by the swimmers themselves with force to stop time. Swimmers must exert force between 1.5 and 2.5 kg against the touchpad which is enough to stop the clock immediately and record the time. High-speed cameras are available as back-up system, in case the touchpad results are missing or too soft. Timekeepers in the control room inspect the pictures sent by the High-speed cameras which is capable of taking 100 images sent per second.[33,34] An overall picture of the system can be seen in Figure 25.

3.5.2 Formula One

Formula One is known as one of the fastest motorsports globally, with cars sometimes speeding up 200 miles an hour and changing speed at a rapid pace as they accelerate and decelerate throughout each lap. Unlike athletics and swimming, it is hard to for humans to time keep fast moving cars and the sound of the event can be overwhelming. Formula One has one of the most advanced and complex tracking systems in the world, which requires an accurate system keeping track of position every car during every second of the race.

In the late 1980s, each Formula One car was fitted with a transponder the size of a matchbox that sends out radio waves and a different wavelength is set to each car so that there is no interference between cars. Timing loops, which are the receivers for these transponders, are made up of wires that span the width of the circuit. These wires are protected by being encased in silicon and are kept about one inch below the driving surface to minimize the risk of damage. The timing loops are placed at intervals around the circuit, usually 150 meters apart. The data is sent to the control centre and then sent back to the live timing screens. The interval in the timing loops gives us an indication of where each car is at any given time.

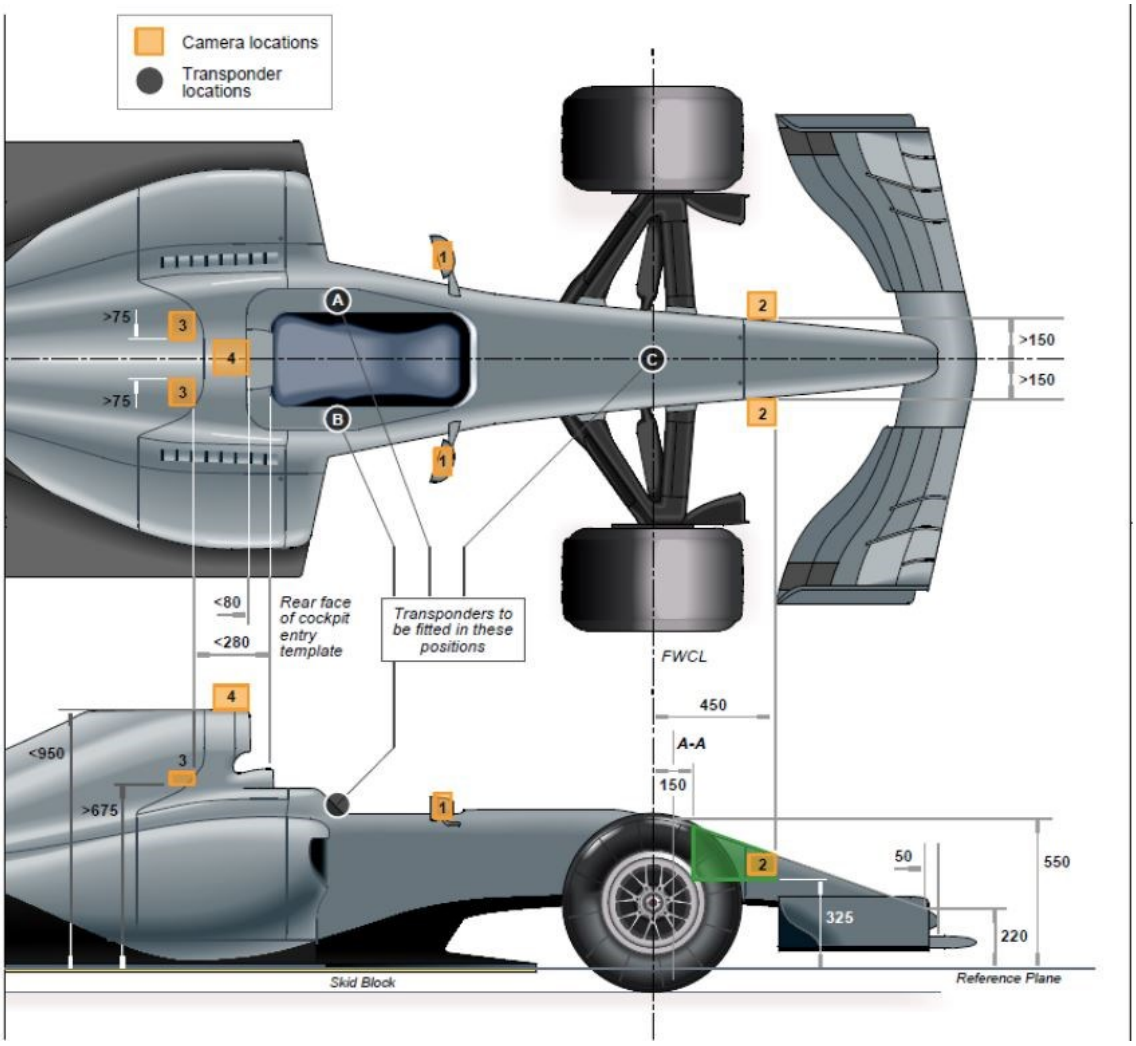

Figure 26. Transponder and Camera locations in Formula one car[35]

At critical spots on the track, such as in the pit lane, the start-finish line, the grid slot, the Drag Reduction System (DRS) detection point, and the DRS activation point, additional sensors and cameras could be placed to get accurate timing. For important calculations such as lap times, sector times, DRS activation, and pit lane times, the timing loops discussed are placed precisely on the track. For example, there will be a timing loop at the start and end of each sector; this is how sector times are calculated. There is a timing loop precisely placed at the DRS detection point, which will allow the system to calculate if there is a one second gap between two drivers at that location. The pit lane has a timing loop at the end of the pit entry and at the start of the pit exit. This timing is displayed to fans showing how much time each driver is spending in the pit lane.

The most important of course is the start-finish line, where a timing loop is placed. And this is how lap times are calculated. Within a thousandth of a second, Transponders on F1 cars allow them to be accurately tracked.

There is a backup system in case if a transponder or timing loop breaks, each sector line, as well as the start line, has an infrared camera that is able to identify and detect each car on track. This system can accurately time the cars in case the transponder fails. On top of that, another backup system is in place. Time linked video cameras are placed across the side of the circuit, as well as on the cars. These can time the cars as they go through the entire lap. At the start-finish line, a beam of light extends across the track. As an F1 car drives past and disrupts the beam, the time is recorded. The beam is powered by a separate source to ensure that it remains operational even if the entire system loses power.

Each F1 car is equipped with multiple cameras from the front to the back as seen in Figure 26. In the event of a close finish, these cameras can be used to determine who came out ahead. On a Grand Prix weekend, prior to the drivers taking to the track, all systems are calibrated by driving a test F1 car around the track to and ensure that everything is working properly.[36]

Formula One is considered as the competition with the highest level of accuracy with all this measurement leaving no room for controversial moments.

4 Analytics in Sports

Sports analytics plays a crucial role in improving performance of the team and preparing for the future games. Data collection is necessary for this reason. Statistics is used to describe what has happened in a game and Analytics use statistics to create predictability. Analysts use data by scouting opposition team, players, team tactics, key player attributes to make detailed predictions and suggestion for coach on how to approach the opposition team.

4.1 Opta Data

Opta acquired by Stats Perform is the largest data collector of events on teams and players. They collect up to 2000 actions per football game which can accumulate close to one million of data in a season. Opta takes in information on every single event on the field for example a pass, a shot, throw-in, and a tackle.

Opta generates real-time performance data through a combination of human annotation, computer vision, and AI modelling, resulting in more comprehensive and detailed data than ever before. The world's leading broadcasters, digital publishers, clubs, and betting operators are users of Opta data because of its accuracy, depth and speed while providing applied insight and intelligence.[37]

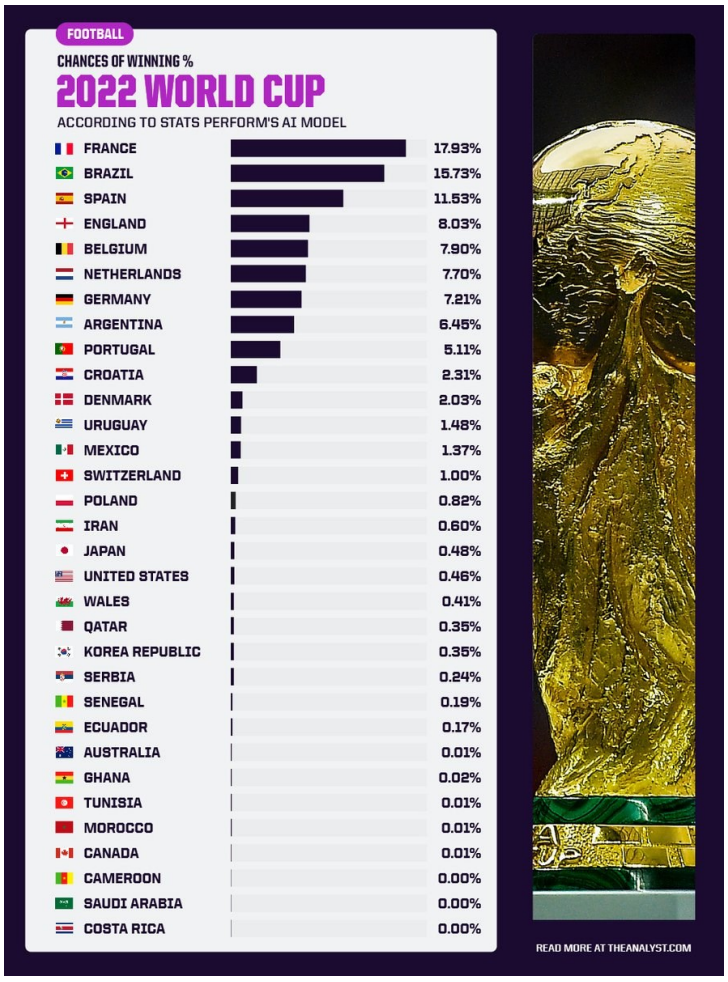

Figure 27. FIFA World Cup 2022 Opta Prediction[38]

Opta can also give predictions on big games by using machine learning AI and calculate winner of a tournament based on decades of historical, seasonal, and game data as seen in Figure 27.[38] AI predictive models evaluate thousands of data points by adjusting and transform based on a wide range of data inputs, such as the location and conditions of the game, including factors like home advantage, time of day, and whether it's a regular league game or a different game in another competition.

Additionally, team-specific data, such as strengths and weaknesses, historical matchup performance, and recent matchup performance, as well as player specific data, such as strengths and weaknesses, historical and recent matchup performances, are considered. Finally, game situation variables like the current score, time remaining, and whether it's regular time or overtime are also factored in when models make their adjustments and transformations. Betting industry can use these predictions to set up the odds.[39]

Opta data is also used by teams in player scouting for recruitment as they have massive dataset on teams and individual players in other football leagues. Teams in lower leagues with limited budget must operate in smart way as they can’t afford to make mistakes. They can recruit lesser-known players with characteristics similar to an expensive and top player using the Opta database.

Broadcaster of leagues use these data to analyse performance and pundits or experts can give their opinion from match using data statistics for example possession and shots on goal in a football match.

4.2 Wearable Technologies

STATSports and Catapult Sports are leaders in performance analytics technology globally in all major team sports. Coach and fitness trainer including sports science department can track the training performance of athletes from the GPS performance tracker worn by players in a vest in training and in live game

as seen in Figure 28 and use recorded metrics to improve their performance. The GPS is using satellites to pick up positions and speed of individual players.

Figure 28. Professional football players wearing vest with GPS tracker on back.[40]

Performance data is synced to analyst iPad or compatible devices which displays the statistics of players for example distance covered in 5 minutes interval and if overall performance has dipped in final stage of game or practice.

Some metrics that are tracked by the GPS tracker are heartrate, number of sprints, sprint distance, overall distance, power, maximum speed, accelerations or decelerations, speed at angles, heatmap showing sprinting locations in the field etc. All of these data can be reviewed in mobile apps or computer software as seen in Figure 29.

Figure 29. Session analysis in Catapult One[41]

Players returning from injury can use their previous match data to reach the peak fitness target. An important role these statistics metrics that can play is improving players general conditioning and physical monitoring so they can prevent injuries than having to deal with them in near future.[40,41]

Alongside physical fitness needed for the sports, the mental health is now given more priority as well. Olympics athletes are using EEG headset by FocusCalm with mobile app as seen in Figure 30, for brain training to reduce stress, anxiety and being more focus during game state. The headband uses neurofeedback technique to control inner stress, help better sleep and being more productive. The headband uses EEG technology to detect and analyse activity in brain while proprietary algorithms translate those signals into focus calm score.

Bobsled and skeleton athletes can go through intensive moments as their heartbeat can rise high when going down at the speed of 80 mile per hour during competition and race setting and they use EEG headband to make their mind calmer and have better focus. It is essential to calm down after training as it leads to performance and rest including sleep.[42]

Figure 30. FocusCalm headband and mobile application[43]

Athletes use meditation calming apps to bring their competitive state to recovery and relaxation state. Games activities and exercises are used in app to train brain uses score system to tell calm state with low score representing a brain actively working hard and high score as pressure free, less scattered, and more relaxed mind.[43]

5 Simulation in Sports

In recent years, simulation in sports has gained significance as a method to improve the performance of teams and players and acquire a competitive advantage. Athletes are being prepared for countering real-life like situations such as unfamiliar weather conditions, aggressive opponents, and unwelcoming

crowd atmosphere with the help of simulation technology. Sports Simulation training can be replicated in the form of virtual reality and simulation video games, and the technology has become more accessible to general population. With this form of medium, simulations are highly realistic and immersive that can be enjoyable to both professionals and public consumers for training and recreation.

5.1 TrackMan Golf simulator

TrackMan Golf Simulator is an indoor golf simulation system that uses advanced technology to provide golfers with an immersive and realistic golfing experience. The simulator uses the same technology as the TrackMan used by professionals to analyse ball flight, launch and club data. TrackMan golf simulator has the significant benefit of allowing golfers to practice their game in a controlled environment, regardless of weather conditions. This simulator is the perfect solution for golfers living in areas with harsh weather conditions or limited outdoor space enabling them to practice their swing and ball flight indoors.

TrackMan uses Optically Enhanced Radar Tracking (OERT) system to accurately measure club and ball data. Using a full HD video camera and dual radar, this system determines the exact location of the impact on the clubface without the need for markers. The radar system used by TrackMan can take 40,000 measurements per second which allows for an extremely accurate measurement of the time of impact between the clubface and the ball. By synchronizing the camera with radar, TrackMan can capture the exact position of the ball before impact and the clubhead position with a pickup rate of over 90% across all shot types. OERT combines camera and radar technology for short and long-distance ball tracking, and it also captures chip, pitch, and approach shot club data, putting data, and indoor spin axis and spin rate adjustments based on gear effect. [44]

Figure 31: Trackman Indoor Simulation[45]

TrackMan simulation is available in commercial centre and they also offer solutions in private space. As seen in Figure 31, TrackMan simulator provides a Virtual golf experience that is powered by the TrackMan 4 launch monitor. There are over 200 virtual courses to choose from with adjustable daylight settings, and the course graphics are simulated using the 3D scanned courses by LiDAR drone technology, creating a realistic and immersive experience. Player can be of any level from beginner to advanced can choose from a variety of activities in the form of games, whether it is competing with friends and family or simply having fun in the simulation.[46]

TrackMan golf simulator can also be used as a powerful tool for professional golfers. By using the simulator to evaluate their swing and ball flight, professionals can identify areas for improvement and develop a more consistent and efficient swing.

5.2 Football Manager

Football Manager is a popular simulation game developed by Sports Interactive in which players takes on the role of a football club manager with the goal of making club successful which involves making decisions on player transfer, training and improving club infrastructure. The game has extensive database of players and clubs which are collected by a network of over 1,300 researchers

and this makes it a valuable scouting tool for professional clubs, with many clubs admitting to using the game to scout players. The game also provides a simulation platform for managers to experiment with different scenarios and tactics. Additionally, the game has helped players develop their understanding of real-life sport by experimenting with different tactics and formations. Football Manager has become a valuable resource for professionals in the football industry as it is used to find new players and simulate new formations with players.[47]

In Football Manager, players manage all aspects of the team, including the first team, youth teams, and backroom staff of football club. This involves decision making on tactics, team selection, training, transfers, scouting, and contract negotiations. Individual players on their team can also be managed for example assigning them to different positions, managing their training schedules, monitoring their performances and their morals. A preview of the game tactics is as shown in Figure 32 as well as every menu available.

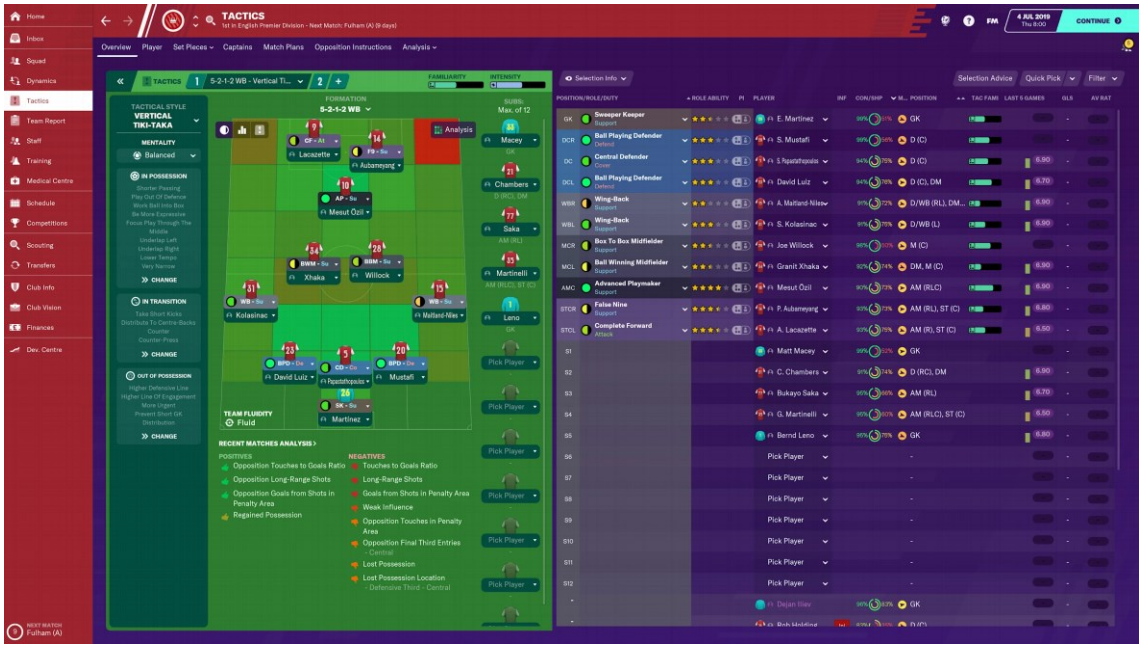

Figure 32. Football Manager Tactics section in the game

Players can scout and sign new players to improve their team with access to the vast database of players in the game from around the world. Potential signings

can be scouted to find the right fit using various criteria such as age, playing position, physical and technical abilities, cultural background and performance statistics, and other variables include transfer fee, wage demand, agent fee and contract length. Players in the game has the ability in employing different tactics for the team managed matching with player skillset for the best result. A wide range of formations and set-piece routines is available for the players to choose from as well as individual player instructions to create a tactical plan that suits their team's strengths.

Football Manager has in-game 3D match simulation which gives players perspectives about the match. Player can make changes to tactics during the match and analyse player performances using a range of in game statistics and metrics. Football Manager allows players to manage the training schedules of individual players, a group of players and the whole team. This includes creating training plans, setting up specific drills, and monitoring player progress.

In the game, there are backroom staffs assisting the manager, which include coaches training the players, scouts reporting on potential players, medical stuff in treating injured player and fitness coach helping in player conditioning. The player can hire, release, extend contract and monitor the performance of staff members to ensure the team is performing at its best. The game has the important feature of managing financials of the club as it gives players with the ability to manage their club's finances, including setting budgets, negotiating contracts, and managing transfer fees and salaries.[48]

6 Limitations and Drawbacks

Most of the technologies brought into the sports are for assisting officials in the decision making for the fair outcome but there have been multiple cases of malfunctioning of technologies when called upon and some of them also acted as an obstacle in the playing field. Issues are always raised about reliability and accuracy of the technology in the rare cases even they are consistently correct most of the time. In some cases, the limitations of technology in use have given

the edge to new technology by competitor as it failed to meet the expected standard set by sport associations. Although the accuracies of the technologies used has improved drastically compared to last decade, problem still arises with the complexity of the technology.

6.1 Spidercam

Spidercam, a computer-controlled camera system used in sports broadcasting that provides dynamic and unique perspectives to viewers around the world. The Spidercam can move silently above stages and into every corner of a stadium, providing high-quality HD footage from a variety of angles. The system uses cables which are redirected by the pulleys to hold the camera in the desired position as can be seen in Figure 33 and allow it to move and capture footage from different angles. Four winches control the cable movement, and a central processor operates the winches. The system is controlled by a pilot and camera operator, and every move can be saved and reproduced with 100% accuracy. The top speed the system can go is 8 meters per second and the maximum flying area is 250 meters square.[49]

Figure 33. Spidercam [50]

Spidercam is known as one of the controversial technologies as it is used by broadcasters to show a close view of the field with its close in zoom feature from every point of interest for the TV audience only. There have many cases of Spidercam interfering with play in cricket for example like ball hitting the camera or the suspender cables holding the camera.[51] According to the laws of cricket, if the ball comes in contact with camera positioned over field, the ball played is called dead ball deeming it not legal. There is a recent incident of the human operated camera accidentally hitting the player and knocking him to the ground but no serious injured is caused and the camera is temporarily suspended from use in that match.[52] Spidercam is still operated in global scale in major sporting events despite the dissatisfaction of players as it can get too close to the playing zone of players.

6.2 System Failure

Power failure impacts the sport most and particularly on sports those that rely on electronic equipment and technology. Some of the general problems of power

failure include delayed or even cancelled game if the issue cannot be resolved quickly, safety concerns for players and fans during a night game and ventilation system stops working in stadium causing temperatures to rise.

System Failure caused by power fail is one of the common problems in technologies for sports which causes disruption of the play. Many sports events rely on technology for scorekeeping, timing, and instant replay. If the systems fail, this may lead to inaccurate or delayed results because of technical difficulties. It can also disrupt television broadcasts of sports events which can be frustrating for important moments of the game.

In football, goal line technology GoalControl has been dropped by French football league after errors in 2 consecutive cup matches as they are not considered reliable anymore. In one match it wrongly indicated in referee’s watch that a goal has been scored after bouncing down from the crossbar, but it was ruled out after the realization of referee about the technology error. This malfunction was caused by the intensity of LEDs in the stadium which distorted GoalControl cameras, leading to the referee's watch to wrongly vibrate signalling a goal.[53,54] Hawk-Eye goal line technology is used in the French league in following season replacing GoalControl.

7 Conclusion

The aim of the study was to learn about the technology used in the sports stressed during competition. The thesis discusses how data is collected in sports and its usage in analytics for predictions and suggestions for approaching the next match.

Major sporting events give us glimpses of technological advancement with implementation of the latest technologies. One example is the introduction of Field Support Robot, an autonomous robot introduced in Olympics in Japan to support the retrieval and transportation of throwing objects such as hammers, javelins as quickly as possible and reducing the workload of the support staff

greatly during COVID period. Technologies in sports must be utilized in assisting the sport only without any interference in the game.

AI becomes more valuable as the amount of available data increases, allowing it to learn and make more accurate predictions and actions. Although player data collection is necessary in helping the team, there should be boundaries for protecting privacy of players as they are constantly monitored even in their personal life.

Simulation technology is revolutionary in terms of its realistic imitation in virtual environment and its application in perfecting skillsets of professionals in golf with the inclusion of fun activities. Football Manager is one game that has inspired many enthusiastic players to take leap in sports industry and some of them have gone onto become analyst and real manager of club.

One topic that is not discussed in the study is that security of system is more important than realized to stop intrusion in the system operating the sport as any penetration in the system can have costly consequences. Also, many of the technologies are only discussed briefly as most of them are proprietary.

Sports holds significant cultural and societal importance, invoking a range of emotions from the followers of their respective teams. The consequences of a wrong decision can alter the trajectory of an athlete's career and impact the lives of millions of people.

While older sports technology has become outdated, they played a crucial role in paving the way for advancements towards perfection. The utilization of modern technologies has improved decision-making accuracy and efficiency, ensuring that game results reflect fair outcomes and reducing despair among people towards officials maintaining game rules. Despite being underappreciated by some, these technological innovations in all aspects of sports bring the experience to new heights, offering breath-taking immersion to the audience.

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