Goal-Line Technology in Soccer: Discussion and Evaluation of Systems

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***Abstract*—One of the most heavily debated issues in the world of sport is whether technology can positively impact a sport without being intrusive. In the world of soccer, the issue of incorrectly awarding or not awarding a goal has been a source of significant controversy. To reduce the chance of making a wrong call, goal-line technology (GLT) systems have been proposed and implemented at the highest level of the game. This report introduces the concept of GLT, discusses the image processing techniques that play a big part in a successful GLT system, namely object detection and object tracking, and explains the working of two GLT systems used in soccer that use image capture technology to make split-second decisions, namely the systems proposed by Hawk-Eye and GoalControl.**

***Index Terms*—Soccer, goal-line technology, ball tracking, object detection, object tracking, Hawk-Eye, GoalControl**

I. INTRODUCTION

SOCCER is the world's most popular sport. Viewership for the 2014 FIFA World Cup Final in Brazil was estimated at 1.01 billion, the single largest for any sporting event ever recorded. Such a large global presence and following automatically places intense scrutiny upon the most fleeting of incidents on the soccer field. Thousands of crazy fans jump up in protest or gleeful cheering when the referee makes a controversial decision that might impact the game in a huge way, and there are several examples of such incidents throughout the course of soccer history. Due to the speed at which the modern game is played, the possible presence of obstacles that might hinder the referees' views, the intense pressure on referees, human error and many other factors, the frequent occurrence of such incidents during the course of a 90-minute soccer game is not altogether surprising.

With the advent of modern technology, an increasing number of voices have called for the introduction to soccer of cutting-edge devices and gadgets equipped with tools to make these controversial decisions on behalf of the referee. Arguably the most important of these decisions involve whether a goal has been scored. In order reduce human involvement in the matter of goals, several proposals have been made to install goal decision systems, ranging from a chip on the ball to a magnetic field within the area enclosed by the goalposts.

Two proposals – Hawk-Eye and GoalControl – have emerged as front-runners in the business. Both these systems employ a number of high-speed cameras, installed at various positions around the stadium and pointing towards one of the two goals, that detect whether the ball has crossed the goal line or not. This report includes a significant understanding of these systems, and their approaches to determine the legitimacy of a goal.

II. BACKGROUND AND MOTIVATION

An inherent quality of sport is that it is unpredictable; that is the beauty of sport. The human element involved in sport inherently creates several situations where a judgment call must be made by the official. A tennis ball that lands out might be called "in"; a baseball batter might strike out despite a clear "ball" pitch; a basketball team might be awarded possession despite themselves having touched the ball last before it went out of bounds. While judgment calls such as these are more often than not a part of the game, even the smallest such incident might have severe repercussions due to the competitive nature of sport.

The famous 1966 FIFA World Cup final between England and Germany was controversially decided by one of the most famous judgment calls in all of soccer. As the game reached its final stages, 11 out of 30 extra-time minutes had been played with the score tied at 2-2 when England striker Geoff Hurst struck the ball against the vertical bar; the ball landed square on the line (see Fig. 1) before being cleared by a defender.


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***Fig. 1**: Geoff Hurst's goal during the 1966 FIFA World Cup final*

Due to the lack of available technology and in accordance with the official rules, the referee and the linesman convened to discuss their individual points of view, and subsequently awarded a goal to the England team; despite angry reactions from the German players, the goal stood. England went on to win their first World Cup. Retrospective analysis shows that the ball did not fully cross the line, meaning the goal should not have been allowed.

Can such a significant error be corrected today? With significant research and improvements in the field of image processing and vision, as well as the availability of super high-speed cameras to track even infinitesimal incidents, the answer is a resounding yes.

III. LITERATURE REVIEW

A. *Goal-line technology*

In simple terms, goal-line technology (GLT) in soccer is a way to determine whether a goal has been scored. A goal is scored when the ball is anywhere within the confines of the two vertical poles, known as goalposts, and one horizontal pole, known as the crossbar.

As per FIFA's GLT testing manual, "The objective of goal-line technology is not to replace the role of the officials, but rather to support them in their decision-making. The GLT must provide a clear indication as to whether the ball has fully crossed the line, and this information will serve to assist the referee in making his final decision." The guidebook also states the four basic requirements a successful GLT system must fulfill:

- The goal-line technology applies solely to the goal line and only to determine whether a goal has been scored or not;
- The GLT system must be accurate;
- The indication of whether a goal has been scored must be immediate and automatically confirmed within one second; and
- The indication of whether a goal has been scored will be communicated only to the match officials (via the referee's watch, by vibration and visual signal).

B. *Use of technology in other sports*

Cricket and tennis are two sports that have embraced technology in order to assist officials in making judgment calls. Cricket has employed TV replays since the early 1990s to accurately determine run-outs, and more recently has included Hawk-Eye technology in its repertoire to determine the outcome of an LBW decision. Tennis has used Hawk-Eye since 2002 to accurately determine the landing position of the ball and reduce human error.

The stop-start nature of both cricket and tennis is a great boon to technological intervention. Since both sports have seconds-long "plays" separated by pauses, a decision review system can be called for between plays without severely affecting the natural flow of the game. Sports such as basketball, baseball and football are also conducive to technological intervention in between plays for the same reason. Unfortunately, due to the non-stop nature of soccer, the constraints placed on automated systems are far more strict. One of these constraints pertains to the time taken to reach a conclusive decision. Since plays are continuous without delay as well as uninterrupted, the GLT system employed in soccer must not only be able to instantaneously reach a conclusion, but do so in a non-intrusive manner.

C. *External factors affecting GLT systems*

The GLT system must be able to eliminate external factors such as player obstruction, partial visibility of the ball, etc. The presence of several players on the goal line is a common one, and at no point must the GLT be unable to make a decision. This can be resolved by, for instance, having multiple cameras working simultaneously so that a combination of images obtained by these cameras can be used to accurately predict the exact location of the ball at a given point in time (*Hawk-Eye*, *GoalControl*). Other approaches include using sensor-based technology to determine the location of the ball (*GoalRef*), installing sensors inside the ball (*Cairos*), and more.

IV. OVERVIEW OF A GOAL-LINE TECHNOLOGY SYSTEM

Fig. 2a shows a schematic diagram of a general goal-line technology system. Four high-speed cameras are placed on the four goal sides in such a way that their optical axes are parallel to the surface plane. These cameras are capable of capturing images at 200 fps. Each camera has a processor connected to it. The processor is responsible for recording and processing the images being taken by the camera. A main node, which has the supervisor function, is connected to all four camera processors. It is responsible for evaluating and comparing the results obtained from the four processors. It also sends the alarm signal to the referee's watch when a goal has been detected.

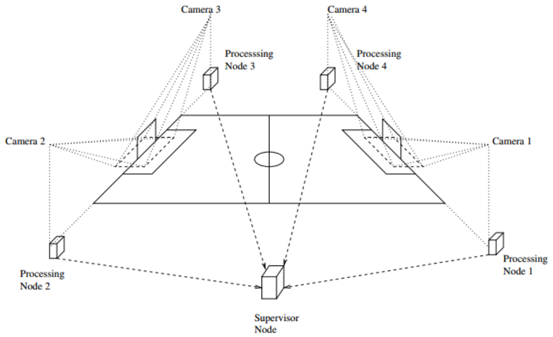


Fig. 2a: *Schematic diagram of a GLT system*

A. *Processing nodes*

Fig. 2b shows a schematic diagram of the processing steps at a camera processing node.

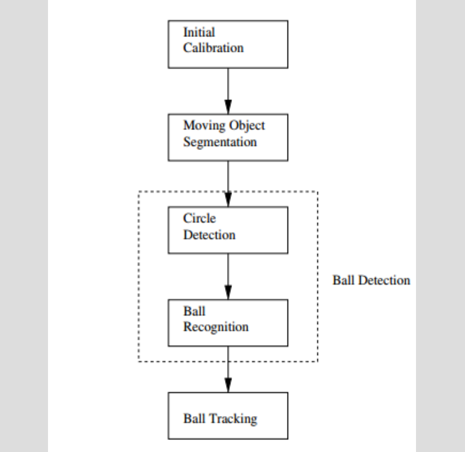


Fig. 2b: *Flow diagram of the processing steps at a node in the GLT system*

These steps are explained below:

i. Initial calibration: A set of four points, one for each camera on the field, is taken so as to observe the correspondence between the ground plane and the image plane. A transformation matrix **M** is evaluated that relates the set of points on the image plane with those on the real plane. The point where the two viewing lines intersect is the point estimate of the ball (see Fig. 3).

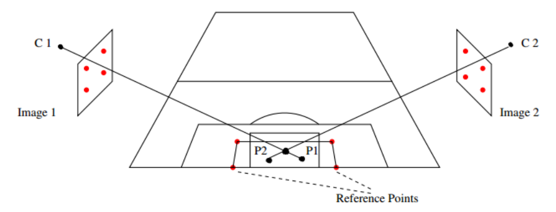


***Fig. 3**: The intersection of the lines formed by the four reference points produces the point estimate of the ball*

From the formula of transformation of projections from one plane to another, we have

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{33} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \tag{1}$$

or, $x = \mathbf{M}X$. In Cartesian coordinate form, this transformation becomes

$$\begin{aligned} u &= \frac{x_1}{x_3} = \frac{m_{11}X+m_{12}Y+m_{13}}{m_{31}X+m_{32}Y+m_{33}} \\ v &= \frac{x_2}{x_3} = \frac{m_{21}X+m_{22}Y+m_{23}}{m_{31}X+m_{32}Y+m_{33}} \end{aligned} \tag{2}$$

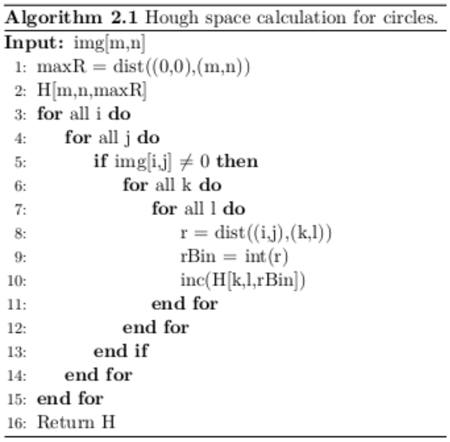
where (u,v) are the coordinates in the image plane and (X,Y) are the coordinates in the real plane. The transformation matrix **M** is obtained by solving equation (1) using the correspondence between the (u,v) plane and the (X,Y) plane of the four points. Repeating this for the two cameras on the two image planes, the projections (P_1,P_2) on the real plane can be obtained (Fig. 3). The intersection of (C_1,P_1) and (C_2,P_2) is the real position of the ball on the field. Then, it is only necessary to calibrate the positions of the two cameras (C_1 and C_2) and the positions of the four reference points once, when the cameras are installed. If the cameras are fixed, these calculations are valid at all times.

ii. Moving object segmentation: This process is very essential to a GLT system, as it focuses the area where the ball is to be searched, and also reduces the time for computation. A segmentation algorithm analyzes the connected regions from the input image set, allowing for the evaluation of the size of regions and hence the possibility of eliminating large sample spaces where the ball search need not be applied. A background subtraction algorithm is used to distinguish moving points from static points.

iii. Circle detection: The circle detection process is the central process in building a GLT system. The algorithm to identify the soccer ball has to be fast, simple and effective. To do this, the proposed method is split into two parts: *a*) a general circle detection step; and *b*) a ball recognition step. The circle detection algorithm being used is based on Circle Hough Transform (CHT) (Fig 4). The CHT aims to find circular objects of a given radius from the input image set. A number of modifications have been implemented on the circle detection algorithms in the last few years, in order to reduce the burden on computation and reduce the number of false positives.

iv. Ball recognition: Once circles have been detected, they are passed on to a neural classifier that has been trained to separate objects as “ball” and “no ball” objects. Fig. 5 contains examples of objects accepted by the ball recognition process.

v. Ball tracking: This procedure is applied to the regions that were earlier estimated to contain the ball. Once the ball detection algorithm identifies the ball, a tracking procedure is initiated. During this phase, the ball search is applied to all moving regions of the image, with no regard for their position. Then, in each successive image, the ball search algorithm is constrained by a small area around the ball to speed up this step. If the ball is not found in the predicted ball position, the search is repeatedly performed on an increasingly larger area until the ball is found, and the tracking step continues.



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Algorithm 2.1 Hough space calculation for circles.
Input: img[m,n]
maxR = dist((0,0),(m,n))
H[m,n,maxR]
for all i do
    for all j do
        if img[i,j] $\neq$ 0 then
            for all k do
                for all l do
                    r = dist((i,j),(k,l))
                    rBin = int(r)
                    inc(H[k,l,rBin])
                end for
            end for
        end if
    end for
end for
Return H
```

***Fig. 4** : Hough Transform algorithm for circles*

***Fig. 5**: Different appearances of the ball*

B. *Supervisor node*

The supervisor node is responsible for making decisions regarding ball detection and tracking, in accordance with the data obtained from each camera. The supervisor node analyzes the data obtained to decide between the following events: Goal, No Goal, Probable Goal and Line Passing.

Another aspect that the supervisor node must take into account is the position of the ball with respect to the goal plane. For a goal event to be detected, the ball must be detected to be beyond the goal line and inside the goal posts. However, due to the fact that homographic transformations might be affected by small errors in the areas near the woodwork, an uncertainty region is also defined, where the system cannot be sure about the position of the ball. This region is called the "probable goal" region.

Table 1 gives the summary of decisions taken by the supervisor node.

System Decision	Node 1 Answer	Node 2 Answer	Homo-graphic Control	Position Control
GOAL	Ball	Ball	Ball	Inside
NO GOAL	Ball	Ball	Ball	Outside
PROBABLE GOAL	Ball	Ball	Ball	Probably Inside
LINE PASSING	Ball	Ball	No Ball	—
	{Ball, No Ball}	{No Ball, Ball}	—	—

***Table 1**: Summary of supervisor node decisions*

C. Summary of goal-line technology system

The above is a simple model of a GLT system that, in practice, can detect the event of a goal or no goal with significant accuracy. By developing more robust algorithms, faster and more powerful hardware and reducing the chance of errors by increasing the number of hardware components, a very high accuracy can be achieved, making it a foolproof indicator of goal decisions.

There are a few drawbacks, the main one being the cost of installation and operation. The high-speed cameras need to capture data at a rate of 200 frames per second. Over a 90-minute game, that adds up to 1.08 million images. These images also need to be processed at the supervisor node. The cost of each camera is estimated to be around £1,500. In total, it is estimated that the cost incurred at each stadium would be a minimum of £250,000 for initial setup and additional costs for running the system, depending on which system is implemented. Such astronomical figures have been major hindrances to professional soccer leagues around the world, most notably in Germany, where the league refused use of the available technology citing cost as the prime factor.

V. HAWK-EYE AND GOALCONTROL

We now come to two GLT systems that have received acceptance by FIFA to be installed across stadiums. Both these systems use a more enhanced version of the above GLT prototype, using seven high-frame rate cameras permanently pointed towards each goal, bringing the total to 14 per stadium. Both systems approach the problem of goal detection in a similar way. Minor differences lie in the positioning of cameras, and the function of the central unit.

A. Hawk-Eye

Hawk-Eye's foray into the sports video analysis domain began in 2001, when it was developed in the United Kingdom for television purposes in cricket. Originally intended to be used to track the trajectory of the cricket ball in flight, it was later adopted to be used as a support system for deferring contentious decisions to the "third umpire", an official sitting in a video control room and equipped with systems to assist him in making the correct decision. One of the most useful applications early on was in judging leg-before-wicket decisions correctly.

Hawk-Eye's impact in the world of professional tennis has been massive. Starting from 2004, Hawk-Eye's AutoRef system has been used to identify the exact landing position of the ball. Today, it has been used in almost every level of tennis, and has become a ubiquitous part of the game, with the challenge rule that facilitates Hawk-Eye's AutoRef system being incorporated officially into the ATP tour.

Hawk-Eye's introduction to the world of soccer was in 2012, when it was approved (along with GoalRef) and advanced to a second phase of testing. The technology was first tested in an international friendly between Belgium and England at Wembley, although the data was not available for use during the game; only FIFA had access to the system readings. In April 2013, technology was accepted at the highest levels of professional soccer when Hawk-Eye was officially approved by the Premier League for use in its 2013-14 season. The first use of Hawk-Eye was on 17 August 2013 at Anfield, Liverpool. The first time Hawk-Eye verified a goal was on 18 January 2014 at the Etihad Stadium, Manchester.

B. GoalControl

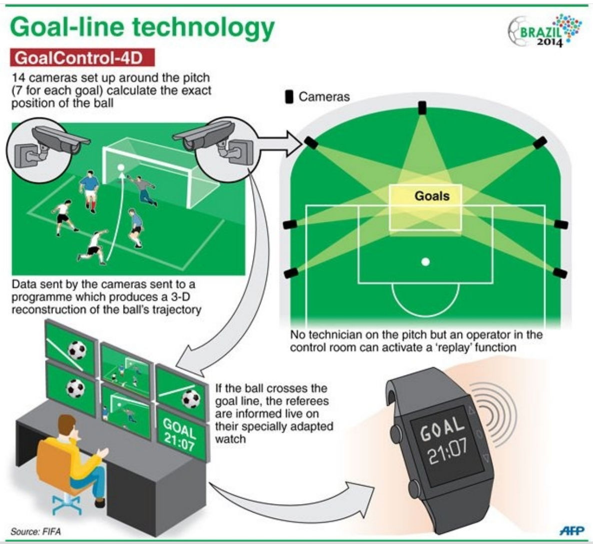
GoalControl is a technology company based in the district of Aachen, Germany. GoalControl's technology was licensed for the first time by FIFA in 2013. Upon successful testing of the camera systems employed in this GLT system, it was used for the first time in the 2013 FIFA Confederations Cup in Brazil where it was used to detect 68 goals throughout the competition. Later, during the 2013 Club World Cup held in Morocco, GoalControl was used only to track the ball (GoalRef was used for display).

In early 2014, a vote was cast by 36 members of the top two divisions of the German Bundesliga. Needing 24 for the motion to carry, only 12 of the 36 members voted in favor of including goal-line technology, citing the exorbitant cost of installation and maintenance per club.

In 2014, history was made when GoalControl became the first company to license a GLT system at the World Cup, when it was officially featured as the review system to be used in the 2014 FIFA World Cup in Brazil. On 15 June 2014, in a game between France and Honduras at Porto Alegre, a shot from France's Karim Benzema bounced back off the goalpost, and an ensuing fumble from the goalkeeper led to an own goal. This incident was the first time GoalControl's system was used to award a goal.

C. Working of the systems

Both Hawk-Eye and GoalControl employ seven high-speed cameras, capable of capturing images at a rate of nearly 500 frames per second. The cameras are constantly detecting movement on the field, and must, with a very high level of accuracy, be able to distinguish between the ball and a human object.



14 cameras set up around the pitch (7 for each goal) calculate the exact position of the ball

Data sent by the cameras sent to a programme which produces a 3-D reconstruction of the ball's trajectory

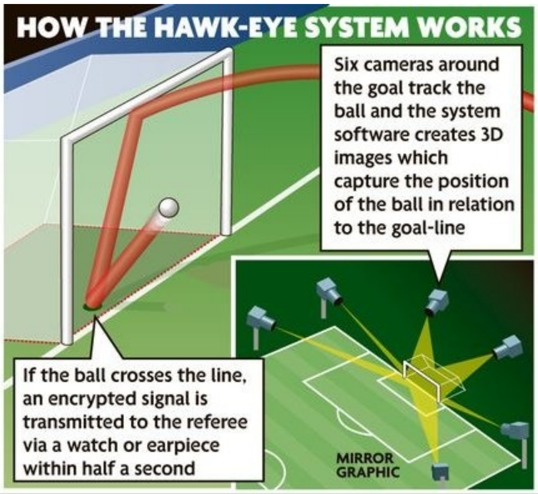
No technician on the pitch but an operator in the control room can activate a 'replay' function

If the ball crosses the goal line, the referees are informed live on their specially adapted watch

Source: FIFA

***Fig. 6a**: Working of GoalControl's GLT system*

At the moment the ball enters the penalty area, designated as the bigger rectangular box enclosing the goal space, the cameras become active and transmit images of the ball to the central unit. This unit is responsible for making the final decision when the ball is in the vicinity of the goal. If the ball crosses the goal line, the central unit sends an encrypted signal to the match official's watch, indicating to him that a goal has been scored. Fig. 6a and 6b show the working of the GoalControl and Hawk-Eye GLT systems, respectively.



Six cameras around the goal track the ball and the system software creates 3D images which capture the position of the ball in relation to the goal-line

If the ball crosses the line, an encrypted signal is transmitted to the referee via a watch or earpiece within half a second

***Fig. 6b**: Working of the Hawk-Eye GLT system*

The two systems promise that as long as 25% of the ball is visible and at least two cameras are able to detect the ball, a decision can be made.

VI. SUMMARY AND CONCLUSION

In this paper, we discuss the motivation in bringing technology to the world of soccer. Eliminating human error is the driving force behind goal-line technology systems today. However, the systems are not perfect yet: while they are very efficient at detecting a goal event up to millimeter levels, the biggest hindrance is the exorbitant costs involved in setting up and maintaining these elaborate systems.

We then explain a proposed model of a general goal-line technology system, and provide an overview of the image processing concepts involved in the working of a real-time GLT system. Finally, we discuss two GLT systems that have gained acceptance and have been used in tournaments at the highest level of the game.

Like any piece of technological innovation, GLT succeeds in simplifying a problem by automating tasks that are difficult and, at times, impossible for the human mind to process. With further improvements in the field of goal-line technology, we can expect reduced costs, less ambiguity and more accuracy when making decisions.

A video presentation, accompanied by a Python program to demonstrate goal-line technology, can be found here.

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