2.1 Introduction
The aim of this chapter is to use the information gained from the literature review as a guide in the development of the apparatus to project and record the impacts of golf balls on turf. It was found in Chapter 1 that, although experiments have been carried out on the impact of elastic spheres on rigid surfaces, the impact of the ball on the green has essentially been ignored. It was first necessary, therefore, to design and develop an apparatus to project golf balls with the desired speeds, spins and angles similar to those found in play (section 1.2). During the development of the ball projection device, a method of recording the impacts was devised. The two sets of apparatus were therefore developed in parallel since modifications in one affected the design of the other.

The United States Golf Association (USGA) was consulted to find its views on the methods that could be used, as were the Acushnet Company and Dunlop/Slazenger Limited. There were frequent discussions with the supervisors for the project and from these, a set of guide-lines for the development of the apparatus emerged. There was a necessity for the apparatus to be light in weight as it was to be used on golf greens. This would limit the damage to the turf and ease the transportation of the apparatus to and from the greens. Each impact caused a pitchmark rendering that particular point on the turf unsuitable for further impacts. The apparatus, therefore, needed to be manoeuvrable after every impact. It was unlikely that a mains power supply would be available near to a green and it was envisaged that the equipment would be powered by a portable generator. As golf would continue to be played on the greens during testing, the interference to play needed to be kept to a minimum. Finally, the initial budget was to be £3,000 paid over three years. This was subsequently increased with an equipment grant of $12,000 from the Acushnet Company.

For convenience, the design of the equipment was separated into three sections; (1) the launching of the golf ball at the green with variable speed, spin and angle; (2) the recording of the motion of the ball before and after impact and (3) the selection and, if necessary, the development of the apparatus to measure the playing characteristics of the green. These are dealt with in the following sections.

2.2 Projecting the golf ball

(i) Choice of apparatus
Commercially available ball projectors are of two types: mechanical and pneumatic. In research both types have been used. Putnam et al. (1983) used a pneumatic projector to project tennis balls at tennis rackets and Thorpe and Canaway (1986a) used both types
FIGURE 2.1. The original baseball practice machine that was marketed in this country for cricket and tennis. The ball rolls down the chute where it enters the gap between two counter rotating wheels with pneumatic tyres and is subsequently projected out the other side.
of machine in the analysis of ball impacts. Of the two types, the mechanical projector is more suited to golf work because of the importance of spin. Pneumatic projectors have limited scope for controlled variation in spin and were therefore rejected at an early stage. Consequently, a mechanical ball projector was obtained. The "Jugs" bowling machine was franchised in the UK by En-tout-cas Ltd. of Leicester and was marketed as a cricket and tennis practice machine. It was originally designed in the United States as a baseball practice machine and is shown in Figure 2.1. It has two identical 410mm diameter wheels with pneumatic tyres mounted on two 90V d.c. motors and with their axes parallel. The wheels rotate in opposite directions (Figure 2.2). When a ball rolls down the chute it enters the gap between the wheels. It is then gripped and fired out of the other side. The speeds of the two motors can be altered independently in order to impart spin to the balls. A ball attains the approximate average peripheral speed of the wheels, while the spin is determined by the difference in the wheel speeds using,

\[
\text{spin} \approx \frac{\text{peripheral velocity of ball}}{\text{diameter of ball}}
\]

If the peripheral speeds of the two wheels are 40\(\text{ms}^{-1}\) and 30\(\text{ms}^{-1}\) then a tennis ball of radius 64mm would attain the following:

\[
\text{spin} \approx \frac{40 - 30}{0.128} = 79\text{rads}^{-1} \text{ and, velocity } \approx \frac{40 + 30}{2} = 35\text{ms}^{-1}.
\]

As originally supplied, the bowling machine was mounted on a ball joint connected to three legs and could be tilted to almost 45 degrees in any direction about a horizontal plane originating at the ball joint. The scale on the machine purported to fire baseball size balls at up to 100 miles per hour (44.4\(\text{ms}^{-1}\)). The spin attainable by the balls is dependent on the velocity at which the balls are projected. This is limited by the upper and lower velocities of the wheels.

---

**FIGURE 2.2.** A schematic diagram showing a method of projecting tennis balls. A ball rolls down the chute and enters the gap where it is gripped by the wheels and projected out the other side. The peripheral velocities of the wheels determine the velocity and spin of the projected ball.
As the velocity of projection approaches these limits, the possible differences in wheel speeds are reduced. This reduces the choice of spin.

It was considered, at this stage, that the “Jugs” bowling machine could have been modified to fire golf balls or used as a model from which to construct a totally new projection device. In conjunction with other projects at the Sports Turf Research Institute, the latter option could have incorporated an adjustable machine to fire footballs, tennis balls and cricket balls as well as golf balls. At this stage, however, the bowling machine was known to work and it was decided to keep to this design as far as was possible.

(ii) Achieving the correct velocity
The new ball firing device was required to project golf balls directly at the ground with speeds up to 30ms\(^{-1}\), spins up to 930rads\(^{-1}\) and angles up to 75° (section 1.3). Initial studies using the machine to fire golf balls found that it could not give the balls these speeds and spins and could not fire at the desired angles. When a golf ball entered the gap, it was not gripped firmly by each of the wheels. The ball then moved along the periphery of one of the wheels resulting in a velocity or angle that was not expected. The gap of 37mm seemed to be too large. The manufacturers of the bowling machine, when contacted, recommended that the gap be two thirds of the diameter of the ball to be fired. For golf balls this was 28.4mm; a reduction of 8.6mm. The options considered in the modification of the bowling machine are summarised in Figure 2.3.

![FIGURE 2.3. The options that were considered during the development of the bowling machine.](image-url)
To decrease the size of the gap between the wheels the first solution involved machining larger wheels and adhering a thickness of rubber to the outside of these. However, there were no firms in the UK that either sold or could manufacture alloy wheel hubs of the correct diameter. It was thought that wheels made out of mild steel (the only type available) would be too heavy and would introduce additional complications such as the need for stronger supports and more powerful motors.

An alternative was to adhere a 100mm wide 4.5mm thick strip of rubber onto the periphery of the existing wheels. This reduced the gap between the wheels to 28mm. When firing golf balls at low velocities, the wheels performed well, but on the first run at a high velocity the rubber became detached proving this solution to be unviable.

![Diagram](image)

**FIGURE 2.4.** A schematic diagram (not to scale) showing the design of the stand to hold the ball projection device in a vertical plane thus enabling the projection of the ball with backspin.

A third solution to this problem was to design a new yoke to hold the existing wheels closer together. When the bowling machine was inspected to see how this was to be done, it was found that the motors could be unbolted and new holes for the bolts drilled such that the axes of the motors were approximately 8mm closer together. This proved to be a successful solution.
(iii) Achieving the correct spin

The bowling machine was required to fire golf balls with backspin. This involved supporting the wheels in a vertical plane. Initially, it was thought that the original tripod stand could have been tilted until the wheels were vertical and the motors then supported from underneath in some manner. However, it would not have been easy to move the apparatus between impacts since the centre of gravity was so high. It was therefore decided to design and make a new support for the yoke, motors and wheels and this is shown in Figure 2.4 and Figure 2.5. The stand had a large backplate onto which the bowling machine yoke was bolted and had a V-nest for extra support to the bowling machine body. The struts were made of 25mm mild steel hollow tubing and there were angled supports attached to the horizontal cross members for strength and stability. With the axes of the wheels in a horizontal plane the wheels were able to project the golf balls with topspin or backspin. With the lower wheel rotating faster than the upper wheel the balls emerged with backspin in the same way as the original machine.

It was becoming increasingly difficult to manoeuvre the ball projection device when supported on this stand. A wheel could have been attached to each of the corners of the bottom of the stand but it was thought that, when the projector was in use, the vibrations would have made it move. Instead, two wheels from a golf green top-dressing machine were attached to the bottom of the stand while a handle was attached to the opposite side (Figure 2.5). The side of the stand touching the ground prevented the apparatus from moving during use. This arrangement enabled the ball projector to be moved after each impact and enabled transportation between greens while ensuring that the stand did not damage greens where the projector was used.

Preliminary tests were carried out on the ball projector using a video camera and a stroboscope in a darkened room. A 10W stroboscope loaned by the University of Leeds and a Sony video camera were placed at the point from which the golf balls emerged from the bowling machine. With a stroboscope frequency of 250Hz about 10 images could be recorded on one frame of video tape. Using a ruler placed in the field of view of the camera it was possible to estimate the distances between images directly from the television screen and hence to calculate the speeds. It was found that the ball projector could project golf balls with velocities up to 35m s\(^{-1}\) and with spins up to about 700rads\(^{-1}\). The bowling machine dials were marked out in mph and a setting of 30mph on each wheel projected the ball at about 45mph (20ms\(^{-1}\)). This zero error was found to be consistent throughout the speed range.

The direction at which the golf balls were fired was measured using a clinometer. This employed a small spirit level which was able to rotate within a circular scale, graduated
FIGURE 2.5. The bowling machine after it had been modified to fire golf balls. The two topdressing machine wheels and the handles enabled trans- portation between greens and between impacts.
every half of a degree. The clinometer was set at the desired angle and placed on the chute on the ball projection device. The angle of the yoke supporting the pneumatic wheels and motors was then altered until the air bubble in the spirit level indicated that the set angle had been reached. Golf balls could be fired at angles up to seventy degrees to the horizontal. At higher angles, the projection of the ball was restricted by the angled struts on the ball projection device stand.

The development of the ball projection device and its stand occurred in parallel with the development of the process for the recording of the impacts. At this stage of the project it was envisaged that the exact values of the spin, speed and angle of the ball after projection would be calculated at the recording stage and were not required from an exact calibration of the projection device.

2.3 Recording the impacts

(i) Introduction

The use of infra-red light beams as timing gates was considered as a method of measuring the velocities and angles of the ball before and after impact. A set of timing gates already in use at the Institute was set up to try and measure the velocity of the ball as it left the bowling machine. As the ball cut the first light-beam a timer was started and then stopped by the passage of the ball through the second beam. However, this was not deemed suitable since an additional method was required to record the spin of the ball. Other methods such as using radar or sonar devices to record the motion of the ball were not considered since the potential cost was high and the analysis required to measure the spin of a rotating object was very complicated.

During the literature review it was found that photometric methods were used most often for recording impacts of spheres with surfaces. Putnam and Baker (1984) used stroboscope photography to study the impact of tennis balls with differently strung tennis rackets as did Maw et al. (1981) when they studied the impact of disc shaped pucks with surfaces of a similar material. Tatara (1981) used high speed cine film running at 5000 frames per second (fps) to study the impact of tennis balls with the ground while Thorpe and Canaway (1986) used ordinary cine film running at 64 fps to record the impacts of tennis balls with different playing surfaces. These methods were evaluated and it was found that the use of cine film was not suitable for this project. Using high speed film would have been far too expensive since each film would have cost about £20. It was envisaged that about 500 impacts were required and since there could only be one impact per film, the budget would have been used up very quickly. A normal cine camera running at 64fps would not have been fast enough to record balls impacting at speeds
over $10\text{ms}^{-1}$. Even at this slow speed the golf ball images would have been more than 150mm apart and the camera would have had to be at such a distance to see multiple images that the spin would have been unmeasurable. The method of stroboscope photography was ultimately chosen since it appeared to be the cheapest and easiest method of evaluating the impacts of golf balls on turf. It was envisaged that a Polaroid type of instant film would be used which would provide instant records of the impacts. This was the method employed by the USGA and the Acushnet Company in the analysis of the flight of a golf ball after impacting with golf club face.

Preliminary tests on the bowling machine used stroboscope photography employing a Sony video camera and a 10W stroboscope as a light source. However, this source was very weak compared to the amount of background light that is present out of doors and a more powerful stroboscope was needed. A new stroboscope, a Drelloscope 1017N, was subsequently tested and purchased. It was able to run at up to 600 flashes per second, with a flash duration of less than 10\(\mu\)s and with a maximum power output of 200J at 50Hz. It had an illumination area of approximately 7m\(^2\) at a distance of 2m. The power unit was driven by a pulse generator which provided 10V spiked pulses at the desired frequency.

Initially, this stroboscope was used in conjunction with a Nikon FE 35mm still camera to look at impacts on small pieces of artificial turf. The ball was fired indoors in complete darkness and the camera shutter opened using the "B" setting, while the stroboscope was switched on manually at the appropriate time. The camera shutter was then released after the impact. The film was thus exposed with images of the ball at equal points in time along its incoming and outgoing path. Although the images obtained were ideal for the purposes of analysis, it was not a very refined system since it required the co-ordination of two people to ensure that the delivery of the ball and the opening of the shutter occurred at the same time. An automatic method of activating the stroboscope and camera as the ball entered the field of view was needed and the use of electronic "triggers" was researched.

(iii) Activating the camera and stroboscope

An electronic trigger was designed and built using standard components, the circuit diagram for which is shown in Figure 2.6. A high powered infra-red emitter was located on one side of the chute with a detector placed on the opposite side (infra-red light was used to minimise the effect of sunlight on the detector). The 500k\(\Omega\) potentiometer connected to pin 2 of the operational amplifier was used to set the voltage level representing the background light close to the voltage level of the detector. When a ball passed in front of the detector, its voltage dropped below that of the background radiation
FIGURE 2.6: A circuit diagram of the trigger that was developed to activate the camera and strobeoscope as the ball entered the field of view of the camera.
and a pulse was output from the amplifier. This output was then passed to the input of the first 555-timer which subsequently output a square pulse, the length of which was determined by the RC value across pin 6. The falling edge of the output pulse from the first 555-timer caused the second 555-timer to output a pulse half a second long. The final pulse was used to drive a solenoid (replaced by a relay in Figure 2.6) which activated the shutter release of the camera. It was possible to alter the time delay before the output pulse by changing the RC value across pin 6 of the first 555-timer. This was done using a switch to increase the resistance from 100 kΩ up to 470kΩ in 90kΩ intervals. The resistance could be altered continuously throughout this range using a 100kΩ potentiometer connected in series to these resistors. It was necessary to have a variable time delay since the travel time of the ball to the point of impact was different at different velocities and angles. A diode was placed in the 12V line so that incorrect battery connections would not damage the components. The circuit was encased in a diecast aluminium box measuring 14mm x 100mm x 75mm and the 12V power supply, inputs and outputs were connected to 4mm insulated terminals using 4mm banana plugs. Red LED's were connected across the output of the two 555-timers and were attached to the lid of the box. The first indicated the passage of the ball through the light beam while the second indicated the triggering of the camera after a set time delay.

It was found that it was difficult to predict the length of time required for the solenoid to push against the shutter release spring of the camera and hence to set the time delay on the trigger. Camera systems were evaluated and a direct method of using the trigger to activate the camera was found. Consequently a Bronica ETRS camera was purchased which could be activated remotely by electronic means: closing a switch across the relay input on its motor-wind caused the camera shutter to open. The solenoid on the trigger was therefore replaced by a relay switch. The triggering of the camera occurred almost instantaneously with the output of the trigger and the time delay could be set with much more confidence.

The stroboscope was switched on manually at this stage, so as an added refinement the trigger was used to activate the pulse generator which drove the stroboscope power unit shown in Figure 2.7. When used on the “gate” mode, the pulse generator only produced pulses when the gate input voltage was above 1V. This pulse was provided by the second 555 timer in the trigger and was the same pulse as that which closed the trigger relay. The electronic trigger was therefore used to activate both the camera and stroboscope as the ball entered the camera's field of view.
FIGURE 2.7. The complete set of apparatus used to photograph the impact of a golf ball on a green.
(iii) Exposing the film

The Bronica camera had the advantage of interchangeable backs which held different types of film. It was thus possible to set up the system using Polaroid instant film to check that the golf balls were landing in the centre of the camera view and that the camera and stroboscope were being triggered at the appropriate time. It was then possible to change the film back to one containing 220 rollfilm for permanent records and enlargements of impacts.

A distance scale was required in the picture in order to calculate the velocity of the ball through the picture frame. Having a scale in the field of view while the impact was taking place either obscured the view of the impact or reflected too much light from the stroboscope. However, the camera had the facility for multiple exposures and it was possible to pre-expose each frame with an image of a scale placed in the plane of the impact of the ball. This plane was determined by the line of pitchmarks that were visible after setting up the system. The polaroid instant film was used for finding the correct exposures for the scale and for the impact so that one image did not obscure the other.

![Diagram of the frame of the tent designed to block out the background light from the camera.](image)

**FIGURE 2.8.** A schematic diagram to show the construction of the frame of the tent designed to block out the background light from the camera. The frame is usually covered with thick black cloth which has a hole in the end nearest the bowling machine through which to fire the golf balls.
It was necessary to block out the background light during the photograph of the impact because the camera shutter was open for a relatively long duration (one thirtieth of a second) and the intensity of background light was so much greater than that provided by the stroboscope. A small tent frame was constructed from lightweight "Dexion" metal measuring 1.5m long by 1m high by 1m wide and having a plastic 100mm diameter wheel on each corner. The camera and stroboscope were attached to a horizontal support which also had two wheels. This ensured that the stroboscope and camera remained in the same place relative to the tent frame whenever the latter was moved. The frame was covered with thick black cloth with a hole in one end through which the ball could be fired. This is shown schematically in Figure 2.9. One side of the cloth could be lifted up in order to move the camera and stroboscope nearer or further away from the bowling machine according to the angle at which the ball was being fired or to alter the camera settings. The bowling machine was attached by a single length of Dexion metal to the frame at the end through which the ball was fired so that when the bowling machine was moved after an impact, the tent, camera and stroboscope lamp moved with it. The bowling machine was pulled backwards since it was difficult to push it along with the tent and keep them both aligned. Restricting the connection between the ball projector and the tent to a single length of metal reduced the vibrations that were passed from the projector stand to the tent frame.

Since the apparatus was to be used on golf greens far away from any power source, a portable power supply was needed. A Robin 1.5kW generator was purchased which provided enough power for the bowling machine (700W) and the stroboscope (200W). The generator was also chosen because it was light enough to be lifted by one person and was relatively unobtrusive, therefore not distracting golfers.

(iv) Summary
The complete set of apparatus is shown in Figure 2.7 and to summarise, a typical golf ball impact is carried out as follows,

1. A golf ball rolls down the chute of the ball projector and cuts the infra-red light beam.
2. The ball enters the gap where it is gripped by the wheels and projected, with the required spin, speed and angle, through the hole in the tent wall towards the ground.
3. As the ball enters the field of view of the camera, the trigger, set to the required time delay, opens the camera shutter and activates the pulse generator which drives the stroboscope.
4. The ball rebounds, the camera shutter closes after one thirtieth of a second and the film automatically winds on.
5. The ball projector, tent, camera and stroboscope lamp are all moved about 100mm ready for the next impact.

After each impact, the depth of the pitchmark created was measured using a USGA green hardness tester (Figure 2.15). This consisted of a brass sphere the size of a golf ball threaded onto a shaft 120mm long. A freely rotating wheel was threaded onto this shaft. The sphere was placed below a metal shoulder on the level ground with the shaft vertical. The wheel was then rotated upwards until it became restricted by the shoulder. This provided a reference distance between the bottom of the sphere and the wheel. When placed in a pitchmark below the shoulder, the wheel was rotated upwards along the thread until it again became restricted. The distance between the bottom of the sphere and the wheel was now larger, the extra distance indicating the depth of the pitchmark. The number of revolutions were counted since each revolution indicated an upward movement of one twentieth of an inch. This gave an estimate of the depth of the pitchmark.

2.4 Application in the field
An example of a photograph of a golf ball impact is shown in Figure 2.10. The ball is entering from the right at 23.6ms⁻¹ at an angle of 50° to the horizontal and with about 125rads⁻¹ backspin. It can be seen that the ball slows down after impact (to 3.8ms⁻¹) and rebounds at an angle much larger than the angle of incidence (72°). The spin of the ball has been modified to topspin.

![Diagram of ball projector, tent, camera and stroboscope lamp](image)

FIGURE 2.9. A schematic diagram showing the enclosure used to reduce background light during the photograph of a ball/turf impact.

Although the apparatus and method used to create this photograph is relatively simple in principle, its use in a field situation is relatively difficult. One of the lessons learnt during
this project was to be prepared for any eventuality and above all to be patient. By the end of the project an accessory kit had been assembled which contained screwdrivers, screws, Allen keys, soldering iron and all manner of electronic spares.

Problems in the field usually related to the electronic trigger required to activate the camera and stroboscope. One necessity was to label clearly all wires connected to the trigger. This was soon discovered when the battery was connected the wrong way round resulting in the loss of the 555 timers, op-amp, emitter and detector. Consequently, a diode was placed on the 12V input line of the trigger and spare detectors, emitters and chips were included in the accessory kit.

One of the practical considerations, when on the green, was to plan the orientation of the apparatus with respect to the path of the sun. If the sun shone onto the detector, it caused false activation of the trigger. If it shone into the tent then the stroboscope photographs became washed out because of too much light. Other practicalities to be taken into account were the size and shape of the green and the position of the flag since play was to continue throughout testing. Surprisingly perhaps, golfers were not restricted by the apparatus as it was usually placed at the back of the green with the flag placed near the front. The greatest problem, in fact, was having the time to answer the questions asked by passing golfers who were understandably bemused by this odd behaviour on a golf green.

When on field work, it was found to be advantageous to have an assistant to aid with the transportation of the apparatus to and from the green on which the tests were carried out. Another advantage was that the assistant could answer the constant barrage of questions!

During the study of the impacts it was found that it was essential to have a fixed procedure so that the camera, stroboscope and projection device were all set correctly. First of all, the bowling machine was set at the correct velocity and using the clinometer, at the angle required. The tent frame was then attached to the ball projection device with the single length of Dexion and the tent cover erected upon it. The tent material had a slit in the side nearest the projection device (see Figure 2.9). Two rectangular pieces of material were attached along this slit using Velcro so that a square hole was created in the side of the tent. The ball was then fired through this hole. The camera and stroboscope could then be screwed onto the support attached to the tent frame and positioned so that the impact point was viewed.

The camera was first loaded with Polaroid film and several test impacts were carried out so that the system could be checked. The main task, at this stage, was in determining the correct time delay for the camera and stroboscope to allow for the passage of the ball from
FIGURE 2.10 A stroboscope photograph of a typical impact of a golf ball with natural turf (the ball enters from the right).
the infra-red light beam to the point of impact. Once this was found, the camera was loaded with 220 roll film and a series of tests carried out. Once the angle of incidence and the velocity of the impact was fixed, the settings of the timer and stroboscope could also remain fixed. The complete apparatus could then be moved so that the next impact did not land in a previous pitchmark. It was possible to increase the backspin of the impacting ball without the need to vary the position of the camera and stroboscope and without having to alter the time delay of the trigger. This was achieved by decreasing the velocity of the top wheel on the projection device and increasing the velocity of the bottom wheel by the same amount. Thus, the velocity and angle were kept fixed while the spin was increased.

Before any impacts were studied, the roll of film was marked by taking a photograph of a piece of card on which were details of the golf course, the date and the tests to be carried out. This ensured that the films could be identified after they had been developed. Series of tests were marked by photographing a piece of card on which test information was written.

As discussed earlier, each photograph of an impact was composed of an image of a grid placed in the plane of the impact and the stroboscopic photograph of the impact itself (Figure 2.10). The grid was used as a frame of reference during the analysis and is discussed in the next section. It was exposed using natural light and the camera settings required to obtain the correct exposure was determined using Polaroid film. The camera settings required for the grid and for the impact were very different (f11 at 1/500th, say, against f22 at 1/30th).

With these practical considerations in mind, the photograph of an impact would have taken place as follows. First, the grid was exposed onto the photograph and the camera settings changed in preparation for an impact. The side flap of the tent was fixed in place and the golf ball projected at the turf. The side flap of the tent was lifted up and the position of the impact checked to determine whether it had occurred in the field of view of the camera. Notes were then taken of the picture number, the frequency of the stroboscope, the pitchmark size and any other general observations.

The system was checked when the velocity or angle of impact was changed using the Polaroid film. Regular checks were essential since it was very easy to forget to change camera settings and anyone can forget to remove the lens cap!
2.5 Analysis of the photographs

(i) Introduction
The films containing the photographs of the impacts were developed at the STRI using standard techniques. Methods of analysis were then required to remove the information from the pictures. Initially, each picture was printed onto photographic paper and the analysis carried out directly on the print. However, this was a long and expensive process and a quicker and cheaper option was to project the images onto a white sheet. The negatives were then analysed directly. A projector with the correct film holder was not available so an ordinary photographic enlarger was used with a fan mounted on its cooling fins to prevent overheating.

This section describes the methods used to analyse the photographs of the impacts and gives some indication of the errors involved. A photograph of a typical impact is shown in Figure 2.10. The grid provides a reference from which to measure distances to enable the calculation of the velocities. Exposing the grid in the same plane as the impact reduced the effect of distortion of the images due to spherical aberrations in the camera lens. However, the grid was not always clear over the whole of the photograph and two methods of analysing the pictures were employed. These methods, along with a method of calculating the three dimensional spin of the ball from two dimensional photographs are described in the following sections.

FIGURE 2.11. A method of calculating the velocities and angles before and after impact using a grid exposed onto the photograph.
(ii) A method using co-ordinates representing the position of the ball

Using this method the co-ordinates of points on the ball were read from the scale on the photograph and the distances travelled in the duration between images calculated. Consider an image of the ball on the photograph surrounded by a square with sides equal to the diameter of the ball and whose middle point lies on the centre of the circle. The upper left hand corner of the square was chosen to represent the position of the incoming ball's images. The upper right hand corner was chosen to represent the position of the outgoing ball's images. These correspond to the points \((X_1, Y_1), (X_2, Y_2), (X_3, Y_3)\) and \((X_4, Y_4)\) in Figure 2.11.

Since the grid was placed directly on the ground, the co-ordinates were read with respect to the direction of the average slope of the turf at the point of impact. If the frequency of the stroboscope was \(F\), then the velocities before and after impact are,

\[
V_i = F \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2} \tag{eqn. 2.1}
\]

\[
V_f = \frac{F}{M} \sqrt{(X_3 - X_4)^2 + (Y_3 - Y_4)^2} \tag{eqn. 2.2}
\]

The subscripts "i" and "f" denote the incoming and outgoing ball respectively and "M" is the number of images used in the calculation. The direction of the motion of the ball, to the horizontal, can be calculated using the following equations,

\[
\Theta_i = \tan^{-1} \left( \frac{Y_1 - Y_2}{X_1 - X_2} \right) \tag{eqn. 2.3}
\]

and

\[
\Theta_f = \tan^{-1} \left( \frac{Y_3 - Y_4}{X_3 - X_4} \right) \tag{eqn. 2.4}
\]

where the subscripts "i" and "f" again denote the incident and rebounding ball. Usually, there were only two images before impact. After impact, however, the ball was moving much slower resulting in many images of the ball.

The orthogonal circles seen on the golf balls in Figure 2.10 and shown schematically in Figure 2.11 enabled the calculation of the spin before and after impact to be made. The numbers written at the points where the circles crossed were used to ascertain the direction of rotation. The spin was calculated by measuring the angle through which the lines on the ball rotated using a ruler and a protractor. An example would be, for instance, angle \(\Phi\) in Figure 2.11. Lines on the ball were chosen that were relatively straight and as many images as possible were used. It was possible to mistake the direction of rotation of the outgoing ball; for instance a rotation of 45° in an anticlockwise direction could be mistaken as 315° in a clockwise direction. This could indicate either a small topspin or a large backspin. Knowing the settings of the bowling machine when
the ball was fired resolved this uncertainty. For example, if the ball had been travelling initially with zero spin in the example just given, it would have been unlikely for the ball to rebound with backspin. If a ball rotated through $\phi$ radians in $N$ images, then,

$$\omega = \pm \frac{\phi \times F}{N}$$

where the "+" sign denotes topspin and the "-" sign backspin.

Appendix B contains the calculations required to estimate the errors in the use of this method for calculating the velocity and angle before and after impact. It was found that an error of 1mm in placing each of the co-ordinates $X_1$ to $X_4$ and $Y_1$ to $Y_4$ accumulated to an error of 1.4mm in the calculation of the distances $L_1$ and $L_2$ in Figure 2.11. In general, the distance across which $L_1$ and $L_2$ were measured was about 70mm and hence the percentage error in these values was approximately 2%.

The error in the co-ordinates produces an error in the calculation of the angle to the horizontal of the ball's motion. If the distance between two images was about 70mm and the ball was travelling at 45° to the horizontal, then an error of 1mm in each of the co-ordinates gave a range in the angle of 43.4° to 46.6° for the angle. This was represented as an error of ±1.6°.

The error in the measurement of the angle through which the ball rotated was estimated by repeatedly measuring the angle and finding the standard deviation of the mean. The rotation of a ball was measured repeatedly using images in which the lines on the ball were distinctly curved (as in Figure 2.11). It was found that the standard deviations of these measurements became larger than about 5% if the line was further than half a radius from the centre of the ball. Thus, only lines which were within a half a radius of the centre of the ball were used. Taking the measurement over a number of images helped to reduce the inaccuracy of using slightly curved lines to measure the rotation of the ball.

(iii) Systematic errors using the co-ordinate method
Systematic errors could have occurred when aligning the grid along the true plane of impact. As described earlier, several preliminary impacts were made in order to check that the correct exposure on the camera was being used and that the time delay was correct. The grid was aligned to the line of pitchmarks created. Systematic errors could have occurred at this point since the grid may have been placed at an angle to the plane through which the ball passed or in a parallel plane either nearer or further away than the true plane of impact. In Appendix B it is shown that if lateral displacement is less than one and a half times the radius of the ball or if angular displacement is less than 10°, then the errors incurred are not significant. It was found that these criteria were easily met in practice.
(iii) Analysis of the photographs using the distances between images

If the grid was not exposed correctly onto the photograph then it was difficult to use it as a co-ordinate system for the calculations in the previous section since the 1mm intervals were not visible. Usually, however, the grid was clear enough to see the main lines and as an alternative scale, the distance between two vertical lines and along a horizontal line was measured (denoted by "l" in Figure 2.12). If there were more than two images before or after impact then the distance across as many images as possible were taken and the calculation for the velocity divided by the number of images. The angles of the incoming and outgoing ball were measured with respect to the reference line using a protractor. The spin was measured using the method described in the previous section.

![Diagram](image)

**FIGURE 2.12.** A method of calculating the velocities of the ball before and after impact. The distances are measured directly from the photograph and converted to "real" distances using the reference line. This gives a scale if the distance "l" in the photograph is known.

The errors were estimated by repeating the same measurement on the same photograph a number of times and calculating the standard deviation of the mean. The angles before and after impact were found to have a standard deviation of less than $\pm 5^\circ$ while the distances used in the velocity calculation had an error of about $\pm 1.5$mm. Thus, a conservative estimate of the errors in measuring the angles of incidence and rebound and the distances between images was $\pm 1^\circ$ and $\pm 2$mm respectively. Since the distance between images for the incoming ball was about 70mm, the error in the distance measurement was about 3%. The errors occurring in the measurement of the angle of rotation of the ball were the same as in the previous section. This method could not take into account the distortions in the lens or the effects of spherical aberrations and was therefore to be used when the co-ordinate method was not suitable.
(iv) A comparison of the two methods for analysing the photographs

Table 2.1 shows the distances between images before and after impact (L₁ and L₂) and the angles of incidence and rebound (θ₁ and θ₂) for five photographs calculated using the two different analysis techniques. The titles "coord" and "ruled" refer to the co-ordinate method and the method using a ruler to measure the distance between images. It was found that, in all but one case, the results did not vary significantly between the methods when the errors described in the previous sections were taken into account. This indicated that the distortions due to spherical aberrations in the camera lens were minimal. It was decided, therefore, that the method using a ruler and protractor to measure directly from the photograph was the most suitable since it involved the least number of stages in the analysis. The number of stages in the co-ordinate method could have been reduced by the use of a digitiser to enter the co-ordinates representing the ball directly into a computer.

<table>
<thead>
<tr>
<th>No.</th>
<th>L₁ (mm)</th>
<th>L₂ (mm)</th>
<th>θ₁ (°)</th>
<th>θ₂ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coord</td>
<td>ruled</td>
<td>coord</td>
<td>ruled</td>
</tr>
<tr>
<td>1</td>
<td>81</td>
<td>83</td>
<td>32</td>
<td>32</td>
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<td>32</td>
</tr>
<tr>
<td>5</td>
<td>83</td>
<td>80</td>
<td>33</td>
<td>34</td>
</tr>
</tbody>
</table>

TABLE 2.1. A comparison of the two methods of photograph analysis for five photographs. The distances L₁ and L₂ and the angles θ₁ and θ₂ refer to the distances and angles before and after impact respectively.

(v) A method of calculating three-dimensional spin using two dimensional photographs

During the analysis of the pictures using the methods described above, it was considered that estimates of the side spin would help to explain odd results that occurred. The method described in Appendix C was developed to calculate the three dimensional spin of the ball using the co-ordinates of points on images from the two dimensional photographs. It consists of three stages, the first modifies the two dimensional co-ordinates from the photographs to points in three-dimensional space using a method called relief displacement. This is required since points nearer the camera than the plane containing the co-ordinate system are displaced outwards from the centre of the photograph. The second stage calculates the spin axis of the ball using vector analysis and three dimensional geometry. The third stage calculates the magnitude of the spin. It is then possible to calculate the spin in three dimensions.
It was found that the method worked well but that errors accumulated quite quickly due to the subtraction of co-ordinates that were very close together. This occurred because the errors in taking co-ordinates from the photographs were quite large compared to the size of the image of the ball. The method of calculating the three dimensional spin from two dimensional photographs, therefore, would work well if the images of the ball were larger. This could be achieved by having a longer focal length lens or a bigger sports ball and would possibly be more suitable for tennis, cricket or football.

2.6 The physical characteristics of golf greens

At this stage, it is necessary leave the acquisition and analysis of the stroboscope photographs in order to consider the apparatus for determining the characteristics of the greens on which the stroboscope testing was to be done. The relationships between the results of the impacts and the characteristics of the greens will show the effect of maintenance and construction on the ball/turf impacts. This will be carried out in Chapter 4 where the photographs of impacts will be related to the tests described in this section. Existing tests that were simple to use were chosen to measure the green characteristics. Eleven types of measurement were used and these are outlined below.

(i) Ball rebound resilience

Ball rebound resilience is expressed as,

\[
\text{ball rebound resilience} = \frac{\text{Bounce height}}{\text{Release height}} \times 100 \quad \text{eqn. 2.6}
\]

This test has been used predominantly for the assessment of football pitches and tennis courts (Holmes and Bell, 1986). Heights of drop were chosen that were relevant to the sport; for instance, footballs were dropped from a height of 3m. Colclough & Canaway (1988) dropped golf balls from a height of 5m. This was a compromise between the heights that golf balls fall from in play and the size of an apparatus that was manageable. Figure 2.13 shows the ball bounce apparatus. Pulling a cord connected to a carrier containing 12 balls on top of the 5m pole caused a ball to be dropped. The rebounding ball was filmed using a video camera against the backdrop of a scale marked out in centimetres. The camera was placed approximately 5m from the scale and a telephoto lens used. This was necessary to reduce parallax errors. The video recording was then analysed frame by frame. If air resistance is neglected, then the ball rebound resilience is related to another commonly used measure of rebound - the coefficient of restitution, \( e \), where:
velocity of separation

\[ e = \frac{\text{velocity of approach}}{\text{velocity of separation}} \quad \text{eqn. 2.7} \]

and hence,

\[ \text{Ball rebound resilience} = e^2 \]

Originally, the coefficient of restitution was considered to be a constant. It has been found, however, that the coefficient of restitution of a golf ball on a hard surface decreases with velocity and increases with temperature (Briggs, 1949).

(ii) Clegg impact soil tester

The Clegg impact soil tester (Clegg 1976, Lush 1985) shown in Figure 2.14 has been used in the past for the measurement of the firmness of road bases and for the assessment of cricket pitches. An indenter is dropped down a guide tube onto the surface to be tested. An accelerometer located in the hammer measures the peak deceleration as it hits the surface and the result is displayed in multiples of 10g, where \( g \) is the acceleration due to gravity. A 0.5kg cylindrical indentor is used most commonly and is dropped from a height of 300mm. A 1kg indenter dropped from a height of 300mm has the same momentum as a golf ball travelling at about 50ms\(^{-1}\). This is greater than the velocity attained by a golf ball hit with a driver. Three 1kg indenters were developed to try to gain an insight into the maximum forces experienced by a golf ball on impact with the green. The three indenters developed were, a 1.0kg cylindrical indenter, a 1.0kg cylindrical indenter with an end shaped like a golf ball and a 1.0kg hammer with a Titleist golf ball adhered to its end. These are shown in Figure 2.14. An assumption that would be useful in later models is that the ball does not deform. The golf ball shaped indenter and the indenter with a golf ball adhered to its end were designed to study the effects of the elastic properties of the ball on the impact with the ground. It was ensured that the lowest point of each indenter was dropped from 300mm so that direct comparisons between the deceleration values obtained could be made.

(iii) Penetrometer

A penetrometer, designed for the USGA, was used as a measure of the “hardness” of the greens and is shown in Figure 2.15. It has a 51mm long probe with a diameter of 8mm reducing to 4.8mm at the tip. The shaft onto which this probe is threaded moves vertically through the penetrometer body but is restricted by a spring. When the probe is pushed into the ground, the shaft is forced in the opposite direction. The apparatus reaches equilibrium when the bottom of the penetrometer body touches the surface. Part of the probe penetrates into the ground while part has been forced vertically into the penetrometer body. An amount equivalent to that penetrating the ground protrudes out the
FIGURE 2.13. An apparatus used to drop golf balls from 5m. Pulling a cord connected to the ball carrier on the top of the pole opened a mouth through which a golf ball dropped. The rebounding ball was filmed using a video camera against the backdrop of the scale.
FIGURE 2.14 The Clegg Impact Hardness Tester used as a measure of hardness. The original 0.5kg indenter is shown attached. The three other indenters, when screwed onto the main shaft, weigh 1.9kg.
FIGURE 2.15. The Stimpmeter, above, and below, from left to right, the USGA penetrometer, the USGA green hardness tester and the 600mm soil corer.
top of the penetrometer body. Here, the shaft is graduated in one sixteenths of an inch. It is thus possible to measure the amount of the probe penetrating the ground. The speed and duration of the measurement affects a reading. If the penetrometer is continually pressed on the ground then the probe slowly penetrates the soil. This is due to the sustained downwards force due to the spring. There are two handles at right angles to the penetrometer body. One handle can be rotated half a turn into the body so that the shaft is fixed in position. This ensures that the shaft does not move once the probe has penetrated to its maximum extent and the penetrometer body touches the surface. The larger the penetration of the tip the smaller the amount of the shaft that protrudes out the top of the penetrometer body and the higher the reading. Thus, a “soft” surface is indicated by a large penetration and a high reading.

(iv) Green speed
A device called a Stimpmeter has been used to measure the “speed” of golf greens (Stimpson 1974, Radko 1977, 1978). The Stimpmeter, shown in Figure 2.15, is a V-shaped ramp down which a golf ball is rolled. The ball is placed behind a notch at the top of the ramp which is then tilted forward. When the angle of the ramp reaches about 22° the downwards force of gravity pulls the ball over the notch. The ball rolls down the ramp and across the turf with an initial speed of 1.9 m s⁻¹ as measured using timing gates. This is slightly lower than simple theory might suggest due to the groove that the ball rolls down and the frictional forces experienced by the ball.

The distance that the ball travels across the green is taken as a measure of its speed. The normal procedure is that the most level part of the green is selected and two balls are rolled along the same path but in opposite directions. This procedure is intended to eliminate the effects of any minor slope.

(v) Soil moisture content; Organic matter content; soil composition
Soil properties were determined by laboratory analysis of soil cores taken using a soil sampler 180 mm long and with a diameter of 19 mm (Figure 2.15). Ten cores were taken from each green and were wrapped in plastic bags to conserve their moisture. In the laboratory they were weighed, dried at 105°C for 24 hours and reweighed to determine their moisture content. An accepted representation of the soil moisture content is the percentage ratio of the dried weight to the original weight (Piper 1950).

Soil organic matter content was determined by loss on ignition. The dried cores were ignited at 400°C for 8 hours and then reweighed. The resultant loss in weight on ignition of the organic matter was expressed as the percentage of the weight before ignition. This is the standard method used at the Sports Turf Research Institute and is described by Baker (1985).
FIGURE 2-15. The level is apparatus (above) was used as a measure of the evenness of the greens. The optical point quadrat frame (below) was used to evaluate the species composition of the greens.
FIGURE 2.17. The friction sled (lower left) and the traction disc (lower right) used as a measure of playing quality.
A particle size analysis of the soil from each green was carried out in order to determine the soil type. The sand fractions were determined by sieving the dried soils through successively finer sieves and the silt and clay fractions were determined by sedimentation (Piper 1950).

(vi) Surface evenness/roughness
In terms of putting, one of the most important features of the green is the surface evenness. This was measured using a profile gauge and consists of ten 6 mm diameter rods spaced 50mm apart in a wooden frame (Figure 2.16). The rods are free to move vertically so that when the frame is placed on the playing surface the rods are displaced by bumps and hollows. Each rod is graduated so that its displacement can be measured to an accuracy of \pm 1mm. The roughness of an area was expressed as the mean of ten sample standard deviations of 10 x 10 readings (Holmes and Bell, 1987). The smaller the value of the mean the more even the green.

(vii) Ground cover and species composition
This was studied with an optical point quadrat frame (Laycock and Canaway, 1980). It consists of a horizontal softwood frame 600mm long, on which are mounted two rows of five pins, one row being 20mm above the other and the pins being 100mm apart within rows (Figure 2.16). The apparatus was placed on the turf and sightings were taken down the tips of the pairs of pins on to the vegetation. When the tips were in line, whatever was below was recorded as a species of grass, dead plant material or bare ground.

(viii) Sliding friction
The sliding friction of the surface was measured using a device similar to that used by Thorpe and Canaway (1986). Three half golf balls were adhered 115mm centre to centre to the three corners of a triangular sled (Figure 2.17). This was placed on the ground with the golf balls contacting the ground and with a 10kg weight on the sled, the total weight of the apparatus being 11.2kg. The whole apparatus was towed across the ground at a constant speed using a Newton meter. The speed was determined by the operator and was required to be just enough to overcome the inertial forces resisting the initial movement of the sled. This was estimated to be between 0.5 and 1ms\(^{-1}\). The force required to pull the apparatus divided by the weight of the apparatus gives an estimate of the coefficient of friction at this speed.

(ix) Ball/surface traction
The traction of the green was measured using an apparatus similar to that described by Canaway (1975). Although this test was used to study the player/surface interaction for running sports, it was thought that it might provide a good measure of the shear strength of the green. Three golf balls were adhered to the bottom of a 12mm thick mild steel disc
in place of the usual sports shoe studs (Figure 2.11). This was then screwed onto a 1m long shaft which passed through the centre of two 10kg weights. The apparatus was dropped from a height of 150mm and a torque wrench used to measure the torque required to twist the disc through the turf.

2.7 Summary
The literature review was used as a source of information from which to develop a method of projecting and recording the impacts of golf balls on turf. The projection device subsequently designed employed two counter-rotating pneumatic wheels to project the golf ball. These could be varied independently to produce spin. Stroboscope photography was used to record the impacts. The camera and stroboscope were activated by an electronic trigger which was initially activated when the golf ball passed through an infra-red beam. The photographs were shielded from direct sunlight by a dark canvas enclosure into which the golf balls were projected. This enclosure was attached directly to the ball projection device so that the whole set of apparatus could be moved together after each impact. It was found that the apparatus worked well in the field although a routine had to be developed to ensure the optimum use of the equipment.

Many of the playing quality tests found in the literature review were used or modified to measure the characteristics of golf greens. The following chapter describes the results of the stroboscope photographs found using the apparatus described here.