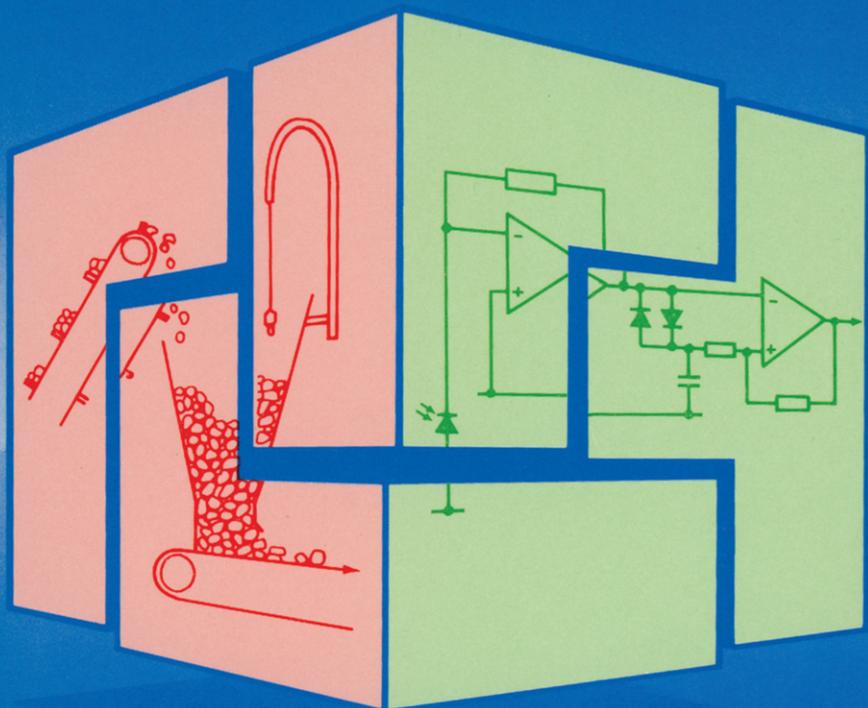


Real Applications of Electronic Sensors

G. Long



Dimensions of Science

Series Editor: J.J. Thompson

REAL APPLICATIONS OF ELECTRONIC SENSORS

Titles in the *Dimensions of Science* Series

Chemical Engineering: Introductory Aspects R. J. Field

Energy and Cells C. Gayford

Human Reproduction and in vitro Fertilisation H. J. Leese

Genes and Chromosomes J. R. Lloyd

Real Applications of Electronic Sensors G. Long

Physics and Astronomy D. McGillivray

Practical Ecology D. Slingsby and C. Cook

Ionic Organic Mechanisms C. Went

The Nature of Electrolyte Solutions M. Robson Wright

DIMENSIONS OF SCIENCE
Series Editor: Professor Jeff Thompson

REAL APPLICATIONS OF ELECTRONIC SENSORS

Graham Long

B.Sc., C.Eng., M.I.E.E.

Manager, York Electronics Centre,
University of York

M
MACMILLAN
EDUCATION

© Graham Long 1989

All rights reserved. No reproduction, copy or transmission of this publication may be made without written permission.

No paragraph of this publication may be reproduced, copied or transmitted save with written permission or in accordance with the provisions of the Copyright Act 1956 (as amended), or under the terms of any licence permitting limited copying issued by the Copyright Licensing Agency, 33-4 Alfred Place, London WC1E 7DP.

Any person who does any unauthorised act in relation to this publication may be liable to criminal prosecution and civil claims for damages.

First published 1989

Published by
MACMILLAN EDUCATION LTD
Houndmills, Basingstoke, Hampshire RG21 2XS
and London
Companies and representatives
throughout the world

Typeset and Illustrated by TecSet Ltd, Wallington, Surrey

British Library Cataloguing in Publication Data
Long, Graham

Real applications of electronic sensors.

1. Sensors. Applications

I. Title II. Series

620'.0044

ISBN 978-0-333-46107-5 ISBN 978-1-349-10107-8 (eBook)
DOI 10.1007/978-1-349-10107-8

To Fiona, Vicky, Alastair and Patrick

Series Standing Order

If you would like to receive future titles in this series as they are published, you can make use of our standing order facility. To place a standing order please contact your bookseller or, in case of difficulty, write to us at the address below with your name and address and the name of the series. Please state with which title you wish to begin your standing order. (If you live outside the United Kingdom we may not have the rights for your area, in which case we will forward your order to the publisher concerned.)

Customer Services Department, Macmillan Distribution Ltd
Houndmills, Basingstoke, Hampshire, RG21 2XS, England.

Contents

<i>Series Editor's Preface</i>	<i>ix</i>
<i>Acknowledgements</i>	<i>x</i>
1 Introduction	1
Brief coverage of the various elements used in the following application chapters – for example, resistor, capacitor, inductor, transformer, diode, photodiode, lens, mirror, prism, Hall effect device, thermocouple and piezoelectric device.	
2 Potatoes and Diamonds	7
Proximity sensors, optical sizing, temperature control, swede topping, check weighing, crop spraying.	
3 Making Shirt Buttons and Sewing Hems	34
Broken drill detection, hole sensing and counting, symmetry detector, crescent notch detector, hem sensor, fabric texture measurements.	
4 Paper Making and Printing	57
Corrugated paper measurements, web break monitor, printing press tension control, synchronisation control for registration, registration of measuring tapes, minimising printing waste, checking felt tip pens.	
5 Bottling Drinks and Food Inspection	73
Bottle fill detector, label detector, soft fruit and Brazil kernels inspection, checking for dirty bottles, egg albumen quality and shell colour measurement.	
6 Chiropody, Dentistry and Other Applications	97
Toe nail bender, gum disease probe, pharmaceutical tablet inspection system, rate of cooling meter for biological specimens,	

electrical power monitor, fuel combustion sensing, shop window security, motor traffic sensors.

7 Basic Facts about Sensing Elements	120
More detailed description of the workings of sensing elements and some of the standard signal processing circuits.	
8 Conclusion	140
<i>Further Reading</i>	<i>143</i>
<i>Index</i>	<i>144</i>

Series Editor's Preface

This book is one in a Series designed to illustrate and explore a range of ways in which scientific knowledge is generated, and techniques are developed and applied. The volumes in this Series will certainly satisfy the needs of students at 'A' level and in first-year higher-education courses, although there is no intention to bridge any apparent gap in the transfer from secondary to tertiary stages. Indeed, the notion that a scientific education is both continuous and continuing is implicit in the approach which the authors have taken.

Working from a base of 'common core' 'A'-level knowledge and principles, each book demonstrates how that knowledge and those principles can be extended in academic terms, and also how they are applied in a variety of contexts which give relevance to the study of the subject. The subject matter is developed both in depth (in intellectual terms) and in breadth (in relevance). A significant feature is the way in which each text makes explicit some aspect of the fundamental processes of science, or shows science, and scientists, 'in action'. In some cases this is made clear by highlighting the methods used by scientists in, for example, employing a systematic approach to the collection of information, or the setting up of an experiment. In other cases the treatment traces a series of related steps in the scientific process, such as investigation, hypothesising, evaluation and problem-solving. The fact that there are many dimensions to the creation of knowledge and to its application by scientists and technologists is the title and consistent theme of all the books in the Series.

The authors are all authorities in the fields in which they have written, and share a common interest in the enjoyment of their work in science. We feel sure that something of that satisfaction will be imparted to their readers in the continuing study of the subject.

Acknowledgements

I would like to thank the following individuals and companies for not only giving permission for their product or process to be mentioned in this book but also for introducing me to many of the areas in which electronic sensors are used.

Mr R. M. Cowlin, Loctronic Graders Ltd

Mr A. Goff, British Button Industries Ltd

Mr P. Harkett, McCain Foods (UK) Ltd

Mr I Smith, Dekalb Inc.

Mr J. Prinz, Dextrodent Diagnostics Ltd

Mr R. Bannister, Burrow House Farm

Mr A. Vollans, Rigid Paper Products Ltd

Mr J. M. Shaw, Ben Shaws Ltd

Mr J. Atherton, Technical Services & Supplies Ltd

Mr C. R. Ellis, Chiropodist

Dr A. Wilson, CCTR, University of York

Mr M. Scott, Eclipse Electrical Engineers Ltd

Mr A. Johnson, Electrical Contractor

Mr A. Tantrum, City Technology Ltd

Mr N. Helsby, Radiocode Clocks Ltd

Dr R. Millar, Department of Education, University of York

Dr L. Rogers, School of Education, University of Leicester

I would also like to thank David Morkill for his encouragement and helpful comments at the writing stage and my colleagues, past and present, in the Essex Electronics Centre, University of Essex, and in the York Electronics Centre, University of York, for all their creative work on many of the projects mentioned in this book.

1 Introduction

In everyday life there are countless problems to be solved. From the Rubik Cube to crosswords we all like the challenge of a problem and are delighted when we find a solution. The more elegant and simple the solution, the more we are pleased. This book describes a range of engineering problems, mainly industrial, which have been solved using electronic sensors.

The middle chapters in this book start by posing the problems and finish up with solutions achieved by the effective use of electronic components. But as the components are the basic tools of the electronics engineer, a brief mention in this first chapter of some of the common components will, I hope, be useful.

An electronic sensor usually relies on a characteristic of some electrical component, be it physical, chemical or even biological, which changes under an outside influence. Many standard components, such as the capacitor or the resistor as well as semiconductor devices, can be used in a number of ways as sensors. By using one particular characteristic of a component some external influence may be measured and the component becomes a sensor. The same type of component may be used again in another part of a circuit to help modify an electrical signal. To avoid it acting as a sensor again, it must be either shielded from that external influence or the effect must produce insignificant results on the electrical signal being processed. Take the humble resistor for example. This is a little blob on a tinned copper wire with bright coloured rings around it. It has a fixed electrical resistance between the two ends of the wire, the value of which can be deciphered from the coded coloured bands. The wire appears to continue right through the blob but it is actually two separate pieces of wire. But is the resistance really fixed? What would the resistance be if a salt solution (brine) were sprayed over the surface? Would the measured resistance go up, stay the same or get less? Brine conducts electricity fairly easily so the answer is less. Therefore if a resistor was placed in the bilges of a ship it might be used to indicate whether the bilge water came from an internal spillage of fresh water or was due to a leak in the ship's side.

A resistor is also susceptible to heat. Depending on what material it is made from, its resistance either increases or decreases with temperature. Manufacturers strive to keep this effect to a minimum in most resistors because people want their radios to work just as well in the sultry tropics as at the bitter North Pole. But there are special resistors, commonly known as thermistors, in which this temperature effect is exploited so that they can be used as thermal sensors. But even thermistors come in a variety of forms. Some are tiny beads enclosed in evacuated glass phials so that they have minimal heat capacity and can be used in sensitive scientific measuring instruments. Others are bulky so that they do not heat up too fast. These second types are used to limit a sudden rush of current when some equipment is first turned on. Their cold resistance is high but rapidly decreases as the material warms up. These few examples demonstrate that even a simple resistor has a variety of uses of which the electronics engineer must be aware even though they may not be immediately apparent.

Capacitors, which look like 'Smarties' when assembled onto a printed circuit board, store electrical charge and energy. The amount of charge which can be stored in a capacitor is dependent on the capacitance between the two plates and the voltage applied across them. Capacitance is defined as the ratio of the electric charge transferred from one plate to the other, to the potential difference between the electrodes which results. The capacitor is often used in electronic circuits to slow down the rate of change of a signal by restricting the current going into the capacitor by a resistor and therefore the rate of rise of voltage across it. The rate of change of voltage, across the capacitor, will follow an exponential law if the resistor is connected to a constant voltage source. Although this is not a sensing technique there are very few electronic sensor circuits which do not have at least one capacitor in them to make sure the sensor system does not react too fast or respond to the wrong external stimulus.

Forgetting about the fixed capacitor (they are temperature sensitive too!) it is possible to use capacitance for sensing proximity without contact. The capacitance between any two objects increases as they get closer together, so if a circuit can be devised to enable this capacitance to be measured and one of the two objects is connected to the circuit, then bells can be made to ring and lights to flash if the other object comes close. There is more about the use of capacitance for sensing in chapters 2 and 3.

There are three basic passive elements used in electronic circuits (passive in this context means that the electrical properties of the component obey a linear relationship and are not modified during use by any other electrical signal, as could happen in a transistor which is called an active device). The resistor and the capacitor have been mentioned already but the third, the inductor, has yet to be described. This is a coil of wire which may be

wound around an iron core for large inductance or around a plastic bobbin for smaller inductance. Inductance is defined as the property of a circuit, which when carrying a current is characterised by the formation of a magnetic field and the storage of magnetic energy. The inductor can also store energy like the capacitor but in the form of a continuous circulating current rather than a static charge. Whereas the capacitor resists a rapid change of voltage across it because such a change would require an inrush of current, the inductor resists a rapid change in current as this would induce a corresponding back electro-motive force in it. Using these two components together can allow the electronics engineer many circuit possibilities, including resonance circuits, but the inductor by itself can be used as a sensor. If the magnetic core, around which the coil is wound, is not continuous but has a slot or air-gap cut in it, then, should a piece of iron be brought close to this gap, some of the magnetic flux will go through the adjacent iron piece as well as through the air-gap and so the reluctance of the overall magnetic path (reluctance can be considered as the magnetic resistance across the air-gap) will be reduced. If an associated electronic circuit responds to the inductance of the coil then the circuit can be made to indicate when the iron is present. This type of arrangement is often used to detect the teeth of a gear wheel passing and hence the rotational speed of a shaft.

A close ally of the inductor is the transformer. This consists of two, or more, coils wound around a common magnetic core. Because they share a common core, energy can be transferred from one coil into magnetic flux in the core and then from the core out into the other coil. In sensors, the mutual inductance or coupling between two coils can be used to measure linear displacement if the coils are mounted coaxially and one slides on the axis with respect to the other. This device is known as a linear voltage displacement transducer, commonly shortened to LVDT.

Semiconductors also feature in many sensors and one of the commonest semiconductor devices, the diode, will be mentioned in almost all the subsequent chapters. Not only is it susceptible to temperature changes in a predictable way but it also rectifies and it exhibits an exponential relationship between current and voltage which can be used to create a logarithmic amplifier. A photodiode is a diode on which light is allowed to fall through a transparent window. It is often assumed that when a reverse voltage is applied to a diode no current flows; in fact a minute current does flow and this is proportional to the intensity of light illuminating the diode. If the photodiode is incorporated into a phototransistor then this reverse leakage current is amplified by the transistor up to a more easily managed level. The phototransistor generally gives a slower response than the photodiode alone, so for faster sensors, the photodiode's reverse leakage current is fed

into a special amplifier. If a number of photodiodes are lined up in rows, in regimental style, and a lens is used to focus an image of a scene onto these photodiodes, then by scanning along the diodes one at a time a signal proportional to the light variations in the image may be derived. The smaller the photodiodes and the larger the number used, the more detailed a picture can be recorded. If just one row of photodiodes is used and this row is focused transversely onto a conveyor then, provided the speed of the conveyor is known, a picture can be built up from successive scans. Such a single row arrangement is known as a line array and when incorporated behind a lens in a suitable housing becomes a line camera. If a scan was displayed from a line camera, it would look like a single line on the screen of a television set.

In the previous paragraph lenses were mentioned. It is hoped that some of the examples in the later chapters will show how essential a basic grounding in optics is for choosing an optical sensor or for trying to assess the possibilities of using optical sensing techniques especially in non-contact measurement or inspection. This does not mean that an electronic engineer needs to be able to design a complex lens but, as light can be used in many ingenious ways for sensing, then the basic optical components must be included in the electronics engineer's tool box. The simple convex lens has already been mentioned for creating an image in a line or area camera. If detail is only required in one dimension then a cylindrical lens can be used which artificially extends the effective length of the photodiodes without changing their effective width. Lenses and concave mirrors are also used to increase effectively the active area of single detectors as well as enabling them to have directional properties. A prism or diffraction grating can be used to separate out the component colours in a beam of light so that each can be monitored by a different photodiode. Even straightforward plane mirrors can, as Agatha Christie pointed out, be used to see around corners. The half-silvered mirror, set at 45° , is often used as a beam splitter to enable a detector to observe an object through the same lens system and from the same angle as that used for illumination. Gelatine or coloured glass filters can also be used to great effect and there is more about these in chapter 5 (page 81).

There are also one or two devices which are named after the discoverer of the effect which they exploit. The Hall effect device is used to sense magnetic fields. If a current is passed through the device in one direction and a magnetic field applied at right angles to the direction of the current across the device, then a voltage will be produced on a set of electrodes mounted on opposite sides of the device at right angles to both the current and the magnetic field, and this voltage will be proportional to the product of the current and the magnetic flux density. That is a long-winded ex-

planation but the Hall effect device is useful because it is very small and unlike a stationary coil can measure static magnetic fields. The Seebeck effect is used in thermocouples to measure temperature. When two dissimilar metals are joined together, a minute voltage is created across the junction which is proportional to the temperature of the junction. But to measure this voltage is not so easy as other different metal junctions are created when a voltmeter is connected. To get around this problem two dissimilar metal junctions are used, one in the place where the temperature is to be measured and the other in a fixed known temperature (see figure 1.1). The voltmeter reading then corresponds to the difference in temperature between the two junctions.

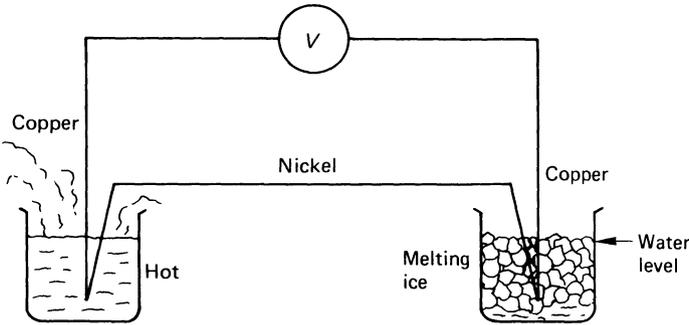


Figure 1.1 *An illustration of a thermocouple circuit*

As thermocouples are more commonly used to measure higher temperatures this second reference junction is often known as the cold junction. Thermocouples have the advantage of depending on a constant effect and they can be made very small so that they have very little influence on the surroundings being measured. Although not as a sensor, the thermocouple can be used in reverse to act as a cooler using an opposite effect called the Peltier effect. Current is passed through the junction (in the correct direction of course) and the point cools until the cooling effect balances the resistive heating effect. Such a cooler can be used to cool down a photodiode array in a camera so that its sensitivity is increased. This type of camera may be used for night observation.

The piezoelectric effect is also incredibly useful. A ceramic material which has been cured in an oven at a particular temperature, with a voltage applied across it at the same time, will generate a voltage across itself at room temperatures when squeezed. The voltage can be very large if the

impact on the device is great. The device is commonly used to generate a high voltage and hence produce a spark in battery-less gas lighters. The same effect is used in a ceramic, record player cartridge to convert the vibrations coming from the record, through the needle, into electrical signals. Just as the thermocouple could be made to work in reverse, so the ceramic material can be made to vibrate when an oscillating voltage is applied across it. Because very small devices can be made of piezoelectric material, they can be made to resonate at ultrasonic frequencies well above our normal range of hearing. An ultrasonic 'conversation' can then be held between two piezoelectric devices through the air with one turning oscillating voltages into longitudinal sound waves and the other vibrating in sympathy to those sound waves and reproducing the electrical signals. Apart from acting as a communication channel, the pair can also be used to detect absorbent objects passing between them. Because sound travels relatively slowly compared with the speed at which electronic signals can be processed, the time taken for a pulse of sound to travel from one piezoelectric device to the other can be measured. Although the speed of sound varies slightly with air temperature and humidity, the time taken can be related approximately to the distance between the two devices. If the ultrasonics sound beam is reflected off a hard surface back to the receiver then the distance to the surface can be determined.

I have tried to introduce some of the basic elements which will appear regularly in the following chapters. There are certainly more sensors which I have not mentioned such as strain gauges, platinum resistance detectors, pyroelectric detectors and microwave Doppler modules to mention but a few, but this is only meant to be an introduction and not a complete catalogue. I hope the applications described in succeeding chapters will demonstrate how basic electronic components can be used to produce simple and effective solutions to sensing problems.

2 Potatoes and Diamonds

In the early 1970s there were few electronics circuits in use on the average farm, except perhaps for electric fences. The idea of introducing anything so unreliable and delicate into such a tough environment would have been considered ridiculous. People were suspicious of new fangled gadgets and the days of delicate glass valves with high internal voltages were only just receding. Electronically controlled fences were probably accepted because they had to generate high voltages to give an electric shock and, as they were not shaken by being mounted on moving machinery but left quietly alone in the corner of fields, they were reliable. It was the coming of good-quality printed circuit boards, much lower operating voltages and cheap transistors which enabled rugged, low-cost electronic sensors to be produced.

POTATO GRADING LINE CONTROL

Take, for example, a sensor used to detect the presence of potatoes in a hopper (see figure 2.1). The hopper might be used to feed a potato grading line and might itself be filled from a large truck full of potatoes by a controlled conveyor. The hopper would have to be filled up when nearly empty and not over filled.

In the introductory chapter, the idea of using capacitance to measure proximity of conducting objects was mentioned. Potato tubers contain lots of starch and water and are therefore quite good conducting objects. Figure 2.2 illustrates how capacitance sensing works.

In the figure the capacitance between the man and the ground is quite large because the surface areas involved are substantial and the distance between the man and the ground is small unless he is wearing platform soles! The capacitance between the man and the probe is small because the sensing plate is small and the man is approaching from a distance. The impedance of a capacitor, that is its effective resistance to the passage of alternating electric current, is inversely proportional to its size. The impedance between the man and the ground is therefore very small compared

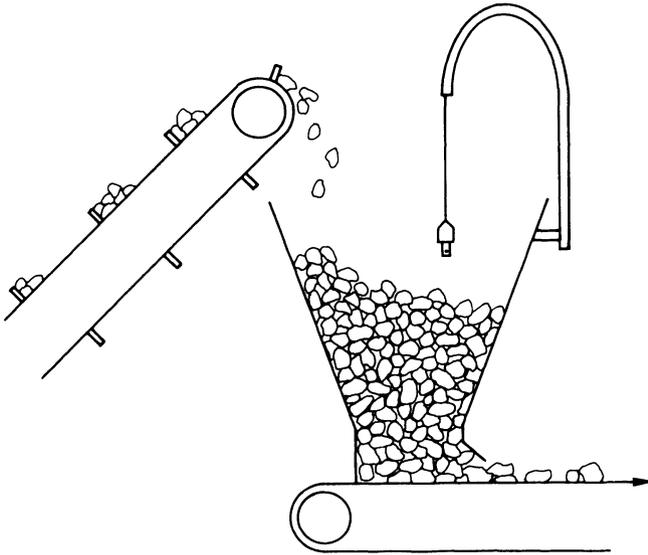


Figure 2.1 *A cross-section through a hopper full of potatoes showing the position of the capacitance probe*

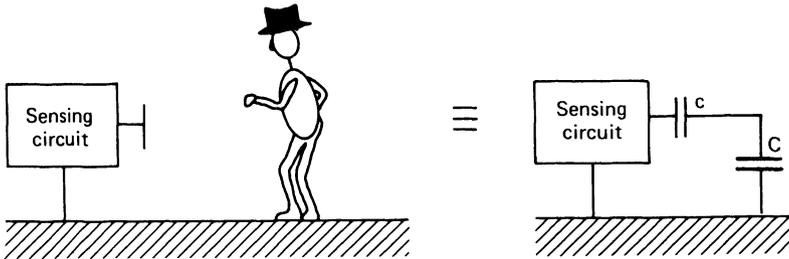


Figure 2.2 *The equivalent circuit for a man approaching a capacitance probe*

with that between the man and the sensing probe and therefore it can be ignored. The man is effectively connected electrically to the ground. Because the circuit is also connected to the ground, the capacitance between the man and the probe can be measured.

There are a number of ways of sensing capacitive changes. In one method two oscillating circuits can be used, one as a reference and the other connected so that the frequency at which it oscillates is fractionally affected by the capacitance of the sensing plate to ground. The waveforms

generated by these two independent oscillators are then mixed and a resulting low frequency, equal to the difference between the two original frequencies, can be detected. This frequency will gradually change as the man approaches the sensing plate. This technique is known as super-heterodyne detection. Such circuits normally include both inductors and capacitors to give stable, high frequency oscillators and have to be carefully designed to avoid false indications being given as a result of changes in supply voltage or temperature. Another method relies on the use of a very weak, high frequency oscillator which will only work if the power lost from the sensing plate is negligible under non-activated conditions. The sensing plate can be considered as a transmitting aerial. In figure 2.2, when the man approaches the plate, some power is dissipated causing the oscillator to stop. When he walks away the oscillator restarts. This system is very difficult to design for general use because the circuit would have to be 'tuned' to suit each particular installation.

All circuits have pros and cons but the one shown in figure 2.3 was used for sensing potatoes. It is rugged and reliable, easy to set up, the components are not expensive and no coils have to be wound. When potatoes are piled up in a hopper they are all close together and in contact with the metal sides of the hopper. The capacitance between the tubers and the hopper is so large, compared with the capacitance between the sensing plate and tubers, that the probe effectively measures the proximity of the potatoes.

Although the circuit does not have a large number of components, its operation is quite complex. On the left is the sensing plate which is made out of a circular piece of double-sided printed circuit board, about 25 mm in diameter. The side of the board nearest to the rest of the circuit guards the sensing plate from effects within the circuit. The circuit incorporating the two transistors TR1 and TR2 is an emitter coupled oscillator. This circuit only oscillates if the base connection of TR1 is held at a fixed potential so that when the voltage at the emitter connection is varied by the signal coming back through the capacitor C1, the transistor TR1 is turned on and off. In the unactivated state the potential of the sensing plate may rise and fall freely but when a conductive object approaches, the potential is restrained and so the circuit starts to oscillate properly. As the potentiometer VR1 controls the amplitude of the signal being fed back through C1, it can be used to set the sensitivity of the sensor. The rest of the circuit responds to the presence of an oscillation and by means of the power transistor, switches off an external contactor coil (not shown) which then will turn off the conveyor filling the hopper with potatoes. By using transistors with good amplification characteristics, a capacitive sensor can be built for a relatively low expenditure. The light emitting

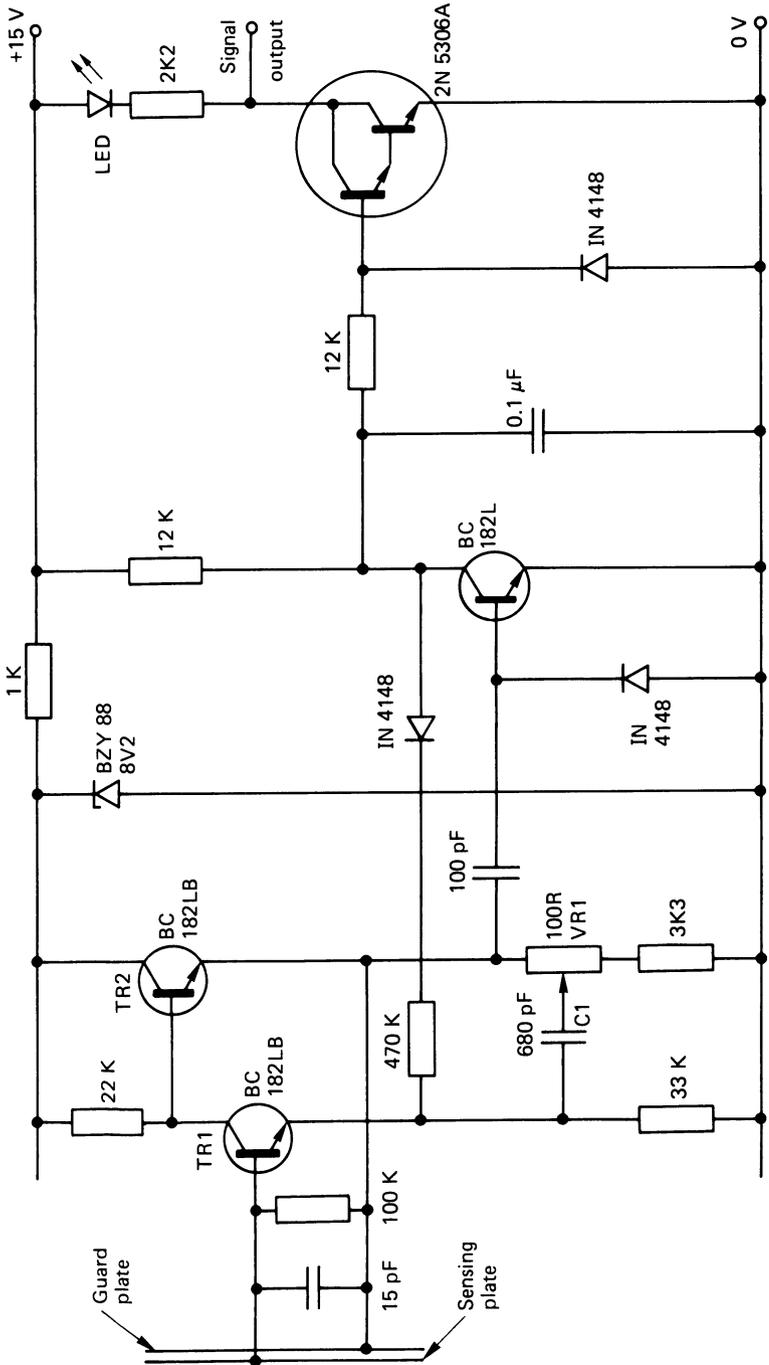


Figure 2.3 Circuit diagram of the capacitance probe

diode, which is mounted in the side of the probe, goes out when the potatoes come near the probe and indicates to the farmer if the circuit is operating properly.

A capacitive probe is used on the pallet box filler shown in figure 2.4 which was built by Loctronic Graders Ltd of Danbury, Essex. The box is not shown in this picture so that the sensor can be seen hanging down from the end of the conveyor. Because potatoes cannot be dropped more than 20 cm without the risk of bruising, the conveyor on this machine is lowered down into a pallet storage box by the hydraulic ram until the sensor detects potatoes or the bottom of the box. Fortunately, a wooden box contains sufficient moisture to operate a capacitive probe. As the conveyor delivers potatoes into the box, the hydraulic ram raises the conveyor up a small amount each time a signal comes from the capacitive probe. Capacitive sensors are also used to detect whether a pallet box has been placed in the correct position before the conveyor descends. Imagine the problems which would be generated otherwise!

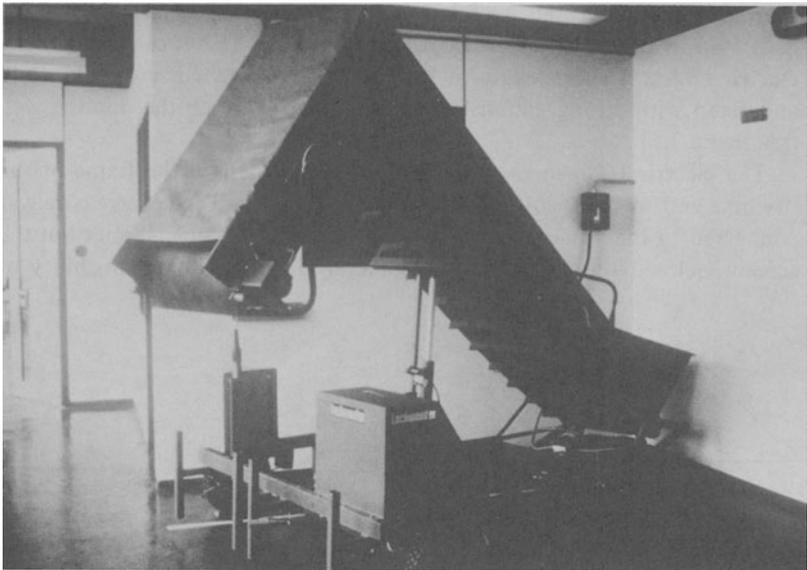


Figure 2.4 *The storage pallet box filler*

MEASURING THROUGHPUT FOR SPEED CONTROL

On a grading line, where only the medium sized potatoes proceed right through, it is necessary to control the quantity of potatoes entering it so

that an adequate number come out at the far end to keep the bagging machines occupied. If the input quantity is too great then the grading sieves may become excessively overloaded. The most straightforward way of monitoring output would be to keep a running average of the number of complete bags produced but the potatoes first pass over a roller table where they are inspected and the quantity reaching the end of the table will vary with the quality of the produce going through. By monitoring the flow onto the roller table, the total throughput can be controlled. The roller table speed can be adjusted to match the incoming flow so that it does not run faster than is necessary to enable thorough inspection of the produce. By comparing the incoming flow with the average number of bags produced, an estimate of the amount being discarded by the inspectors can be determined.

The potatoes rattle down a chute onto the roller table and so, as it is the average mass going through rather than the actual number which is important, it was decided to try and monitor the impact of the potatoes falling a small distance onto the chute. If a piece of coaxial cable is hit, of the type commonly used for television aerials, a small electrical voltage is generated by the frictional effects within the cable. This is called the triboelectric effect. A short length of this cable was stretched across the chute and fixed with strong adhesive along the line on which the potatoes fell (see figure 2.5).

The electrical screen of the cable was connected to the frame of the machine and to the 0 volts supply rail in an amplifier. The centre core was connected to the signal input. The other end was left open-circuit but the screen enclosed the central core completely to prevent the possibility of

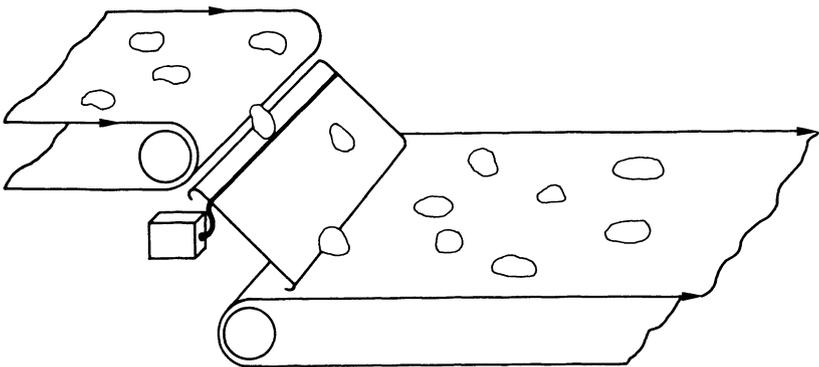


Figure 2.5 *Diagram of the chute, showing the position of the sensing cable*

unwanted electrical noise entering. When a potato fell onto the cable, the pulse generated was amplified and used to increment a counter which recorded the total number of such pulses during a set period. Fortunately, as the machine's speed was being continuously adjusted to keep the derived signal reasonably constant, only an approximate count was required from this sensor. If two potatoes fell simultaneously onto the cable, then it was not too serious if the system counted them as one. However the cable also behaved as a poor-quality microphone and so it was necessary to minimise the unwanted vibrations from the chute and the machinery in general. Damping material had to be fitted to the underside of the chute and absorbent mountings were provided.

POTATO SIZING

Conventional sizing methods for potatoes use a riddle, sieve or screen to separate the smaller objects, be they small potatoes, earth or stones, from the larger potatoes. These screens can be made from a mesh of steel wires on a grid pattern and, to enable the crop to be separated into different size grades, a number of screens, with different mesh sizes, can be installed in a grading line, one above the other. Such screens can handle large quantities of potatoes per hour and are normally reasonably efficient. But there are disadvantages too. For example, during a growing season in which there have been alternating periods of wet and dry weather, secondary growth may cause slightly misshapen tubers so that one end of the tuber may be slightly larger than the other. When this type of potato is jogged along on top of the screen, the smaller end may well lodge in the mesh, like an egg in an egg cup. Subsequently, another potato knocks it further into the mesh and then the grid becomes blocked or the potato is knocked repeatedly until it passes through with flat sides and becomes unattractive to a potential consumer.

Another disadvantage is that marketing requirements, with regard to sizing, vary. The crop is commonly separated into at least three sizes; the largest potatoes are preferred by the chip makers, the smallest are used as seed potatoes for the next season and the majority, in the middle section, go for general consumer use. Sometimes this category may be divided again into three or more bands by a further set of screens. Depending on market requirements, the farmer may wish to adjust the grading sizes from time to time. There are many occasions when it would be convenient to be able to adjust the screen size from day to day to accommodate natural variations in the crop being processed. Many grading lines are run by farmers' co-operatives and therefore the crop being processed may not be

just from different fields but also from a variety of farms with different soils and farming methods. If mesh screens are used it can take up to four hours to strip down the grader and replace the screen with an alternative size. This laborious task is hardly an incentive to encourage the farmer to 'tune' the machine to give the best output as much worthwhile production would be lost during the screen replacement.

There is a third disadvantage to the mesh screening system. Because of the nature of the process, the mesh sizes the produce according to the two minimum dimensions of a potato and no measurement of the longest dimension is made. Therefore, in terms of volume or weight, the sizing is very approximate. Except for the largest potatoes, which will be peeled and sliced into chips before cooking, the majority of the crop will be cooked whole. As the cooking time for a potato depends on its volume, particularly for baked potatoes, it would be advantageous if all the potatoes in one sack were of the same shape and size. Selection by weight achieves a much better approximation to equal shape than mesh sizing because the potato tries to minimise its surface area during growth to approximate to a spherical form but it is still possible, because of a number of environmental factors, for a long thin tuber to grow and, of course, for such a long thin tuber and a spherical tuber to have equal weights. Weighing every potato at a total processing speed of several tonnes per hour would require very ingenious and rapid handling mechanisms. The ideal would be to measure the three prominent dimensions of each potato and grade them according to shape and size.

One system which was devised for doing this consisted of a square orifice or window through which the potatoes were projected. Around the orifice were positioned banks of light emitting diodes and phototransistors so that an optical mesh was formed through which the potato passed. The width and breadth were measured by recording the number of beams obscured in the vertical and horizontal directions, and the length was estimated from the time taken for the potato to pass through the window. Potatoes were transported on V belts to the measuring position and then projected through the window. It was assumed that the potato was travelling at the speed of the conveying belts. A mechanical sorting system arranged the potatoes on the V belts so that their major axis lay in line with the transport direction and there was adequate space between successive potatoes to enable the system to record the measurements reliably. From an electronic point of view this was a straightforward system which gave consistent results but the mechanical problems of making sure that every potato was presented properly were enormous. In countries where most of the potatoes grown are large and fairly uniform, this technique has been employed but in the UK, the sizes and shapes differ so considerably

that the mechanical handling problems are far harder to solve. The other major disadvantage is that to achieve viable throughput to justify the machine's expense, it would be necessary to project the average British potato through the window at 80 mph!

It was soon realised that it would be much better to simplify the mechanical handling, keeping the number and complexity of the moving parts to a minimum, and to make the electronics work flat out. The electronic equipment would be all solid state and therefore the machine's life and maintenance requirements greatly improved. The roller table (see figure 2.6), which was mentioned above as an inspection area, has remarkable properties.

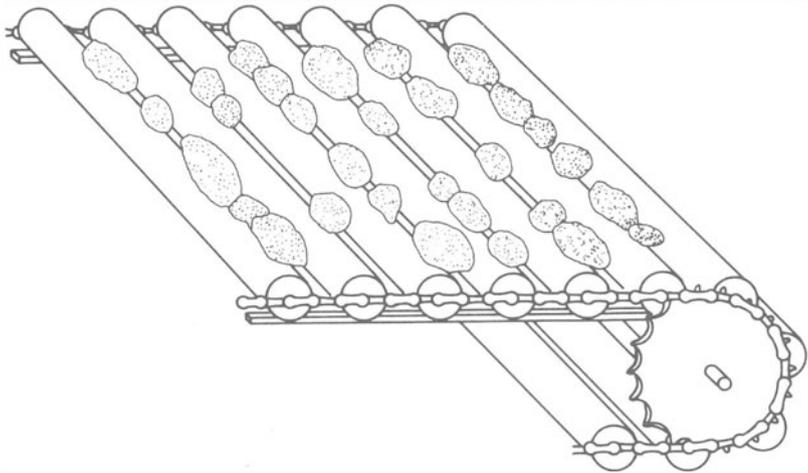


Figure 2.6 *Sketch of the roller table*

It has a capacity for separating out the crop into single advancing lines. Because of the continuous rotation of the rollers and the approximately elliptical form of the potatoes, any extra potato is soon accommodated into an adjacent line by a shuffling process and, in each line, the rotation causes the potatoes to orientate themselves with their longest axes in line with the parallel rollers. It is just like tipping the crop onto a set of linked rolling pins, being dragged along the table top, and achieving both orientation and singularisation within a small distance. By changing the designed length of the rollers, a variety of machines can be produced to cater for different throughputs without any need to change the transport speed.

The mechanics of the roller table are interesting to investigate but further elaboration here would be inappropriate.

Some mechanism must be devised to measure the longest dimension of the potatoes transversely on the roller table. By positioning a camera above the end of a roller table just before the potatoes fall off, it is possible to scan across a row of potatoes, which just happen to lie conveniently with their longest axes in this direction. Because the roller table is moving forward continuously at a constant rate, a line camera can be used to acquire a whole picture of the potatoes by recording successive scans. The line camera consists of a row of tiny photodiodes located behind a lens which are interrogated by electronic circuits and produce a signal which is similar to that for a single horizontal line on a television screen. The amplitude of the signal is proportional to the brightness of the image falling on the photodiodes. The line camera also features in chapter 3 (page 43) and more detail on how it works is given in chapter 7 (page 136). By sensing the difference in light levels between the potatoes and the background and counting the number of photodiodes illuminated by the image of a single potato, its length can be calculated.

Obtaining a high contrast image, from which measurements could be taken of a row of unwashed potatoes on a dirty and dusty background, is not straightforward. The simplest way would be to arrange for the camera to 'see' a silhouette because the potato is opaque. But a light under a roller table would soon be completely coated and obliterated by dust. If the light were above the table then the camera lens, under the table, would be coated instead. How can a brown object be easily distinguished from a brown background? Even if the background starts off white, purple or pink, it will quickly become brown after a tonne of spuds has passed by. One way of doing this is to highlight the potatoes against an unlit background by illuminating them from an oblique angle. Figure 2.7 is intended to show how this was done on the roller table.

The lights were a couple of car fog lamps which were positioned to cast even illumination along the last row of advancing potatoes. A shield or mask ensured that the rollers were not lit at the point observed by the line camera. These lamps produced an ideal beam for this application and had the advantage that they could be supplied from 12 volts DC, so eliminating any rapid fluctuations in light levels which might have been caused by lights being fed from an alternating supply, like the mains electricity system. Because the light did not fall on the rollers, but only lit up the last row of potatoes, it did not matter what shade of colour the rollers were. Photodiode arrays in line cameras come in a variety of lengths and so it was possible to choose one of a number of different sized cameras accord-

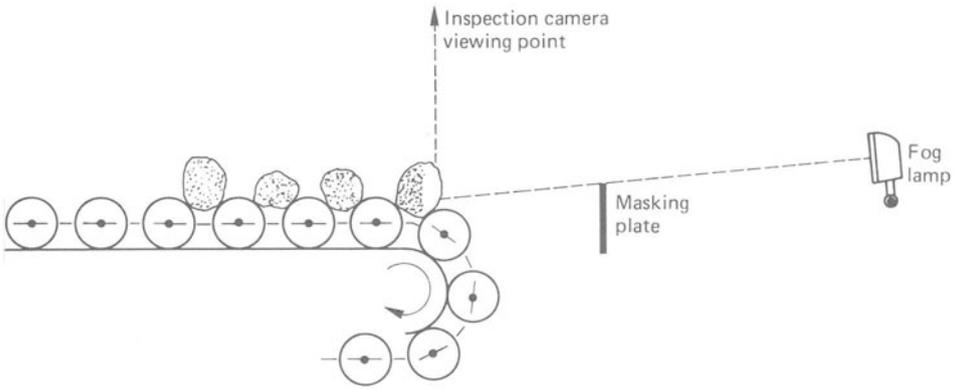


Figure 2.7 *The way in which the last row of potatoes is illuminated without the roller table being lit at the viewing point of the camera*

ing to the roller table width selected for a given throughput but still retain the same measurement resolution.

A microprocessor system was used to sample the camera's signal at regular intervals so that, as the potatoes advanced, successive scans enabled a 'picture' to be built up and stored in electronic memory. Using this 'picture' the system could determine the maximum length of each potato and, by assuming symmetrical proportions about the longest axis, it could measure the approximate shape and volume. If two potatoes were touching end to end, then the software in the microcomputer was sophisticated enough to recognise that there were two potatoes rather than one by checking the V formation in the 'picture' formed between two potatoes.

To synchronise the camera scans with the roller table movement and hence the potatoes to be measured, a toothed wheel was affixed to the end of the shaft which drove the roller table. A light emitting diode and a phototransistor, contained in a single housing called a slotted opto-switch, were mounted on either side of the toothed wheel so that the light beam would be broken by the passing teeth and so enable the system to detect the position of the rollers. Because the rollers were pulled along by chains running over sprocketed wheels, the shaft position could be used to indicate when the middle of the potatoes, which was the same as the middle of the gap between the rollers, was passing. By knowing this, a prediction of the complete volume could then be obtained.

The advantages of the electronic sizing system were mainly that the potatoes were not subjected to vigorous mechanical shaking and forcing through sieves or meshes. The grading sizes were numbers set in the com-

puter and therefore could be altered quickly and easily by typing in a different number. The potatoes were deflected to the appropriate receptacle by pneumatically operated fingers, controlled by the computer, as they left the end of the roller table. By being able to measure the maximum length of each potato, the planting problem, associated with seed potatoes, of the tuber sticking in the mechanical planting cup during replanting could be avoided by not allowing any potato exceeding a certain length to be classified as 'seed'. Those potatoes, with ideal dimensions for baking, could be easily selected from the main crop so they could be sold at a premium. None of these features could be accomplished with conventional mesh screens.

The technique also lends itself to further automated inspection, using an auxiliary TV camera mounted upstream above the roller table, for colour selection and detecting black spots on peeled potatoes prior to entering a food processing line for crisps or frozen chips.

DIAMOND SIZING

By a strange coincidence, while developing the potato sizer, a request was also received from an industrial diamond producer for a sizing system. Fortunately there was no clash of commercial interests and therefore the two sizers could be developed simultaneously with the two clients benefiting mutually from any new discoveries.

Although shape measurement was still the prime requirement, there were important differences to be borne in mind during the design stage. The potato had a low unit cost and therefore, for the machine to pay for itself in a reasonable time, a considerable throughput was necessary. Only a fraction of a second was available for the inspection of each tuber. But for a diamond, minutes could be allowed for each individual inspection. Therefore while parallel sizing was essential for potatoes, serial presentation for diamonds was preferred.

A coarse measurement resolution was sufficient for the potatoes so that the image in the camera was many times smaller than the object – the image length of the average potato occupied some 20 photodiodes. For diamonds it was the other way round, with the lens mounted closer to the diamond than to the photodiode array so that a magnified image was produced (see figure 2.8). Obviously this catered for the much smaller object size and also improved the measurement resolution.

The industrial diamonds were launched, one at a time, from a vibrating bowl feeder onto a chute made of two contra-rotating rollers. This is far

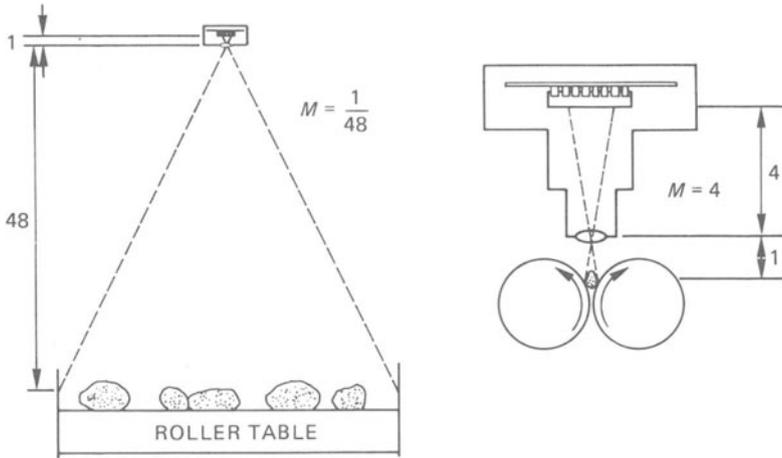


Figure 2.8 Diagram showing the differences in optical magnification between the potato and the diamond sizers

easier to show in a practical demonstration than to draw but I hope figure 2.9 will help.

Because of the contra-rotation, no object could stick as a result of friction but gently slid down at more or less constant speed. By positioning the camera at right angles to the rollers and scanning transversely, the length of the object could be estimated from when it was first 'seen' by the camera to its last appearance, and the width measured by detecting the maximum number of photodiodes illuminated as the object passed by. The rollers were matt-black and miniature torch bulbs illuminated the diamonds as they passed the camera. On reaching the end of the rollers, the monitoring microcomputer could energise one of a number of air jets to blow the diamond into an appropriate receptacle. Imagine deflecting a potato with an air jet!

Just as the optimum shape for a baking potato required an aspect ratio (length:width) of about 1.5, so an industrial diamond, which could be mounted with others on the end of a drilling bit, also required an optimum aspect ratio of about 1.5. If the diamond is long and thin, it may be easy to secure but could easily fracture under load when drilling because of sideways stress, whereas a spherically shaped diamond might easily come out of its mounting. So the equipment was used to measure what is known in the trade as 'blockiness', and to sort out those diamonds most suitable for cutter mounting.

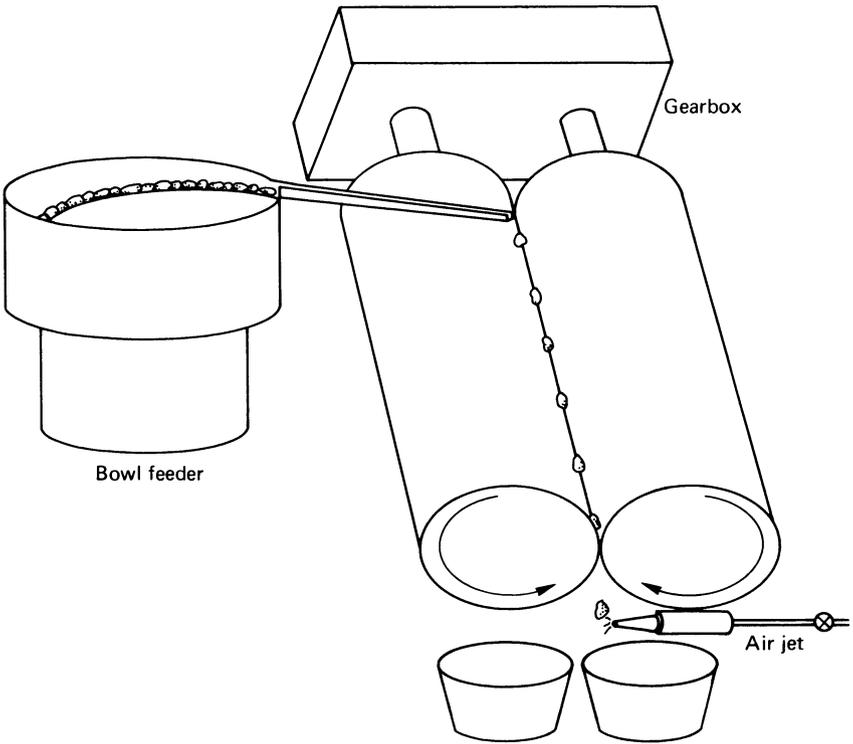


Figure 2.9 *The contra-roller arrangement*

Once again the mechanical presentation system was important because the rollers pre-aligned the diamond with its longest axis in line with the direction of travel, therefore simplifying the computer calculations required. The rollers provided an almost constant transport speed although I must admit I never really understood why. Lighting was a tricky problem; in the long run there was a higher degree of confidence in the camera ‘seeing’ the exact dimensions of a potato than those of a diamond because of the occasional internal or external specular reflections. Specular reflection means mirror-like, as opposed to diffuse reflection produced by a dispersing surface. Slight twists in a diamond might well expose a facet which, by glints of light, would confuse the camera into measuring slightly larger or smaller than the true width. It was for this reason that matt-black, anodised rollers were chosen to absorb stray reflected light.

MAX-MIN TEMPERATURE STORAGE MONITOR

Leaving the luxury world of diamonds and returning to earth with potatoes, large quantities have to be stored during each winter so that they can be supplied to consumers regularly through the season. The traditional method of storing potatoes in clamps (earth-covered outdoor heaps) protected the tubers from severe frosts but did not prevent the tubers, which of course were still living organisms, turning some of the starch into sugar when they were cooled to near freezing.

Nowadays, potatoes are commonly stored in vast, aircraft-hanger type sheds. When storing large quantities of potatoes it is necessary to ventilate the crop and to maintain the average temperature at about 10°C. If the temperature drops significantly below this level then a conversion of starch into sugar takes place within the tubers, and if the temperature rises much above this figure then there is a serious risk of bacterial growth and subsequent decay rapidly spreading through the pile. When the potatoes are put into storage in September/October, plastic drainpipes are inserted vertically in the pile, often at least 4 metres high, so that thermometers can be lowered into the heap to record the average temperature. In a large store there might be a need for up to fifty of these to monitor effectively the temperature and to assist the farmer to locate potential hot spots rapidly.

The problem with conventional glass/mercury thermometers is that by the time they have been pulled up on a string and the temperature read, the bulb temperature may have changed and a false reading may have been taken. Sticking a lump of insulating Plasticene around the sensing bulb reduces the rate of change of temperature but then, invariably, this falls off down the drainpipe at the critical moment. Even keeping the pipes straight when the potatoes are initially stored is difficult, as large masses are involved which can easily shift and therefore extraction of the thermometers on a regular basis can be awkward. To add further to the complications, in order to prevent premature sprouting, the whole store is kept dark, so making thermometer reading inconvenient to say the least.

By using electronic thermal sensors (see figure 2.10), connected by long leads to a central monitoring point, the temperatures can be observed without having to climb over the heap two or three times a day. The central monitor can be either a manually operated unit with a selection switch and a display or, more recently, a small computer which continually cycles around all the probes, checking their temperature values, comparing these with pre-set maximum and minimum temperature limits so that an alarm can be sounded immediately any probe indicates an excessive temperature. Using a built-in clock within the computer, a 'print-out' of actual temperatures, trends and faults can be produced on a regular basis.

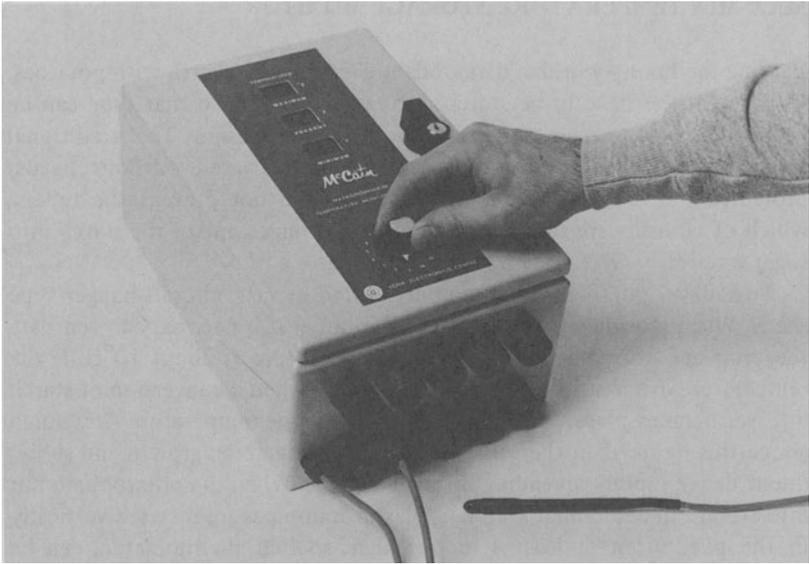


Figure 2.10 *The max-min storage temperature monitor*

There is a further task which a small dedicated computer can usefully perform which is of benefit to the users of large volumes of potatoes, such as the crisp and potato chip manufacturers. The amount of sugar generated within a potato, when it is cooled below 8°C , is proportional to the temperature and the amount of time for which the tuber has been below the critical temperature. The sugar content is directly proportional to the integral of the temperature/time graph below the critical temperature. The sugar content in a potato not only affects the flavour but can also cause extra browning in the cooking process due to caramelisation. Therefore it is useful for the crisp manufacturer to regulate the amount of sugar within the crop to be processed or if that is not possible, to be able to know in advance that the cooking time or temperature may need to be reduced to keep the cooked product consistent. The microcomputer can easily carry out a number of calculations regularly to keep a record of the 'sugar integral' using permanent memory.

There are a number of different electronic temperature sensors which could be used for this application. The most common are the thermistor, the platinum resistance element and the thermocouple. It is the resistance of the first two which provides an indication of temperature whereas the thermocouple is a junction of two dissimilar metals across which a minute

voltage is formed. This effect was described in chapter 1 (page 5). If a resistance measurement is required for a probe situated a long way from the monitoring unit, then the leads connected to it will have an appreciable effect on the reading made. In order to compensate for this, it is common to use a four wire system so that one pair of wires is connected to the temperature-sensitive element, be it a platinum resistance element or a thermistor, and the other pair of wires is connected to a shorting link. The monitoring unit then subtracts the resistance of the shorted wires from the resistance measured across the other pair of wires to find out what the actual resistance of the sensor is. This measurement can be conveniently achieved using a Wheatstone bridge circuit (see figure 2.11).

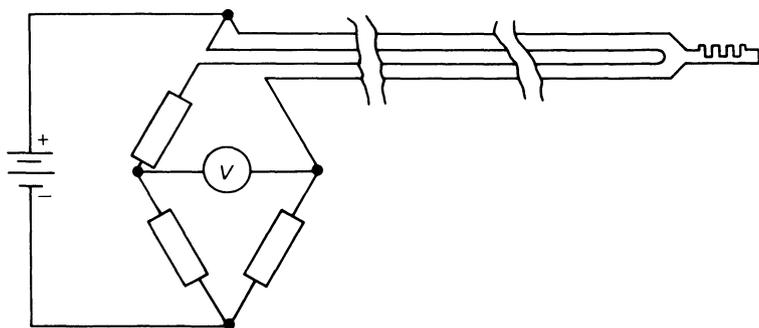


Figure 2.11 *Remote measuring of a platinum resistance thermometer using a Wheatstone bridge circuit*

Careful consideration of this circuit will reveal how three wires rather than four could be used. Alternatively a sampling technique could be used instead of a bridge circuit. It is obviously preferable to minimise the number of wires needed for a system as the cable runs can be very long. A thermocouple sensor would only require two wires but these would have to be of exactly the same two metals throughout, including the plugs and sockets and extension leads; this could make for considerable expense.

It is possible to devise a sensing system using two ordinary copper wires and cope with variable length extension cables. The diode has a temperature characteristic which, when built into a small electronic circuit, can be used to adjust the current flowing through the circuit so that the current is proportional to temperature. Irrespective of the voltage applied across such a circuit, within a reasonable limit, the current remains directly proportional to temperature. Therefore the circuit, which is incorporated into a small metal can of a similar size to a transistor package, may be connected

to a variety of lengths of lead and, provided there is a sufficient voltage available at the device to enable it to work properly, the current flowing will be proportional to the temperature of the can. The circuit used in the sensor is shown in chapter 7 (page 122). The device has a low cost compared with the platinum resistance thermometer and can be calibrated to provide a set current for a given temperature so that probes can be interchanged at will and extension cables added or removed without the need for any recalibration. The arrangement only needs two wires, of ordinary copper, thereby keeping the costs as low as possible. This type of sensor is used for the temperature monitoring system shown in figure 2.10, and a number of these units are used each winter to keep a check on stored crops.

SWEDES

Quite a lot of vegetables need dressing in some manner before they are presented to the final consumer. For instance, if a swede is to be sold in a greengrocer's shop, it looks more attractive if part of the stalk is left on and the root and the leaves are cut off. But if a swede is sent to a freezer company to be diced and then frozen, it is preferable for the stalk to be removed completely as soon as possible. A blade can be fitted to a tractor in such a way that when it is pulled along behind the tractor, it will cut off the swedes from their roots. Also a flail, a nasty whirling wheel with extended spokes, can be mounted on the tractor to sweep off the leaves. But to cut off the stalk, either just where it emerges from the bulb of the swede or about 50 mm above to leave an attractive stalk, is quite tricky because swedes will grow to various sizes depending on the nature of the particular area of soil on which the seed initially falls. A cutter, mounted on the front of a tractor, could cut off the stalk provided its height were adjustable for every swede. The cutter's height could be adjusted by means of an electronically controlled hydraulic ram. Provided the flail is kept well out of the way (for instance at the side of the tractor working on the next rows to be harvested) a curtain of optical beams could be used to measure the height of the bulb of the swede (see figure 2.12).

A column of light emitting diodes is mounted on one side of the area through which the swedes will pass when the tractor is going along, and a corresponding column of phototransistors is mounted on the other side. Each detector is associated with a corresponding emitter on the other side at the same height. In order to make sure that adjacent detectors do not respond to the incorrect emitter because of the close proximity, the emitters are turned on sequentially, at a high frequency to make sure that nothing is missed, and the appropriate detector is sampled at that time.

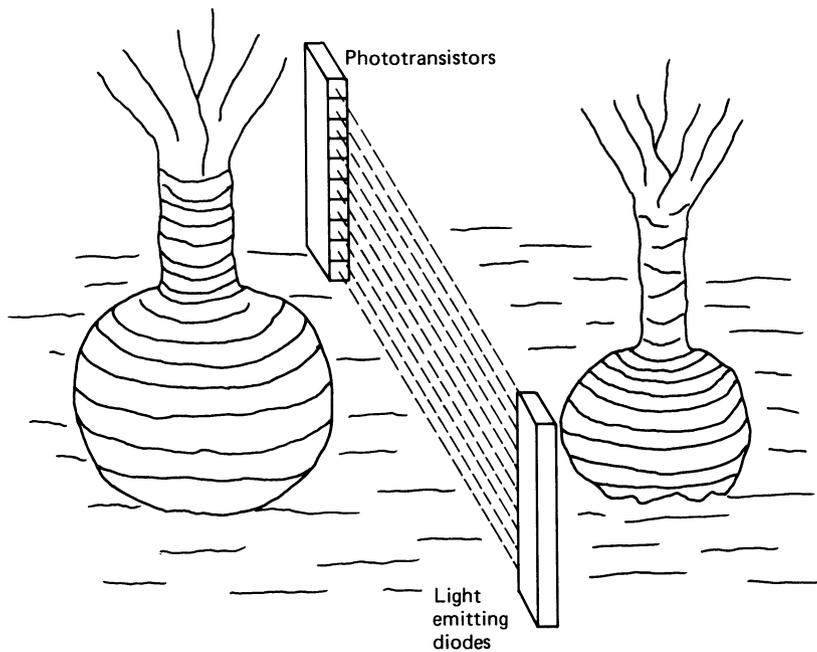


Figure 2.12 *Optical beam arrangement for measuring the shoulder height of swedes*

This technique allows for slight misalignment of the sensors in the vertical direction and for small vibration effects to be catered for without loss of performance. Because of the electronic determination of height, cylindrical rather than spherical lenses can be used in front of the columns of detectors and emitters to concentrate the beams, so enabling a wide spacing between source and receiver to be set. Two such cylindrical lenses can be cheaply constructed from a piece of Perspex rod, cut in half lengthwise, and the sawn surfaces polished with Brasso.

This arrangement will indeed enable the height of an object passing through the beams to be measured to within the resolution set by the vertical spacing of the phototransistors, but it will not ignore the stalk! To make the equipment ignore the stalk and therefore measure the height of the shoulder at the base of the stalk, two identical light curtains could be employed, spaced apart by the width of the widest stalk. Only those light beams obscured up to the same height in the two curtains would be used to register the swede's height. This can be achieved by 'ANDing' the signals emanating from beams at the same height. Although this would solve the problem of ignoring the stalk, it involves the expense of a duplicate light

curtain. However, if the speed of the tractor remains constant at a pre-determined level, then a time delay can be used to provide the same effect. If a beam is only obscured for a duration corresponding to the passing of the widest stalk or less, then that signal can be ignored and the longer signals used to record the height. The tractor's speed could also be monitored from a sensor on one of its non-driven wheels and fed into the measuring equipment so that any speed could be catered for. However, usually one particular optimum speed is chosen for a harvesting operation.

The height sensor is mounted a convenient distance in front of the cutter to make sure that there is sufficient time for the hydraulic ram to move the cutter to the new position as each swede is encountered, and also to prevent debris from the cutting operation falling on the sensors. The choice of whether the cutter should remove all the stalk or leave a part of it on, can be made by setting the physical vertical position of the cutter to an arbitrary distance above the height controlled by the measurement.

Finally, it is important to remember that with any equipment designed for dealing with natural produce, there will always be one or two rogue specimens which defy the design rules. I had no sooner got the above equipment working than my farming client produced the swede shown in figure 2.13!

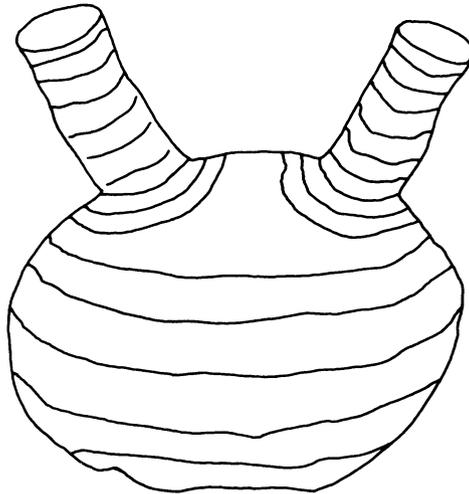


Figure 2.13 *A double-stalked swede*

CHECK WEIGHING OF PACKETS OF CRISPS

Potato crisps are sold by weight. The packets have either to contain a minimum weight or the average of a random sample from a batch has to be above a minimum weight. But the crisps are made from a natural product and the volume occupied by a given weight of crisps can vary depending on the shapes involved and the way in which they tumble into a bag. There is a dilemma here for the crisp manufacturer because on the one hand it is not desirable to give away any extra crisps in the bag as this would reduce the profits of the company, but on the other hand it is important that the bag looks full when bought by the consumer or the company may acquire a reputation for stinginess. However it would certainly be worthwhile, in order to keep a generous reputation, to add one or two extra crisps to occasional packets where necessary. How could this be done?

Crisp bags are made from a continuous band of plastic, on which is pre-printed the company's name and other product information, which is folded into a tube into which the crisps fall in pre-measured weights. The tube is heat sealed at regular intervals, as each load of crisps falls in, to form bags (see figure 2.14).

Fortunately, because of the need to heat seal the vertical join, there is no printing on the edges and the seal is transparent. By shining a beam of light down the tube, so that the newly deposited pile of crisps is well lit compared with the sides of the tube (just like the potatoes on the end of the roller table in the sizer — see figure 2.7 (page 17)) and positioning a line camera, scanning in the vertical direction, outside the vertical join in the tube, it is possible to discern the height of the crisps in the bag prior to sealing so that one or two extra crisps may be added if deemed appropriate. For a very small increase in the total number of crisps made, all the crisp bags are full and the reputation of the company is enhanced. The image seen by the line camera is distinct, the height resolution need not be very accurate and little signal processing is required so that the relative cost of the equipment will be inexpensive.

It would be wrong to complete this section, having started it with the title 'Check weighing', without mentioning a couple of electronic techniques commonly used for weighing. Strain gauges are probably the most frequently used sensors. The strain gauge comprises a resistive film element laid down in a zigzag pattern so that the lines of the zigzag lie in the same direction as the applied strain. The gauge is usually bonded to a metal component to be placed under strain, and expands or contracts with that component. The expansion or contraction causes an increase or a decrease in the total resistance of the element because, as the element stretches, the cross-sectional area reduces simultaneously and therefore the resistance

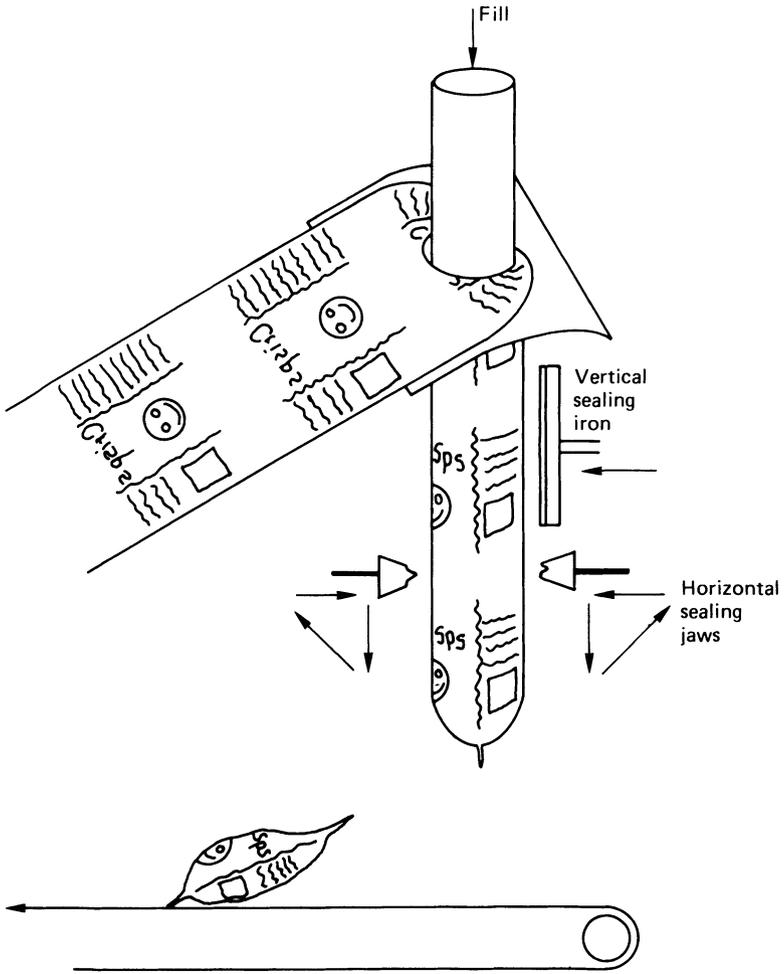


Figure 2.14 Sketch to illustrate bagging machine

increases. Although the gauge is also sensitive to temperature, this problem can be overcome by bonding another identical gauge to another adjacent part of the metal component not under strain (perhaps at right angles to the first) so that a difference between the two can be taken to eliminate the temperature effect. Alternatively, if the strain of a cantilevered beam is being measured then by fixing identical gauges on each side of the beam (one side in compression and the other being extended) and using the

change of resistance of both, not only will twice the signal be available but also the temperature effect will be cancelled out. The Wheatstone bridge arrangement can be used conveniently for this.

A second method of weighing uses the force balance. Here a counteracting force is produced by a coil repelling (or attracting) a magnet attached by a linkage to the weighing pan. The position of the magnet is sensed and the current in the coil is regulated so that the magnet is always kept in the same place. Therefore the force generated by the coil will always be equal and opposite to the applied force (in this case a weight). The magnet position sensor may utilise a beam of light, emanating from an LED and being received by a phototransistor, which is partially obscured by the leading edge of the magnet. For ease of explanation, it is assumed that more light reaches the receiving phototransistor when the magnet descends. If a weight is placed upon the weighing pan, the magnet attached to it will start to descend. More light will then fall upon the phototransistor and the electronic controller will then increase the current in the coil to compensate for this movement and restore the magnet to its original position. Similarly, the inverse happens when the weight is removed. The current flowing in the coil is therefore directly proportional to the weight applied. Because a non-contact position sensor is used and as electronic circuits respond very fast, the weighing pan hardly moves.

Producing a counteractive force is known as 'feedback' and the technique of trying to minimise movement is called the null-effect. The null-effect is much exploited in electronic sensing and control because the measurement accuracy does not depend on a linear relationship within the internal sensor (in this case the optical beam position sensor). The force balance is also used for measuring pressure (the Bourdon tube and bellows both create an external force or movement when pressure is applied internally) and a similar system using the null-technique and 'feedback' is described in chapter 6 (page 111) under Electrical Power Measurement.

CROP SPRAYING

To complete this agricultural chapter, modern farm management techniques require occasional spraying of a crop with insecticides. Although this can be done from an aeroplane or even a helicopter, it is more common to use a long spraying boom fitted to the back of a tractor with a high wheel base (see figure 2.15). A small amount of the crop will be destroyed where the wheels pass but this loss will be less than the alternative cost of hiring an aeroplane, especially for typical British acreages. The boom spraying method is also more accurate and normally avoids the problem of over-

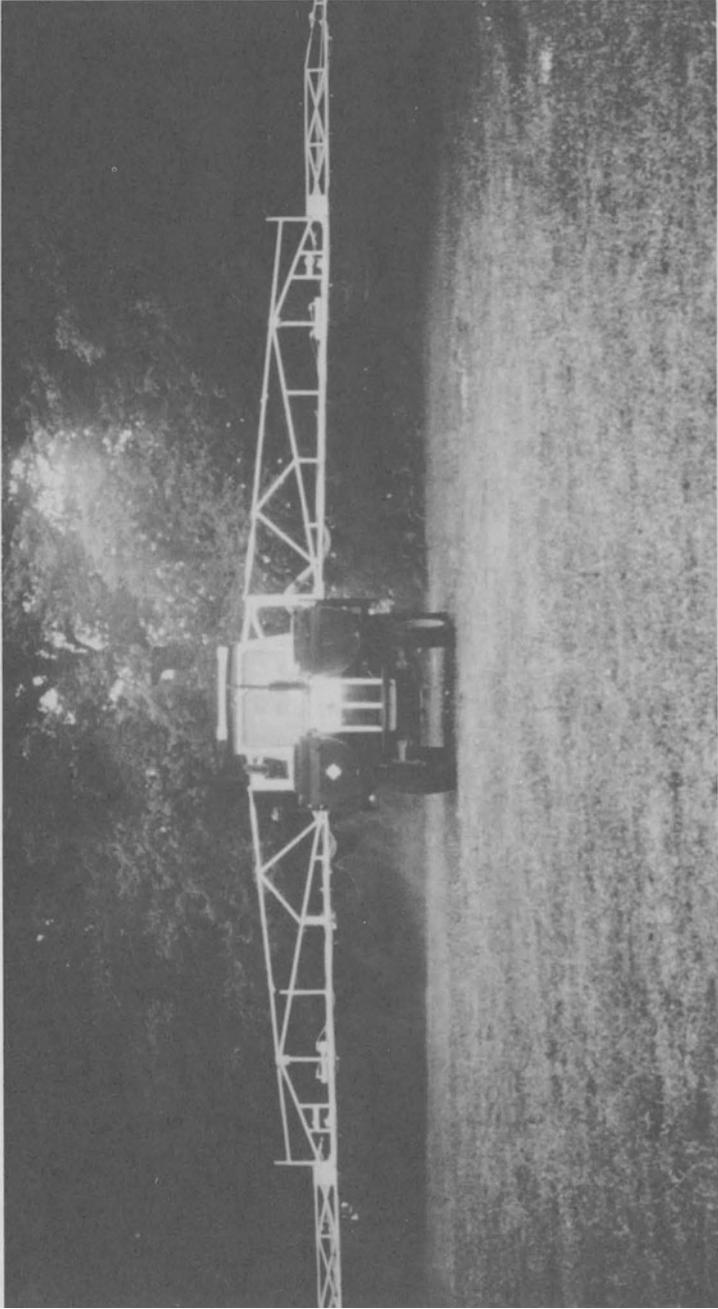


Figure 2.15 *A distant view of a typical spraying tractor*

spraying or leaving areas completely uncovered. ‘Tramlines’ are created at sowing time by blocking off two seed channels in the seed planter in line with where the spraying tractor’s wheels will come later on. In this way mis-spraying can be avoided between alternate ‘bouts’, the name given to each pass up and down the field (see figure 2.16). This is all very well for nice rectangular fields but only a few British fields have four square corners. If the end hedge or fence lies at an angle to the sides of the field, then it is impossible for the farmer to avoid some mis-spraying.

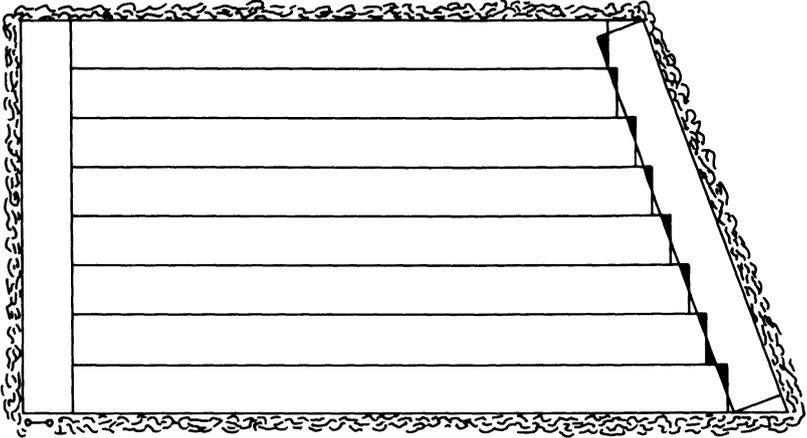


Figure 2.16 *Plan of a sprayed field showing the relative position of the bouts*

To help with this problem a small electronic controller can be installed in the cab of a tractor (see figure 2.17) and the nozzles on the boom connected through a set of valves so that they can be turned on and off sequentially. The controller incorporates a knob, across which is drawn a line which the driver of the tractor aligns with the approaching hedge. To one of the front wheels is attached a speed sensor so that when the driver presses the start or stop button, the controller is able to switch the valves at a rate proportional to the angle of the hedge and the forward speed of the tractor. The spraying process therefore starts and stops parallel to the hedge.

If the knob produces an electrical signal proportional to its rotational position or the angle at which it is set, then to obtain a result which can be used, with the speed signal, to control the timing of the spray valves, the tangent of the angle must be found. Without the complexity of a micro-computer this may seem an impossible problem to solve. What is needed is an electronic network which has a tangent characteristic so that when a

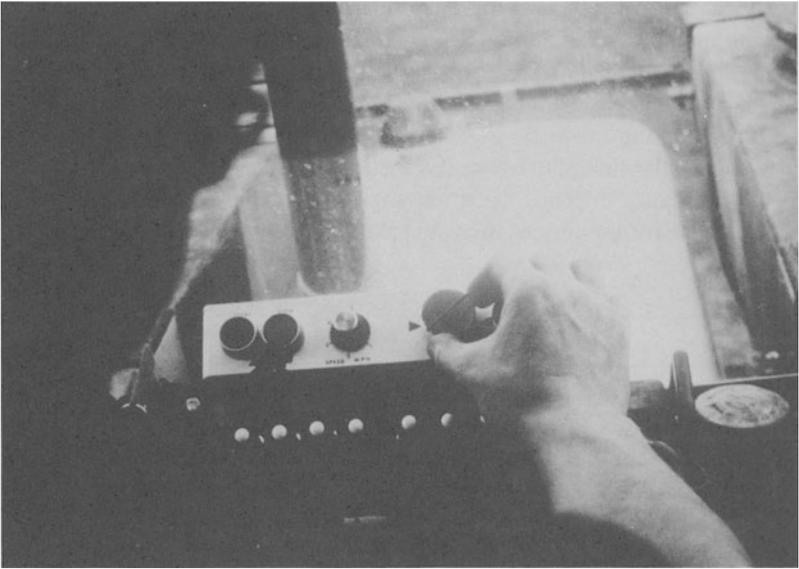


Figure 2.17 *Inside the cab showing the electronic switching unit (the driver is setting the line on the top of the knob parallel with the approaching hedge)*

voltage or current is applied to it, the emerging signal represents the tangent of the applied voltage or current. The diode has an exponential characteristic and although this is not identical to a tangent characteristic, by using a number of diodes, connected to resistors of various values so that the influence of each is different, it is possible to create a good approximation to a tangent characteristic over the small range required (see figure 2.18).

This type of circuit achieves the necessary conversion required to the signal, and the equipment worked well when tested over the white lines of a football pitch. It also worked correctly when used for spraying and, apart from the extra cost of the multiple valves, provided a low-cost solution to the spraying problem. This is one of the many applications in which the diode features as an essential element in electronic circuit design, contributing to a successful final result.

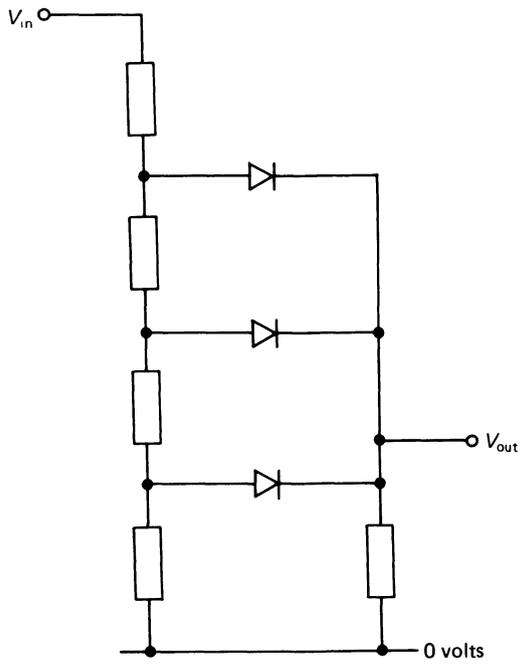


Figure 2.18 *Circuit diagram of a typical diode network*

3 Making Shirt Buttons and Sewing Hems

Do you know how shirt buttons, or for that matter any buttons used as fasteners for garments, are made? I had always assumed that they were sawn off discs from an extruded plastic bar with the holes as tubes already in the bar. But no; first a flat sheet of resinous material is cast, and blanks, almost the same diameter as the final buttons, are punched out from the sheet before it has cured. Then the blanks are drilled and the surfaces machined. Finally they are polished before dispatch. The main reason for the process is so that subtle layering can be built in during the initial resin casting to enhance the resulting reflective properties.

As a result of the recession during the early 1980s, there is now only one factory left in the UK which makes garment buttons. It is called **British Button Industries** and is based in York. In order to maintain its market share against imported buttons, mainly from the Eastern Bloc countries, it is vital for the company to maintain the high quality of its products. It is important, of course, that the button looks attractive and will enhance the appearance of the garment on which it will be sewn. The cosmetic features are checked during final inspection of a batch sample, and, on the rare occasion when faults are detected, the whole batch is discarded because it would take too long for the inspector to check each and every button. But also, the manufacturer must check that the button is strong and has the necessary features (such as holes) to enable it to be sewn on a garment. Should there be any inadequacies in these standards, the consequences are more serious especially where buttons are to be sewn on by machine.

Imagine an automatic sewing machine coping with a button that has only one hole or no holes. The absence of a hole could cause a sewing needle to break which might lead to a nasty eye accident for the machine operator. **British Button Industries** wanted an inspection machine devised to eliminate such a possibility by checking that every button had the correct number of holes.

A BUTTON HOLE DETECTOR

A drill breakage is the usual cause of absent holes, even though it happens rarely. Therefore, initially it was thought that it would be best to monitor the presence of the drill points coming through each button in the drilling machine so that not only would every button have all its holes but also, should a drill break or wear significantly, the operator could be alerted immediately to prevent the manufacture of scrap buttons. As mentioned in chapter 2 (page 8), the capacitive effect can be used to detect the proximity of potatoes. Figure 3.1 attempts to show in cross-section how sensors could be mounted in the base under the button to detect the drill points coming through during the drilling cycle. Obviously, electrical contact could not be used because the drills would rapidly wear away the contact plate surface.

There is however a serious drawback to this method of monitoring because the capacitance between two parallel plates is not only inversely proportional to the distance between them but also proportional to their surface areas. The surface area of a drill point, especially of the type used

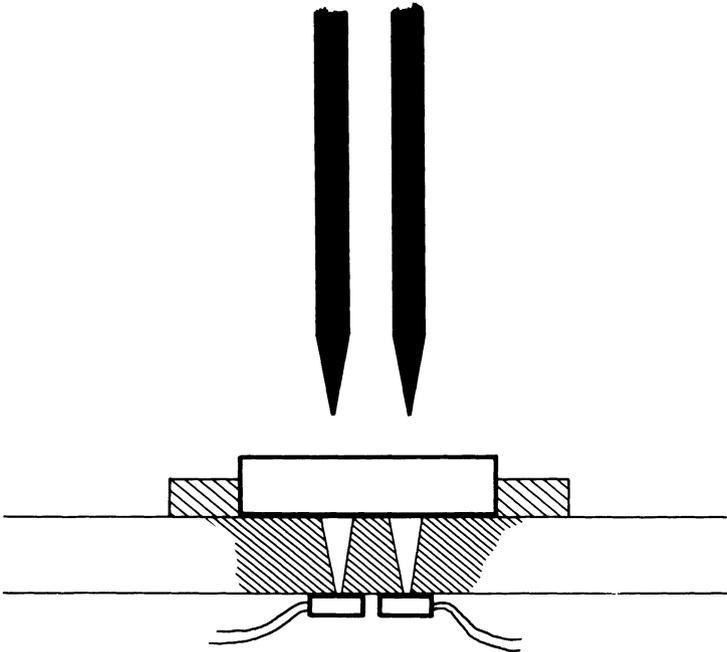


Figure 3.1 *Cross-section of a button being drilled*

for drilling these buttons, is very small and so the resulting change in capacitance caused by movement of the drill point would also be very small. As the drill point became worn and the penetration through the button diminished, the surface area would increase because of wear, and the distance between the end of the drill and the sensing plate would also increase. These two changes work in opposition to each other and therefore the capacitance change would be smaller than if only one effect occurred. Also, in many of the drilling machines, the button blanks are fed by gravity and occasionally, but fortunately rarely, one button blank manages to escape and jump past the drilling station into the receptacle. Detecting drill breakages and wear would be useful, even though difficult. However, such a technique cannot guarantee that every button has the right number of holes in it.

Attention was therefore turned to ways of inspecting the buttons once they had left the drilling machine and were within separate equipment so that a batch of drilled blanks or finished buttons could be loaded into a hopper ready for inspection. This meant that an inspection technique needed to be devised and also a mechanism designed for handling the buttons at a reasonable throughput. Obviously if the inspection technique chosen did not require precise alignment of the holes in each button, then the mechanical presentation part would be much simpler to design and construct and more reliable in service. As most of the buttons are only translucent, it was thought there might be some possibility of comparing the amount of light coming through each button against the transmission through a perfect one and, by this means, determine how many holes were present. Figure 3.2 shows the type of arrangement envisaged, with a small light source on one side of the button and a collimated phototransistor on the other used to sense the brightness of the silhouetted button.

If the button were completely opaque, then the light transmitted through would be directly proportional to the area and number of holes present. But because buttons are nearly always translucent, as the number of holes increases so the incremental difference becomes smaller and smaller, and therefore it is less easy to distinguish how many holes are present. In the case of button inspection, distinguishing between three holes and four would be the most difficult. The relative light levels measured can be shown diagrammatically as in figure 3.3.

In order to see if it would be possible to increase the signal difference, the optical transmission spectrum of the button material was studied. If an absorption point on the spectrum had been found, even in the near infrared in which a number of low-cost light sources are available, then the technique could have been used. But, as can be seen from the transmission

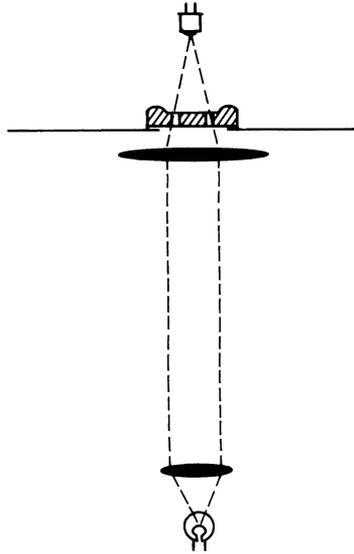


Figure 3.2 Sketch of arrangement for measuring the intensity of light transmitted through a button

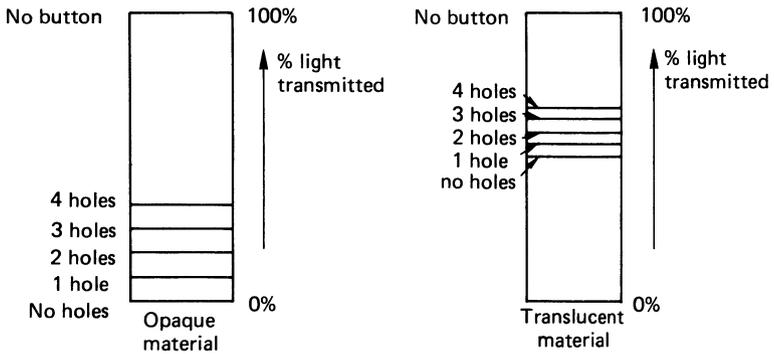


Figure 3.3 Diagram showing the relative transmitted light levels through opaque and translucent material

spectrum for this type of material (figure 3.4), no convenient absorption band was available.

Although the above suggestion could not be implemented, it did have the advantage that the button could be presented in any orientation. So

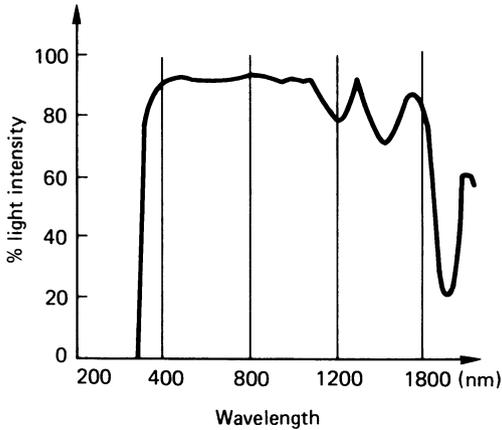


Figure 3.4 *Typical spectrum for transparent plastic*

what other ways are there of checking the number of holes? What about counting them? If the counting is done circularly, say clockwise, and is only performed for one revolution, then the orientation does not matter. If a tiny light is mounted on a rotating shaft under the button and a phototransistor senses the amount of light coming through the button then, in one revolution, the number of flashes should indicate the number of holes present. This technique also has the advantage that any variations in the transmission properties of the button material are only of secondary importance. If this seems a good method to try, how fast will the shaft and hence the light have to go round? The buttons need to be inspected at a rate of about ten per second. If they are moved over the inspection area smoothly then the amount of time in which they remain approximately in line with the axis of the shaft is only a minute fraction of the 100 milliseconds available for each button. In fact the inspection is like a snapshot and, to avoid blurring, only one millisecond is available. To complete a whole revolution in one-thousandth of a second would mean that the shaft would have to rotate at 60 000 rpm! Such shaft speeds usually mean that air bearings would be essential and both the noise and the costs would be high.

This is where electronic devices come into their own! By using a circular array of light emitting diodes (LEDs) which are turned on sequentially, it is possible to simulate a rotating spot of light at speeds far in excess of what is mechanically feasible. LEDs come in all sorts of shapes these days and by using triangular ones (apex = 30°) a set of twelve can be conveniently assembled in a ring. As figure 3.5 shows, twelve segments is the

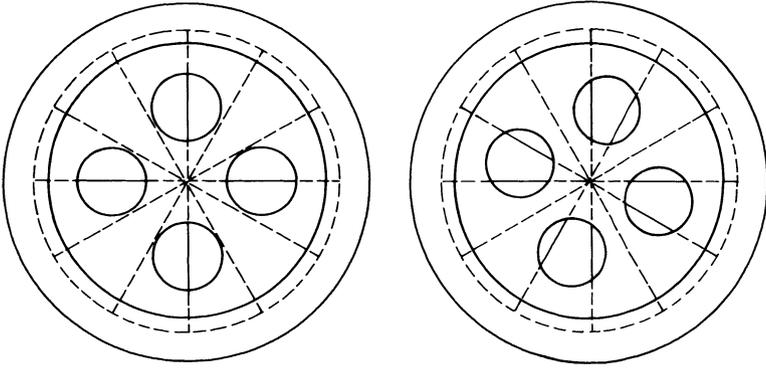


Figure 3.5 *Circular segment arrangement, with button shown in the two extreme positions*

minimum number which could be used to ensure that four holes can be counted irrespective of button orientation. In one of the cases, four of the segments are completely covered by the button and therefore when these are lit up in turn as the light spot advances cyclically, the light reaching the sensor is dim compared with the amount which comes through the hole when the adjacent segment is lit. In the other case, the holes allow four of the segments to illuminate the sensor fully but only partial illumination falls on the sensor when the intermediate segments are lit. Figure 3.5 represents the two extreme conditions, and all other positions of the button create conditions between these.

In order to make the LED array simulate a rotating spot of light, it is necessary to turn on the LEDs sequentially. This can be arranged by using integrated logic circuits comprising a pulse generator which produces a pulse train at a frequency of 12 kHz, a counter which increments up to a count of 12 and then resets itself, and decoding logic for each LED which turns on the LED when the counter reaches the appropriate number (see figure 3.6). The pulse train is therefore divided by twelve and one illumination cycle takes one millisecond. For this application, it is important that each LED should be as bright as its neighbour so that the sensor sees no holes for an undrilled blank or empty space, and therefore it is necessary to fit a pre-set control on each LED segment to take care of manufacturing variations in the emitted intensity.

The phototransistor produces an electrical signal, the waveform of which has ‘bumps’ on it representing the flashes of light through the holes in the button. By synchronising another counter with the rotating logic circuits, the bumps can be counted. But as always with Engineering there

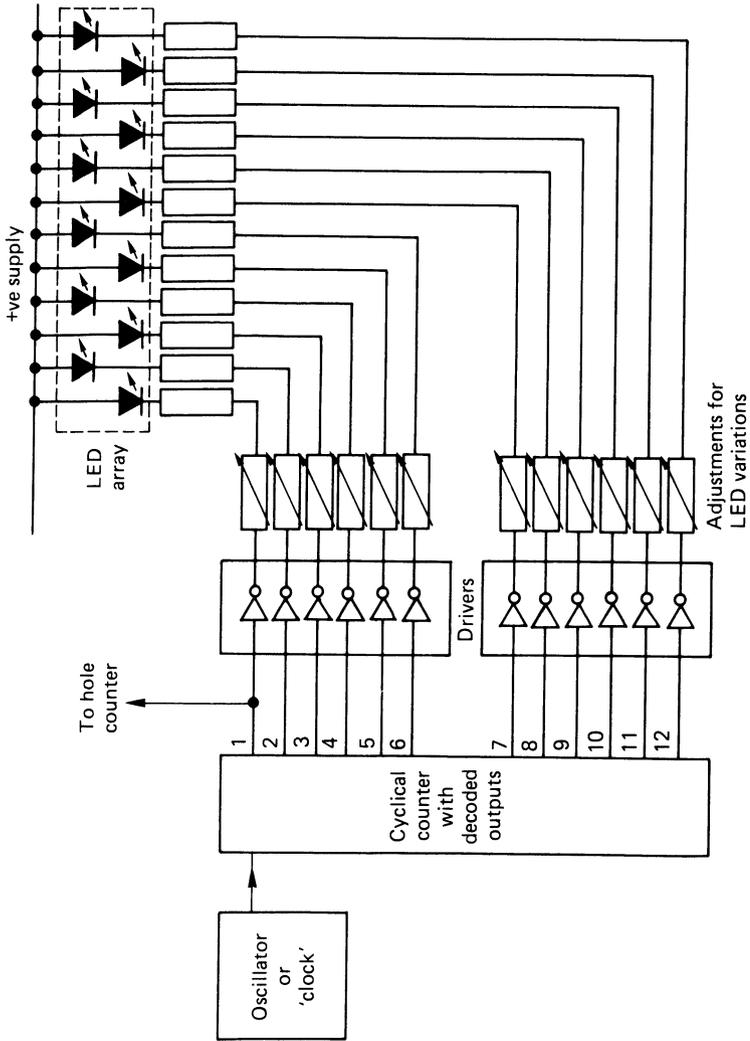


Figure 3.6 Logic circuit diagram for segment driver

is still another problem to be solved! It may be obvious to a human being that there are four bumps in the sensor's waveform, but if it wavers up and down from one button to another or even during one revolution as a result of off-centre alignment, then how can a circuit hope to distinguish the bumps reliably? One solution to this problem takes advantage of basic electrical components used in a particular combination: the diode and the capacitor. A standard comparator circuit compares two signals (A & B) and its output goes high if input signal A is higher than input B and the output goes low if B is higher than A. Looking at the circuit in figure 3.7 (in which the comparator is simply represented as a triangle) the amplified signal from the sensor is connected directly to one of the inputs of the comparator (V_{in}) but it is also fed through back-to-back diodes to a capacitor and via a resistor to the other input of the comparator. The diodes allow the capacitor voltage to follow slowly the sensor's waveform which represents a running average against which the more rapidly changing signal is compared. Whereas a fixed reference voltage applied to the second input of the comparator would have made it give quite unacceptable answers, this very simple but elegant circuit copes admirably.

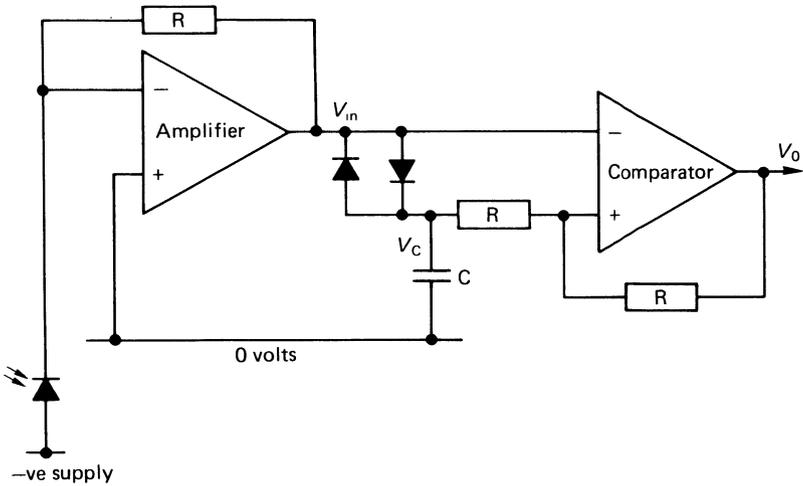


Figure 3.7 *Comparator circuit diagram*

The sort of waveforms seen at the two inputs of the comparator are shown diagrammatically in figure 3.8.

The presentation arrangement for the buttons also involves another phototransistor and illuminating LED, mounted in what is known as a

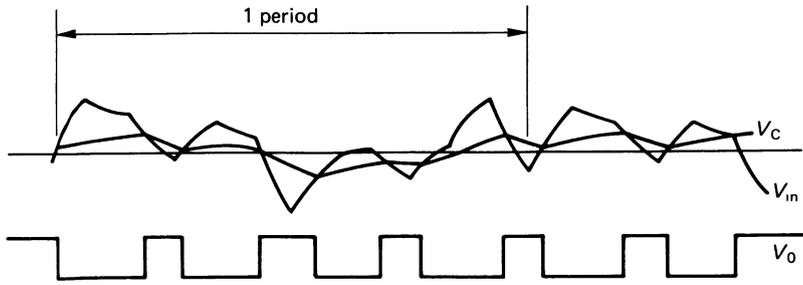


Figure 3.8 Waveforms for the comparator circuit

slotted opto-switch. This is used to inform the electronic circuits when the button to be inspected is exactly over the circular array. Each button is pushed over a glass plate by one of the arms of what is affectionately termed a 'spider', and a disc, mounted on the same shaft with holes drilled in it at regular intervals, passes through the opto-switch. When the leading edge of each hole in the disc passes through the switch beam, then the button is inspected. The physical arrangement is shown in figure 3.9.

Once the buttons have been inspected then the electronic circuits control a flap which allows good buttons to be deflected into one receptacle and faulty ones to fall into a reject bin (see figure 3.10). In case of a failure in the electrical signal then all the buttons will be rejected and no faulty buttons will be passed. As in all sorting systems there is bound to be a very small number of errors for a variety of reasons (alignment, vibration, reflections etc.). The decision circuitry has to be designed to deflect only perfect buttons.

I hope the description of this inspection system has shown how straightforward electronic components can be used to make an effective but not too expensive electronic sensor without resort to video cameras and micro-processors which in any case would be unlikely to work fast enough in this application. But I have not finished with buttons yet and I will have to eat the words I have just written. After the machine I have just described had been working for a while, some new equipment was purchased which combined the drilling and machining operations. However, although it was still necessary to check for missing holes, there was now another problem. Very occasionally the holes could be misplaced because of drill wandering or incorrect alignment, and obviously this fault was undesirable and could lead to sewing needle breakages in the same way as having insufficient holes. Unfortunately the hole counter could not detect asymmetry and therefore a new approach was required.

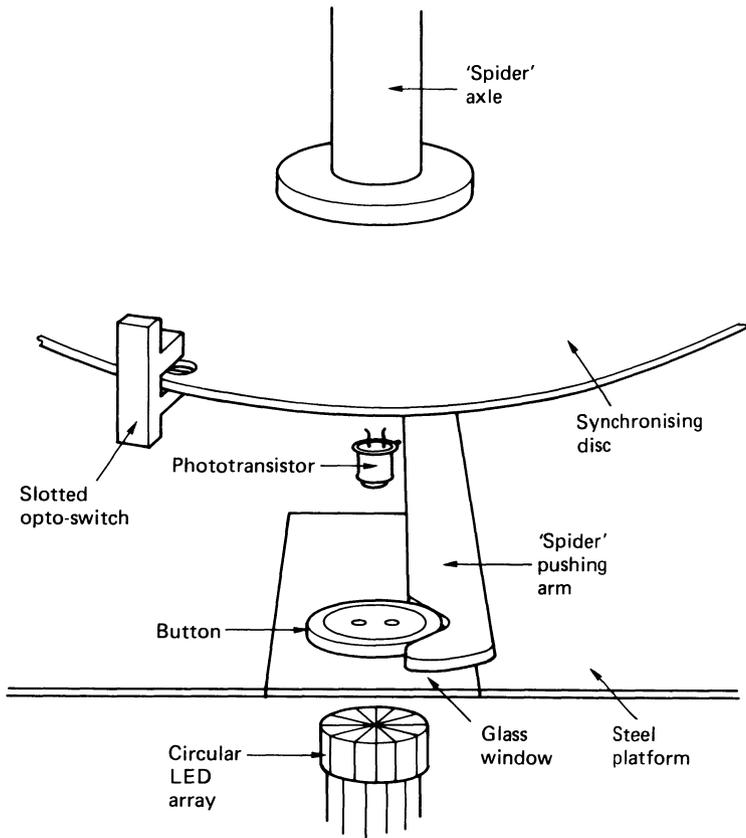


Figure 3.9 *Sketch of the inspection arrangement*

Preserving the idea of rotation or at least a simulation of rotation, the button can be scanned as it rotates by a line camera. A line camera consists of a row of contiguous photodiodes onto which an image is focused by a convex lens. Electronic circuitry sequentially interrogates each photodiode to establish the intensity of light falling on it at the time by measuring a voltage (more detail on the operation of line cameras is given in chapter 7 (page 136)). A counter is used to keep track of which photodiode is being examined at any one time and because this counts up at a constant rate, the voltages across the photodiodes can be displayed as a waveform on an oscilloscope (see figure 3.11).

If the line camera scans across the holes of a rear-illuminated button then the photodiodes corresponding to the hole positions in the image

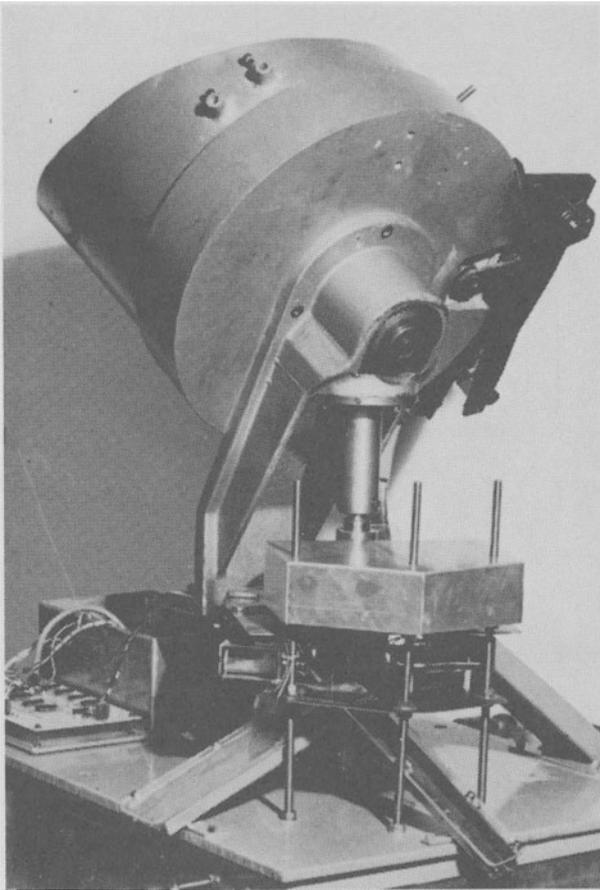


Figure 3.10 *The button sorting machine*

will indicate a higher light level than the rest. Reading the counter when the higher light levels occur gives numbers corresponding to the positions of the holes. If the button is rotated then, as well as the number of holes being counted, the symmetry of the image may also be checked. For any one scan, the holes should appear equidistant from the centre of the button and the holes should reappear, after intermediate scans, simultaneously. A line camera usually has at least 128 photodiodes in it and can have as many as 2048 photodiodes, so there is little problem in resolving the measurements needed.

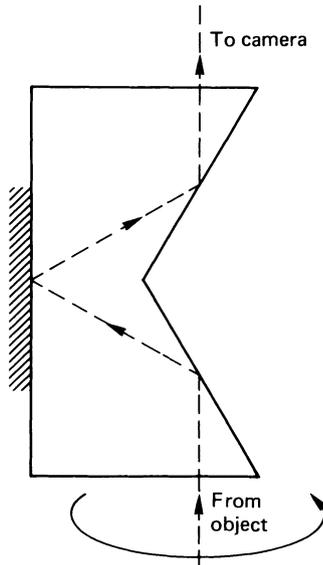


Figure 3.12 *The optical path in a rotatable K prism*

out from a sheet of resinous material before it has cured. The sheet is propelled under a set of hollow punches which repetitively stamp out fresh blanks as the sheet advances. If the edge of the sheet is not quite straight or if it occasionally fails to advance exactly the right amount before the next impression, then small notches in the circumference of the blanks, known as crescents, may occur. These faults may not have as serious consequences as those described earlier in this chapter but they are cosmetically unacceptable and can cause problems in the subsequent drilling process.

To detect these crescents with an optical scanning system seems at first the only way to proceed. But the system would have to look for only a very small fraction missing from the whole object which is difficult to achieve. To illustrate the point, imagine two adjacent rooms with a connecting door and in one of the rooms there are a hundred people. If it was suspected that one of the people had moved into the other room, would it be easier to count the people in the first room to see if one was missing or to look in the second room to see if any one was there? The second alternative is obviously far easier and illustrates that looking for small negative effects does not usually give reliable results.

For a solution to be found, lateral thinking may be required. Could any of the other physical senses be used? The possibility of feeling round the circumference with some sort of probe as the button rotated would at least mean that the crescent notch would be significant with respect to the rest of the smooth periphery of the disc. The probe would have to travel over the surface at terrific speed if every blank button that is made is to be inspected. However, is that not just what a record player needle and cartridge does? If the vibration frequency is high then a sound is generated.

Combining all the previous thoughts, a scheme using a sound sensor was devised. A simple arrangement consisted of a chute down which the button blanks were made to roll. To the underside of the chute was attached a piezoelectric crystal. Just as it does in a record player cartridge, the piezoelectric crystal converts the vibrations to which it is subjected into an oscillating voltage. As the blanks rolled down the chute, they rotated and the perfect specimens swept through without creating any disturbance. But if there was a notch or crescent, even if only a minute one, then a loud clonk sounded once per revolution as the whole disc bobbed down and up. In order to avoid jams in the chute it was necessary to remove blanks with large crescents beforehand, but this was easily done by sliding them over a narrow bridge so that only those with their centre of gravity near the geometrical centre did not topple off. Such arrangements are commonly found in bowl feeders used for this purpose. To detect faulty button blanks, the electrical signal was monitored with a comparator like the one described earlier and if the signal exceeded a pre-set level then the blank disc, on reaching the end of the chute, was rejected.

There was an extra bit of circuitry included which is perhaps worth a mention because it utilises another characteristic of the common-or-garden diode. If a diode is connected in a circuit so that it will allow a current to flow through it when the voltage applied to the anode goes positive with respect to the rest of the circuit, then a small voltage will be sustained across the diode while current is flowing. As the applied voltage increases, the diode will allow more current to flow through it. The diode voltage is only in the region of half a volt. The relationship between the voltage sustained across the diode and the current passing through it is known as the characteristic of the diode and has an exponential form (some more information on this is given in chapter 7 (page 120)). This characteristic can be utilised to help distinguish the loud clonks made by faulty blank discs from the swish of good ones. The arrangement is known as a logarithmic amplifier. If the signals are small then they are hardly amplified at all but if they include large pulses then these are amplified considerably. By also making the amplifier respond only to pulses of a pre-determined duration then any

quick blips, perhaps caused by vibration or dust particles, can be ignored. These electronic processing tricks all help to improve the quality of inspection but it is still vital that the best sensing technique is utilised so that a good margin is available between the good and the bad.

CHECKING GARMENT HEM WIDTH

Enough of buttons surely! Let me tell you about ‘cockles’! It is commonly known that a sewing machine is normally used to join two pieces of cloth together with a straight seam. This is done by laying the two pieces on top of each other and then stitching down one edge at a constant distance from the edge, creating a hem (the trade term for any border to a seam). The material is then opened out after stitching, the hem is hidden and the whole will lie flat on a table top. But if the stitching has wandered towards the edge and back again creating a partially narrower hem then, when the material is opened out, it will pucker up and the resulting hump is known as a ‘cockle’ in the trade. When making trousers or jackets it is particularly important that this humping never happens and so sewing machine operators are carefully trained to keep a constant hem width and especially never to let the hem width become too narrow.

It is a straightforward process to check the hem width during sewing by looking at the distance between the stitches and the edge of the cloth, but if the bottom ply (the lower piece of cloth) is not held in place and gradually moves in under the top ply then not only is a cockle likely to appear but also the stitches could miss the bottom ply altogether. As an aid to training and possibly also for production assistance, it would be very useful if a bell (or perhaps a quiet tone) could sound if the hem did get too narrow during sewing. How could this be detected?

Great varieties of cloth from worsted to light cotton and in shades from black to white are sewn. It would be desirable for any system that might be devised to be able to cope with these without requiring adjustment by the operator. Because of the very different textures likely to be encountered, mechanical probes feeling the relative positions of the two plies might be far from reliable. Measuring the thickness of the material near the edge of the cloth sounds more promising and perhaps this could be done by using a spring-loaded metal plate resting on the upper cloth just beside the needle and measuring the capacitance between it and the frame of the machine. Would the operator put up with the cloth being obscured by this plate just next to the needle? Would there be a danger of static charge building up on the plate as a result of the passage of the cloth under it? If the operator did not object to the plate, then the plate’s height could be

measured by another type of distance transducer to avoid the static charge problem. A potentiometer or variable resistor could be used, where the slider was connected mechanically to the plate, or a displacement transducer with minimal moving parts.

The space around the needle on a sewing machine, both above the material and below, is already packed with levers, bearings and rotating parts and any extra devices must not interfere with these. After bashing our heads against a brick wall for a bit, an optical solution was proposed. Initially it was thought that it might be possible to project a small beam of light up at the underside of the material at an oblique angle so that the bottom ply would cast a shadow onto the upper ply when it moved inwards. By placing two phototransistors looking up at the appropriate places on the cloth just in front of the needle position, the resulting shadow could be detected by comparing the difference between the observed light intensity falling on the detectors (see figure 3.13).

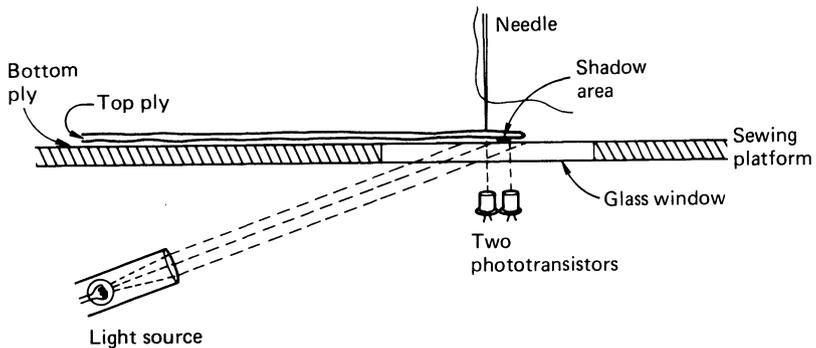


Figure 3.13 *The cross-sectional view of a sewing machine illustrating the shadow observation technique*

However, on inspection the underside of an industrial, heavy-duty, sewing machine more closely, it was found that there was little possibility of finding space for an unbroken oblique beam of light. But having started to think about an optical method and having also considered a differencing method, a workable solution emerged.

A small pre-focused torch bulb was mounted on the arm of the sewing machine adjacent to the needle shaft so that light shone down on the area around the needle. Surely the operator would not object to having a little more light shed on the working area? A removable metal plate in the platform surrounds the immediate sewing area and into this were fixed two

miniature phototransistors, one just in front of the needle and the other to the right at a distance equal to the optimum hem width. The phototransistor by the needle observed the intensity of light coming through the two pieces of cloth just before they were stitched. The other one also measured the light intensity coming through the material but, depending on the hem width, would detect the same or more light depending on whether two or only one piece of material were present. The two phototransistors were connected to a differential amplifier, the signal from which was proportional to the difference between the light falling on the two sensors (see figure 3.14).

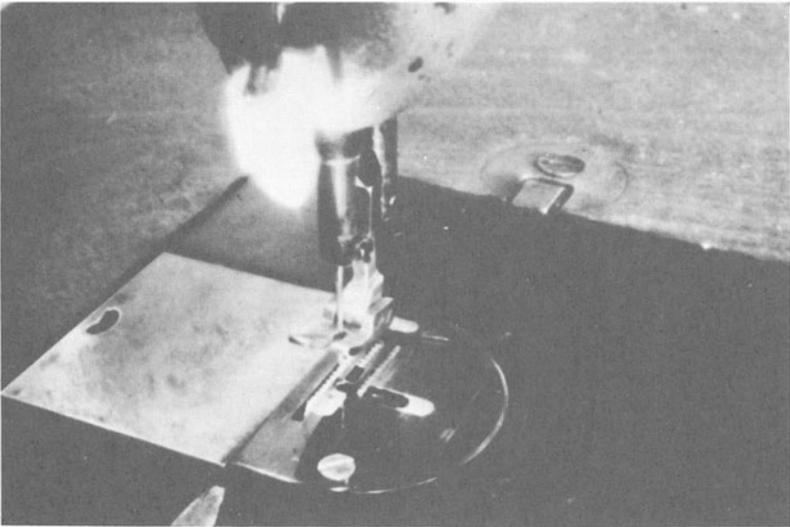


Figure 3.14 *The sewing platform*

Provided the two plies covered both sensors, the output from the differential amplifier was almost zero, but as soon as either the bottom or the top or even both plies moved away from the outer sensor then the difference became large. Bearing in mind the woven texture of cloth, it was necessary to insert a very short delay into the threshold detector, which followed the differential amplifier, to prevent it responding to rapid changes in light intensity through the weave so that the fault had to be present for a significant but very small time. The results obtained from testing this system were better than we could have hoped for. It worked on dark grey flannel for trousers and suits, worsted cloth for jackets and

light cotton for shirts. Of course it is important to remember that it was woven fabric that was being sewn and this is what enabled the system to work over such a large range of materials because of the light coming through the mesh of the cloth. Only corduroy upset the system with its alternate ridges but fortunately, work with this type of cloth only represented a very small fraction of the manufacturer's total throughput. Perhaps when dealing with 'cord for kings', more time can be allowed for making perfect hems!

FABRIC TEXTURE MEASUREMENTS

That most luxurious of fabrics, velvet, has always been much favoured by royalty over many centuries. A cloak made from velvet was something only the rich could afford and to possess velvet curtains in the days of pre-mechanisation would have been possible for only a select few. Modern techniques have now made it possible for velvet curtains and even carpets to be made from synthetic materials. The method by which literally millions of tiny nylon fibres are stuck onto cloth is secret and therefore, although it is ingenious, unfortunately it cannot be described here. However, during the production of this material, it is very desirable to control the general angle at which the fibres are fixed into the cloth. When examining a piece of velvet, a sheen can be seen when the fibres all tend to lie in one direction. If this direction, or even the angle of the fibres to the cloth, changes from one batch to another, it makes it difficult to sew pieces together without the join being obvious. It may be desirable to produce an alternating lean when mowing a grass lawn, but it is certainly not fashionable in curtains and carpets. The aim for fabric is to keep the fibre lean constant and so make the juxtaposition of adjacent pieces invisible.

Until recently, techniques for measuring this lean have been rather crude and very subjective. The main method used was to take sample cuttings from the fabric, in different orientations, and to examine their sideways profile under a magnifying glass, lining up a ruler with the apparent lean of the fibres and using a protractor to determine the angle. There was always a risk with this method that the process of cutting the material might well distort it, and of course destructive testing like this could not be applied in the middle of a customer's purchase! Another way, often used to obtain a rapid assessment of the approximate direction of lean, was to feel the frictional forces between the cloth and fingers in various directions. The fingers slid easily when travelling in the same direction as the lean of the fibres but felt a rough surface in the opposite direction. Even though this was a non-destructive technique, it could only

give an approximate indication of the direction of lean and was extremely subjective.

To produce a less subjective version, a variation on the friction technique could be to measure the sound generated from a flexible strip of roughened metal when stroked across the surface of the velvet material in different directions. If a round, circular sample of the material were placed on a turntable and a tangential arm was rested lightly on the velvet surface, like the pick-up arm on a record player, then the vibrations could be detected with a standard, record player cartridge. Although the noise generated might be far less when the fibres slid smoothly under the head of the arm than when they were opposed to the direction of travel, the technique would be unlikely to yield very precise results and could be very dependent on the method used for cutting the fibres and on their inherent flexibility.

To make a measurement where it can actually be used to monitor and control the fibre alignment process, means that an inspection technique is needed in the area where the adhesive is still wet before the material goes into a drying oven. The frictional and cut sample techniques mentioned above would be quite impractical. A non-contact approach is required. As it is the optical reflective properties of the material that are of major concern, then perhaps an optical method should be applied. For instance, if velvet material with leaning fibres is laid down flat on a table and an observer walks around the table, then the sheen is seen to vary. By placing a sample on a turntable and rotating it, a static observer may see the same effect. Shining a light at an oblique angle from close to the observer produces a periodically varying reflected effect, the amplitude of which undulates in an approximately sinusoidal manner. If the fibres are upright, then the reflected light will not vary as the sample rotates but if there is any lean, then the cylindrical shiny surface of each nylon fibre will reflect light, the intensity of which will vary as the sample goes round. The intensity of the reflected light therefore varies cyclically as the material rotates, giving a maximum signal from a phototransistor, positioned close to the light source, when the fibres are leaning away from the light source (see figure 3.15). The signal 'seen' by the phototransistor looks like that shown in figure 3.16.

Of course, while it may be possible to cut out samples for laboratory tests, any version of this system designed for a production line would have to be inverted so that the light source and the phototransistor rotated while the inspected material progressed underneath. This would give the same results but would avoid any interference with the cloth. Rotating mirrors might be used, instead of actually rotating the light and phototransistor, to avoid the problem of having to make electrical connections to rotating parts.

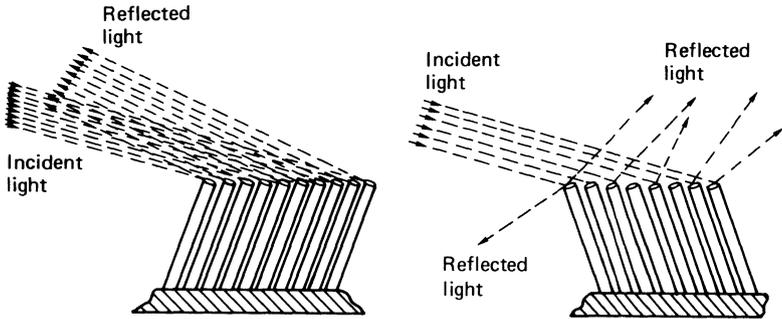


Figure 3.15 *The different reflection effects for fibres facing in opposite directions*

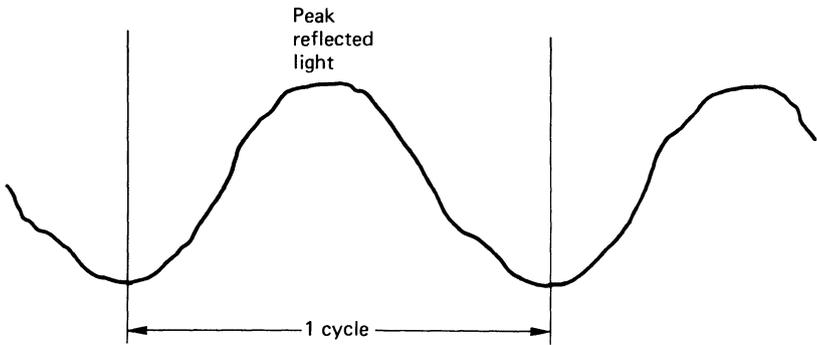


Figure 3.16 *The reflected azimuth waveform*

A system based on this technique was designed and constructed but it was necessary to develop the technique further to obtain accurate information about the vertical angle of the fibres. While the amplitude of the undulating signal did increase as the fibres leant further away from the vertical, there was no direct relationship between the amplitude and the angle. The colour and shade of the material complicated the measurement. One method which tried to resolve this problem relied on measuring the change in intensity of the light coming through the material when a bright light was shone on the other side and the sample was rotated. The direction of the fibres in the plane of the material (sometimes known as the azimuth angle) was found out by using the earlier mentioned rotational technique, and then the sample was rotated about an axis at right angles to this

direction in the plane of the material. Figure 3.17 will I hope illustrate the arrangement.

When the fibres were in line with the beam of light they provided the minimum obstruction to the light and were detected by a phototransistor behind the sample. As the sample rotated, the fibres presented a larger surface area to the incident light and so the transmitted light reduced considerably. It might be assumed therefore that the average angle of the fibres could be determined from the angle of the sample when the maximum light penetrated the material. However a correction factor needs to be applied because, if a plain sheet of a uniform, translucent substance, such as card or plastic, were rotated in front of the phototransistor, the intensity of light falling on the detector would vary according to the cosine of the angle between the perpendicular and the beam of light. Therefore, if the fibres lay at a significant angle to the perpendicular and the thickness of the backing material was also significant, then the peak transmitted light would be measured at a slightly smaller angle than the true angle of the fibres. By applying the cosine correction factor, this technique achieved close correlation with the other fibre lean measurement methods. Unfortunately, although this system gave dependable results, many of the velvet materials have a thick, opaque backing and therefore this technique cannot be used.

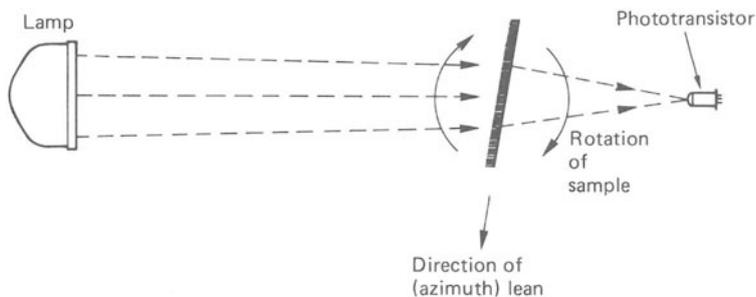


Figure 3.17 *Method for determining the fibre lean angle by shining light through the material*

A second method gets round the problem of the opaque backing but is more difficult to explain. This method uses oblique lighting to enhance the reflective effect obtained from the polished surfaces of the nylon fibres. It was observed that the intensity of light reflected from a cylindrical surface, with only a moderate reflecting efficiency, increased significantly as the angle of the light beam to the surface became more oblique. A beam of light was arranged to shine, from a supporting, crescent-shaped arm,

obliquely onto the sample of velvet and a phototransistor was fixed to the same supporting arm on the opposite side from the lamp, to pick up light glancing off the material (see figure 3.19). With the sample positioned so that the fibres leant at right angles (azimuth) to the crescent shaped arm, the arm could then be tilted from the perpendicular to the horizontal. At some angle of tilt, the fibres were perpendicular to the crescent shaped arm and so the intensity of reflected light reached a maximum (see figure 3.18). From this angle the fibre lean angle could then be determined.

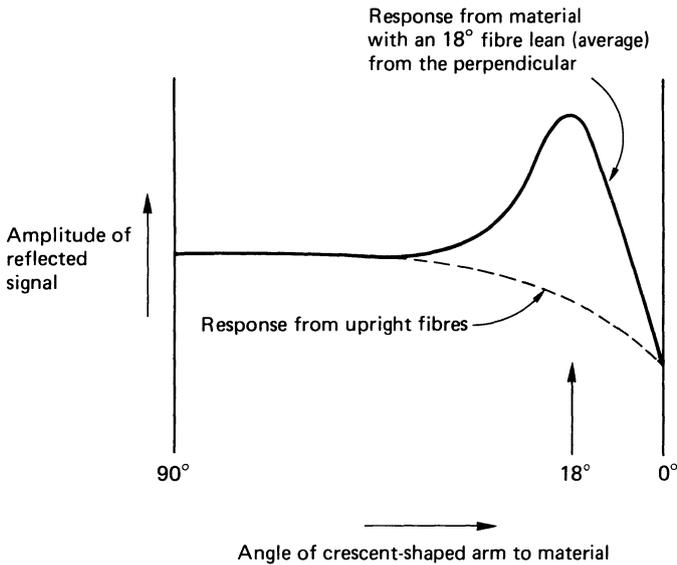


Figure 3.18 Waveform obtained during fibre lean determination

By combining the first azimuth technique with the last method for vertical angle determination, all the required measurements could be recorded, irrespective of the colour of the material, using comparatively simple electronic sensors.

The description of these applications has attempted to show how the careful use of a few, common electronic components can produce elegant solutions for automatic inspection in the garment industry. **All** the factors affecting the inspection technique must be considered at the beginning of the design process and the aim should be to produce a design with a minimum number of moving parts. It cannot be emphasised enough how

important it is to share one's proposals with some other person before starting construction, even if it only helps to clarify one's own mind.

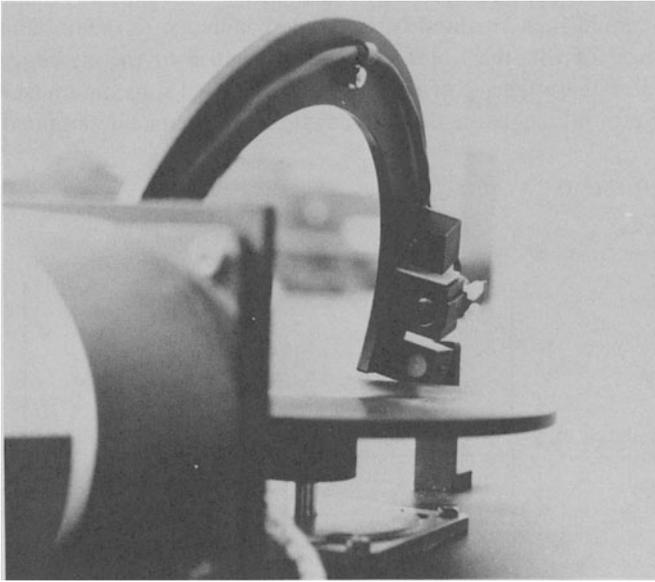


Figure 3.19 *Fibre lean angle instrument*

4 Paper Making and Printing

CORRUGATED CARDBOARD MANUFACTURE

Clothing and garments, which featured mainly in the last chapter, provide suitable protection against the elements for humans but most manufactured items, especially the fragile and delicate, require protective transit packaging to make sure they reach their destination intact. One of the most common types of such packaging is corrugated cardboard which is usually made from reprocessed paper. Double-sided board consists of two outer sheets spaced apart by an undulating sheet which is glued alternately to the insides of the two outer sheets. Because of its inherent strength, which is produced by the closed box construction, it is remarkably effective. A single-sided board is also made which is less rigid and conforms more closely to the object to be packed.

Fluorescent lamp tubes can be easily damaged in transit and so are usually protected by a corrugated cardboard tube. The tube is made from a strip of single-sided board, with the corrugations running transversely. The flat board is creased along three lines, folded and the edges fastened together with an adhesive tape to form a square sectioned tube. This tube can be made on a continuous basis and then cut off into regular lengths to suit a particular fluorescent tube.

It is the cutting of the tubes into equal, constant lengths that presents a problem. Because the tubes are to be used to protect a number of fluorescent lamps packed in a large cardboard box, they cannot be too long otherwise they will not fit into the box easily, nor too short or the protruding electrical connection pins at each end of the fluorescent light will not be guarded against damage. In order to manufacture these protective tubes at an economical rate, it is necessary to run the machine, from which four of these tubes are being produced, at a throughput of at least one metre per second. The machine can either stop and restart every time the corrugated board has travelled the required distance, enabling a guillotine to crop off the protruding lengths, or a cutter can be fitted to a drum which rotates with the same surface speed as the cardboard and has a circumference equal to the tube length required. For the first technique,

an accurate measurement of the length has to be made and for the second, the cardboard speed and the cutting drum's surface speed must be exactly the same. While the second design approach has advantages because the process is continuous, it is difficult to guarantee that the two speeds are equal because of the very nature of the product. In order to ensure that no slippage could occur between the driving rollers and the cardboard, it would be necessary for the rollers to nip the cardboard tightly. But if this were done, then the corrugations would be destroyed and the tube would not serve its purpose!

It is therefore essential, in either of the above designs of machine, to be able to measure the speed of the cardboard accurately so that an exact length can be cut. Because of the length and semi-flexibility of the newly made tubes coming out of the machine, which could be as long as 2.4 metres, it was considered impracticable to sense the far end of the protruding tubes for the purpose of controlling the cutting process. At first a light jockey wheel, driving a shaft encoder, was used to determine the speed but this was prone to jump off the cardboard surface so giving occasional errors. It was then considered whether the corrugations on the incoming cardboard, which were on the upper surface prior to folding, could be used in some way to assist measurement. Corrugated cardboard is made by feeding a sheet of paper into an enormous mangle comprising two rollers, like extended gear wheels, which intermesh with the paper in between to form the internal undulating part. A second sheet is then glued onto this first sheet while it is still located on one of these two geared rollers. Therefore the pitch of the undulations is as accurate as the pitch of the teeth on the meshing rollers. Because the shrinkage of the product while drying is minimal, it is possible to rely on this spacing for future measurement.

To sense and count these passing undulations, a light emitting diode (LED) and a phototransistor were mounted just above the cardboard so that the phototransistor detected the reflected light shone onto cardboard from the LED. The light shone down at an angle onto the cardboard and the phototransistor 'looked' at an angle as well, so that when a wave crest passed by, the pool of light lay within the sights of the phototransistor but when a trough passed the two areas did not coincide. The LED, phototransistor pair can be obtained in a convenient, low-cost package called a reflective opto-sensor (see figure 4.1).

The resulting waveform, produced by the phototransistor, was similar in form to the undulations on the cardboard (see figure 4.2). However the spacing between the corrugations was still wider than the measurement accuracy required. To get round this, an identical pair of reflective opto-sensors were fixed alongside the first pair but set a quarter of the pitch of

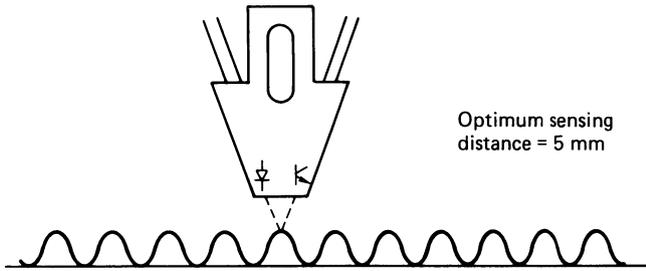


Figure 4.1 *The reflective opto-sensor being used to detect the undulations in corrugated cardboard*

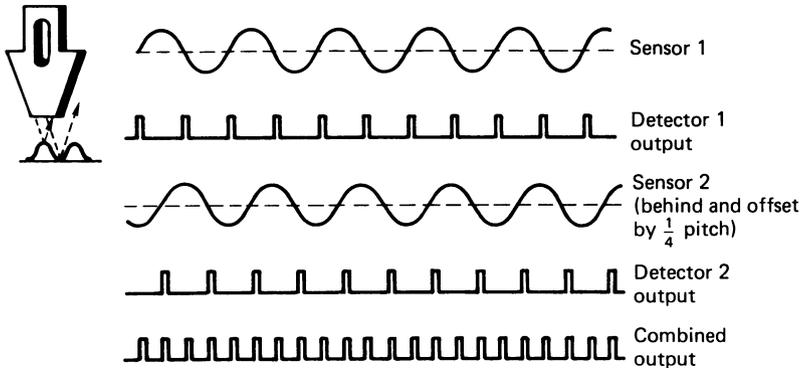


Figure 4.2 *Waveforms and derived count signal*

the undulations further along. By detecting when the two waveforms each passed through the half signal level and combining the results, four counts could be derived per corrugation.

There is another trick which can be played to improve the reliability of detection so that if the cardboard changes colour from batch to batch or even steadily within one batch, the variation in signal level does not cause mis-counting. By placing two of these reflective opto-sensors so that one 'sees' a crest while the other 'sees' a trough and then comparing the two signals, a count can be recorded each time the two signals cross each other. Any change in the shading or colour of the material being inspected will reduce both signals equally but they will still cross over at the same point with respect to the cardboard undulations. This arrangement (see figure 4.3), although requiring double the number of sensing heads, can therefore

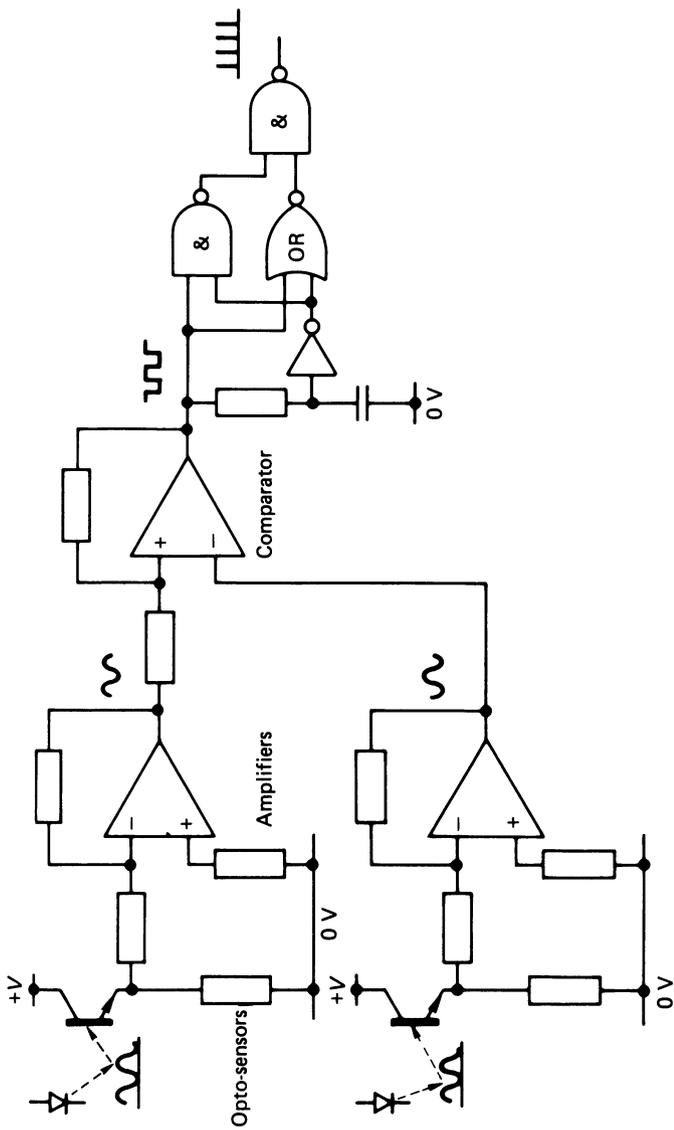


Figure 4.3 Circuit to produce a pulse every time the signals cross over

cope with a large variety of different paper shades without requiring any adjustment of sensitivity and will count every passing undulation correctly even when the cardboard has nearly stopped.

Another area in which electronic sensors can be used to assist in the production of corrugated cardboard is in monitoring for breaks in the freshly made cardboard emerging from the geared roller mangle described earlier (see figure 4.4).

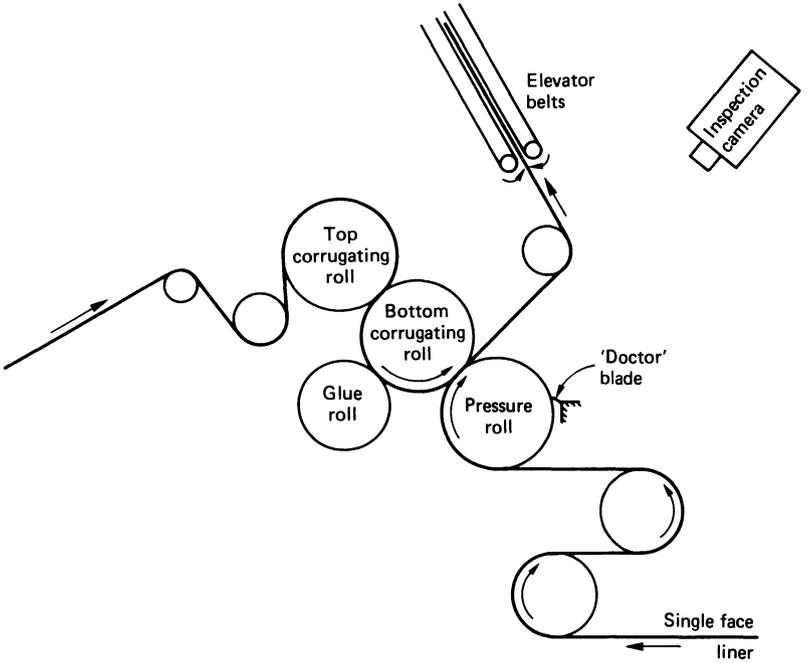


Figure 4.4 Sectional diagram of the rollers in a single-sided corrugated cardboard making machine

Imagine the mess if the web of cardboard starts to stick to one of the rollers instead of parting cleanly from it. With glue being applied continuously, not only is this difficult to avoid occasionally but also the machine is very difficult to clean ready for restarting should a paper break occur. Web break detectors normally consist of a lamp unit, mounted on one side of the web, set up to illuminate a photodetector on the other side if the paper web breaks. These are often mounted at an angle to maximise the area monitored. But if the paper merely sticks to the roller and con-

tinues further round, beyond the place where it would normally part from the roller, then the web may not break immediately and the machine may jam up, with sticky paper wrapped around the roller, before corrective action can be taken. A 'doctor' blade is fitted, further round the 'pressure' roller's circumference, to try to prevent the paper going around more than once.

What is needed is a method of detecting whether the 'pressure' roller immediately after the point at which the card should leave the machine, is clean. Alternatively, the 'doctor' blade, positioned slightly further round, should never be obscured. Instead of continuously 'looking' at the web for breaks, what about 'looking' at a part of the machine which should always be free of paper to make sure it is absent?

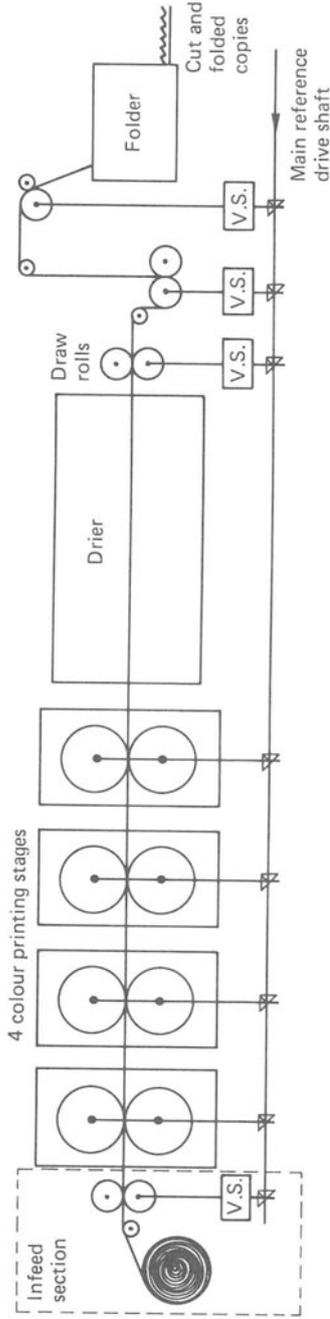
To position dozens of photosensors and illuminators across a 2 metre wide machine to make sure that every part was inspected would be both costly and cumbersome. The operators would be far from pleased if the detectors impeded their access to the machine. However, if a line scan camera, as was mentioned earlier for sizing potatoes and diamonds, was positioned so that it viewed the whole length of the 'doctor' blade, or even the roller surface prior to the 'doctor' blade, using a suitable lens to create an image of the inspected surface on the row of photodiodes, then the operator's region would not be impeded because the camera would be positioned at least 2 metres away from the machine to allow for the field of view of the lens. The camera could be enclosed in an environmentally suitable housing, with a heated window, to avoid condensation forming on the lens. If the 'doctor' blade was painted or anodised matt-black and illuminated well with a parallel fluorescent light nearby, then any paper or light coloured substance could easily be detected by the camera. Similarly, if the illuminated area were matt-white then any darker object would be sensed. A third possibility would be to use the reflective properties of the straight metal blade and position a long fluorescent tube so that the camera would observe the tube reflected in the metal. Then any object which crossed the area, irrespective of its colour provided it was not completely transparent, would appear as a silhouette. This approach has the advantage that the shiny 'pressure' roller itself could be used as the reflecting surface. The fault detection region would be positioned very close to the point where the paper normally left the roller, so enabling a rapid stop response under fault conditions. The disadvantage with this method is that the camera, blade and the light would all need to be carefully aligned.

TENSION CONTROL IN PRINTING PRESSES

Just as in paper and card manufacturing, tension control of the web is also vital in large continuous printing presses. This is not so much because of the fear of web breaks, even though these occur occasionally, but in order to ensure that the registration of what is printed on the paper from multiple printing drums remains precise. The blank paper rolls have to be stored in carefully controlled temperature and humidity conditions prior to usage, to ensure that a constant web tension, within any one part of the press, will produce consistent results. In order to keep the web taut throughout the press, it is essential that the rolls in the various stages each run fractionally faster than those in the previous stage.

This is achieved by using a long reference shaft, which passes along the whole length of the press, to which are directly coupled the main printing drums, usually four on a colour press (see figure 4.5). The 'infeed' stage is made to run fractionally slower than the printing drums to maintain the necessary tension and the following stages, which include a drier, cooler and folding mechanism, all run slightly faster. This is done by using harmonic drives which couple the power through from the reference shaft to the appropriate rolls with an adjustable speed ratio. Because the difference in speed is so small and so critical, the operators of the press need to measure this ratio to within 0.01 per cent.

To achieve this accuracy of measurement it is necessary to measure the rotational speed of a roll in each stage of the press and compare these speeds with that of the reference shaft. There are a number of sensors which can be used to measure rotational speed and these usually come under the heading 'Tachometers'. An electric motor or dynamo will produce a voltage proportional to shaft speed but this would not be nearly precise enough. Shaft encoders, which comprise one or more slotted discs which interrupt optical beams from LEDs to phototransistors to enable the shaft position to be determined, could be used but would need to function rapidly as the shafts turn quickly. They are also relatively expensive and usually need to be fitted to the end of a shaft, which may not be convenient in some positions on a press. The magnetic reluctance probe, which was briefly described in chapter 1 (page 3), can provide a very robust and convenient solution for this application. A standard gearwheel can be affixed to the shaft and the sensor, when positioned close to the passing teeth, will generate an alternating voltage at the same frequency as the passing teeth. Oil, printing ink, dust and paper will have no effect on the sensor's response and only when the shaft rotates very slowly will the signal die away and be of no practical use. Fortunately, in this application the equipment needs only to function when the press is running at speed.



V.S. = Variable speed gearbox

Figure 4.5 *Diagram of four colour press*

The electronic equipment, into which these sensors are connected, is designed to count up the number of oscillations coming from each sensor. The reference shaft counter is set to stop at a pre-determined number and when this is reached all the other counters are stopped. If the numbers of teeth and the shaft and roll diameters for all the sensors are all the same, which in practice they are invariably not, then a count number for the reference shaft of 10 000 would make it possible for the numbers in the other counters to be displayed directly, giving a percentage ratio to two decimal places. A decimal point would have to be illuminated on the display between the second and third digits from the right. By using a separate reference counter for each roll to be monitored, different numbers of teeth and diameters can be catered for by setting the appropriate limit number. Each display is latched (held frozen at the last value recorded) while the counters are reset and then allowed to proceed to count up again.

Fitting gearwheels to a press retrospectively may be quite difficult and time consuming if the press needs dismantling. An alternative method is to apply a repetitive black and white striped (affectionately described as a zebra striped) tape to a shaft and position a reflective opto-sensor, similar to the one described earlier in the section about the corrugated cardboard, above it to detect the passing stripes. While this technique is not as robust as the magnetic gearwheel sensor and a guard would have to be fitted around the sensor to prevent excessive dirt and dust affecting the readings, the tape can be applied quickly with little disturbance to the press.

PRINT REGISTRATION

Reflective opto-sensors can also be used for controlling print registration on the press (see figure 4.6). If the first of the four printing drums prints an extra mark on the paper, say in a margin which will be hidden when the final copy is produced, then the web length can be altered slightly, by a movable roller, between stages in the press to adjust for slight longitudinal misalignment.

The misalignment can be sensed by comparing the relative timing of the printed mark on the paper, applied at exactly the same time as the printed image from the first drum, with a tag fixed to the side of the second or subsequent drums, which is directly related to the position of the print on that drum. Depending on whether the tag leads the mark or vice-versa, the web length is decreased or increased a very small amount by moving an intermediate roller, around which the web passes, up or down. The tag can be detected by a slotted opto-switch which was described in chapter 2 (page 17) in the section about potato sizing.

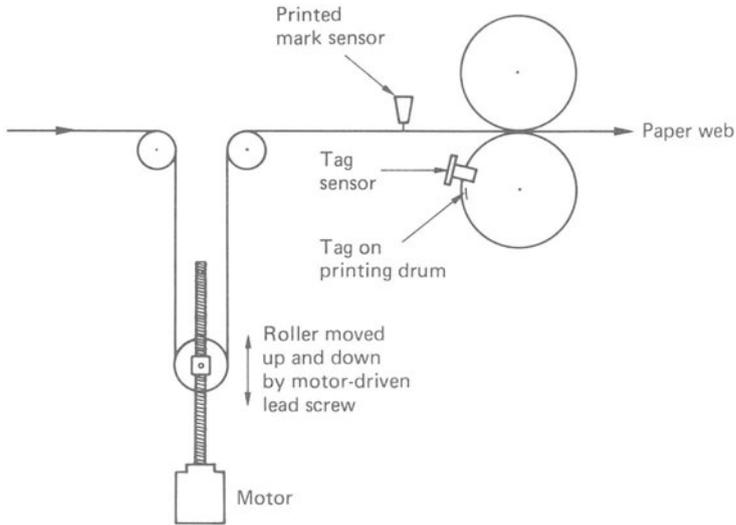


Figure 4.6 *Diagram of print registration equipment*

There are a number of electronic circuit techniques for comparing the timing of two marks, but one reliable way is that shown in figure 4.7 which uses an analogue gate. This is a solid state switch which turns on with a low internal resistance when a voltage is applied to a control pin, and turns off when that voltage is removed.

The tag sensor is connected to the control pin of the gate so that it opens when the tag passes through the slotted opto-switch. The signal from the reflective opto-sensor, which for the ease of explanation can be assumed to go positive while the printed mark is under the sensor, is con-

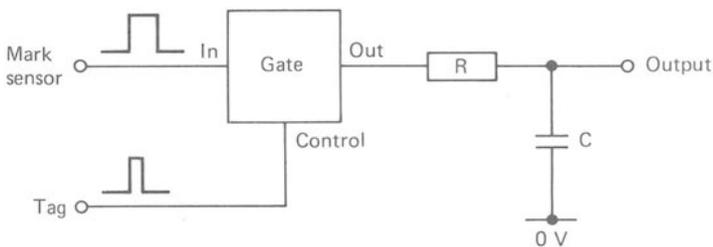


Figure 4.7 *Mark timing circuit diagram*

connected to the input of the analogue gate. To the output is connected a resistor and a capacitor. Assuming that the capacitor is initially charged to half the full signal voltage and that the mark will appear while the tag is half way through the slotted opto-switch, then, before the mark appears, the capacitor will discharge through the resistor and the gate. However, when the mark appears, the input signal will go high and current will flow from the signal input, through the gate and the resistor and charge up the capacitor. Because the mark appears at half time, the voltage on the capacitor returns to exactly where it was before the tag came along. If the mark had arrived late, then the capacitor would not have had time to recharge to the same voltage level, and if the mark had arrived early, then the capacitor would have charged up to a higher voltage (see figure 4.8).

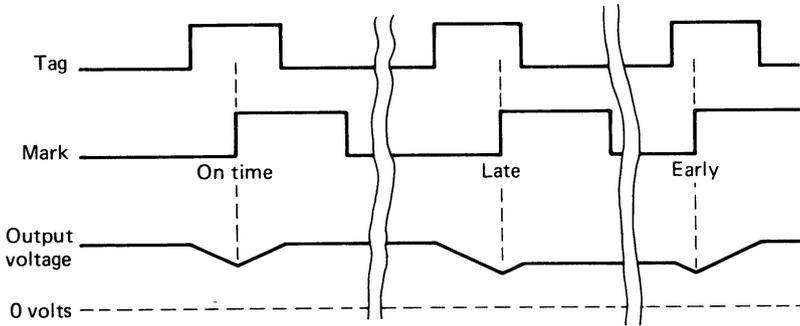


Figure 4.8 *Timing diagrams for the circuit in figure 4.7*

The voltage across the capacitor is therefore proportional to the web length between the previous stage and the present stage, and can be used to control the position of the intermediate roller so that corrective action is taken if the mark does not appear when the tag is half way through the sensor.

An almost identical system is used for controlling the registration of printing on double-sided surveyor's tapes. One side of the tape is printed with an imperial scale and the other with metric. But the zeros of both these scales must start at exactly the same point and the corresponding dimensions must agree all along the tape. The tape is made of steel, for dimensional stability, but even so it is possible for it to slip fractionally while being printed. To describe the whole machine is difficult but the two sides of the tape are printed separately but continuously so that the first side (the imperial) has time to dry, by passing through an oven, before returning to be printed on the reverse side. The printing section uses a tag

to indicate when each 'foot' mark on the first side of the tape should appear, and the metric print on the drum is set to be aligned with this. The electronic controller adjusts the force applied by a brake to keep these two scales precisely in step. The only significant difference between the registration unit on the paper printing press and this tape one, is in the mark sensor. Whereas in paper printing a reasonably large mark can be printed in an area which will later be obscured by folding, cutting or binding, this is not possible on a surveying tape. It is therefore necessary to be able to detect a printed graduation line of not more than 0.2 mm width. To accomplish this, the arrangement shown in figure 4.9 was used.

The light source was made from a row of high-intensity red LEDs focused by a lens, close to the tape, to form a bright line image. Visible light was used so that the operator could see where the detection point was when initially setting up the machine, and LEDs were used in preference to a tungsten filament lamp so that the light could be modulated to compensate for ambient light effects. Compensating for ambient light effects by modulation means turning the light source (LEDs) on and off very rapidly and subtracting the light detected when the LEDs are off from the light level when they are on. A couple of circuits and a short description of this technique are given in chapter 7 (page 132). Because the lines on the tape travel through under the sensing head extremely quickly, this switching has to operate rapidly to make sure no line is missed. A tungsten lamp could not possibly be made to switch on and off at anything like the rate required. Because the light source was designed to produce a line no wider than the line to be detected and the modulation arrangement eliminated the effects of other lights, the photodiode detector was positioned pointing at the illuminated area but no accurate alignment was necessary. It would have been possible to focus the detector and to illuminate the area generally and obtain equally satisfactory operation from the electronic controller, but then the operator would not have known exactly where the measurement of the graduation line was being made. It is also much easier to adjust the light source to project the required visible image than to adjust optics for a detection system where the result cannot be displayed easily in a convenient manner.

MINIMISING WASTAGE IN PRINTING

When a printing press is started up, especially the larger ones, there is an initial period when all the different parts are being adjusted to produce perfectly aligned copy which satisfies the operators. This period is commonly known as 'make ready'. There is little that can be automated at this

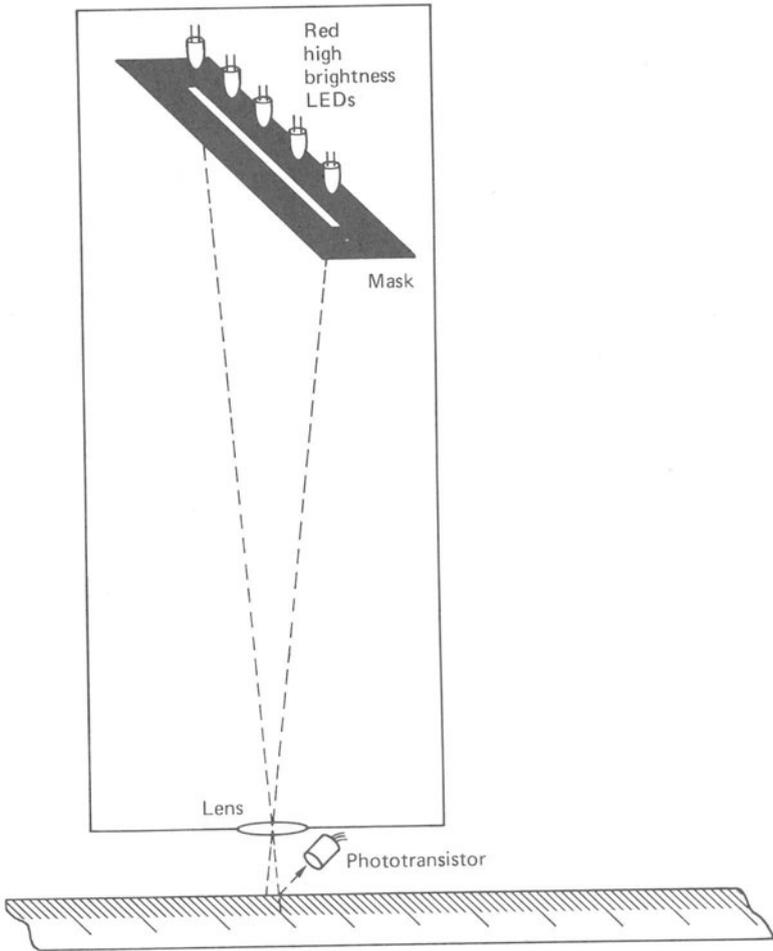


Figure 4.9 *Optical arrangement in the sensor for graduations on a measuring tape*

stage to help the printers reduce this time and therefore save the wasted paper produced while the spread of ink on the printing surfaces is being regulated and other adjustments are being made. On big presses a waste chute is provided so that any such waste paper can be directed automatically to a shredder at the flick of a switch so that precious time is not lost as soon as good copy is produced. The switch controls the position of a flap, chute or gate such that the folded sets of pages (or signatures as they

are called in the business) either continue on to a stacking machine or go to waste.

But while the press is running continuously, there are also times when copies have to be removed from the output without stopping the press. This is because joins in the incoming blank paper have temporarily upset the print registration. The presses are fed from huge rolls of blank paper and when one of these is about to run out, another fresh one, already mounted on a supporting axle, is accelerated up to speed. The paper coming off the previous roll is then suddenly fixed with glue to the new roll so leading the paper from the new roll into the press. Immediately after this an automatic knife cuts the paper coming from the old roll. This means that passing through the press is a portion of double thickness paper, with glue in between, which will not only need to be rejected on leaving the press but also will upset the print registration on a few of the copies following immediately after the join. Until recently it was necessary for the operators to observe when this join or 'splice' as it is known, came through and to operate the waste dump gate to deflect the rogue copies from the stream of good ones. But with the press producing copies at five per second, it was difficult to be sure that the correct number had been removed and therefore many more were deflected than was actually necessary. Also, if an operator failed to be present at the time when the splice came through, the unsatisfactory copies would be allowed to pass on as good ones.

But how could this glue join in the paper be detected? Perhaps it might have been possible to sense the increased thickness in the paper. A contact system using a displacement roller to measure thickness by vertical movement could have been used, but then the paper could have varied in thickness from job to job and there might have been many false alarms due to vibration and fluctuations in tension. This would have necessitated the continuous rotation of the roller and a very free and rapid vertical movement of the supporting arm to have sensed the thickness accurately. Such a sensor might have needed continuous and regular maintenance to ensure reliable operation.

Perhaps a capacitive sensor could have been devised, with a plate on each side of the paper, so that the paper formed the major part of the dielectric. Any increase in thickness, as the paper passed through, would have altered the capacitance and therefore this could have been used to indicate the presence of the splice. The presence of glue, in which there would have been a substantial amount of water, could also have made a significant difference to the measured capacitance. Such a sensor would have had the advantage of having no moving parts. Unfortunately the

moisture content in the paper can vary quite significantly and quite rapidly if one side of a roll has been exposed to a more humid atmosphere than the other, during storage or transportation (such as on the back of a lorry). Also it is already awkward enough for the operators of the press to thread the paper through the press when 'making ready' without asking them to pass the paper through an extra narrow, parallel plate capacitor as well.

If the glue had contained a coloured dye then perhaps this could have been detected by a phototransistor with an appropriate optical filter in front of it. But then the printed text or pictures might have obscured the glue from the sensor. It would appear that all the possible sensors suggested in the last three paragraphs would have had problems associated with them, so making them less than suitable for the task.

It is hoped that the implemented solution will demonstrate the advantages of thinking about the system as a whole and not just concentrating on one aspect, like the nature of the thing one wants to detect. The press is a fixed piece of machinery and the length of the paper passing through it is for all intents and purposes constant. Therefore, at any one time, there will be a fixed length of paper, corresponding to a certain number of copies, between the place where the splice is made, at the beginning of the press, and the dump gate where the emerging folded copies are deflected if unsatisfactory. By taking an electrical signal from the controls which initiate the splice, for instance when the cut-off knife operates, and counting a pre-set number of copies, the position of the copy with the splice in it can be predicted precisely. The number of copies produced by the press is exactly proportional to the number of rotations of the printing drums and therefore a copy count can be implemented by using a magnetic reluctance probe and a metal protruberance on one of the driving shafts in a similar way to that which was used for the tachometer described earlier in this chapter (page 63). The splice controller includes a variety of relays and contactors with spare contacts, one of which can be used to indicate when the knife operates. When the equipment was installed, the number of counts needed was quickly determined, by simple trials, to make the dump gate drop the splice copy exactly and also to reject the minimum number of subsequent copies to allow for print registration correction. Pre-set counters were set to the number of copies in the press and to the number to be discarded at each splice.

The removal of these copies is now entirely automatic and not only is the minimum number of copies discarded, thus making considerable savings for the company, but also the sensing of the splice is reliable because a contact closure is used which actually causes the splice to

happen! Although an electronic sensing technique for thick paper or glue has not been described, it is hoped that the effectiveness of indirect rather than direct sensing, for this particular situation, has been demonstrated.

FELT TIP PENS

This chapter, in a book about electronic sensors, could not end by describing an application which conveniently avoided the use of sensors. It is debatable if writing implements can feature in a chapter about printing but at least felt tip pens are closely associated with paper and ink.

Felt tip pens are now made in abundance and multicoloured packs are standard items in toy shops and stationers where they are very popular with children. A felt tip pen consists of an outer plastic tube and a felt insert filled with water-based ink. The felt insert is pressed down onto the fibre tip by a plastic plug at the top. A manufacturer of these pens was anxious to make sure that none of his firm's pens ever left his factory incomplete. It was a straightforward enough process for someone to check if all the visible components of each pen were present (the fibre tip, the outer case and the top plug) but the felt insert remained invisible. Although every colour in the spectrum seemed to be included in the range, none of the outer casings was transparent. Was an X-ray camera needed to see the insert?

In chapter 2 (page 9) the capacitance probe was described in an application for detecting potatoes. It was the water content of these which enabled the system to work. The probe would not respond to an insulator. Most fortunately, the water-based felt tip pens are always encased in plastic and never in metal housings. Therefore by reshaping the end sensing plate on the potato capacitance probe to a long rectangle rather than a round disc so that the maximum sensitivity could be obtained when a felt tip pen passed it by, this type of probe could be used to inspect automatically every pen emerging from the production line. No child would then be disappointed at finding a dud pen on Christmas day!

5 Bottling Drinks and Food Inspection

Quality and quantity inspection are essential in any industry but in the food industry they are a vital part of the manufacturing process. Samples of the product are taken away regularly for checking in a laboratory and continuous inspection of the product on the line is also necessary. Modern electronic scales can be used rapidly to check-weight every item produced so that a guaranteed, minimum weight is delivered to the customer. Measurements of size and shape can be made, as was described for potatoes in chapter 2 (page 13), and items can be counted electronically. There are many pieces of electronic equipment available for carrying out quantity measurements.

Measuring the quality of food or drink is more complex as often the requirement is to make sure that impurities are not present, rather than measuring the amount of the constituent parts present. When a food manufacturer is asked to specify what impurities have to be detected, the usual answer is “anything” and when asked to indicate the minimum particle size that must be detected, the answer is often “not visible to the naked eye”! Neither of these vague specifications is helpful to the potential inspection system designer but they do illustrate the scale of the problem for which a solution has often to be found.

LIQUID LEVEL DETECTOR

In the soft drinks business, quite a few of the products made involve filling a bottle partially with a concentrated syrup and then topping up with carbonated water. In the process the returnable bottles are vigorously washed and then pass through a machine which delivers a metered dose of syrup into each bottle. They then pass into a second machine which fills each bottle up with fizzy water. When full, they are capped and put into crates (see figure 5.1).

If the syrup is coloured, as in the case of ‘dandelion and burdock’ then it is immediately obvious to an inspector if one of the bottles has somehow managed to pass through the system without collecting its appropriate

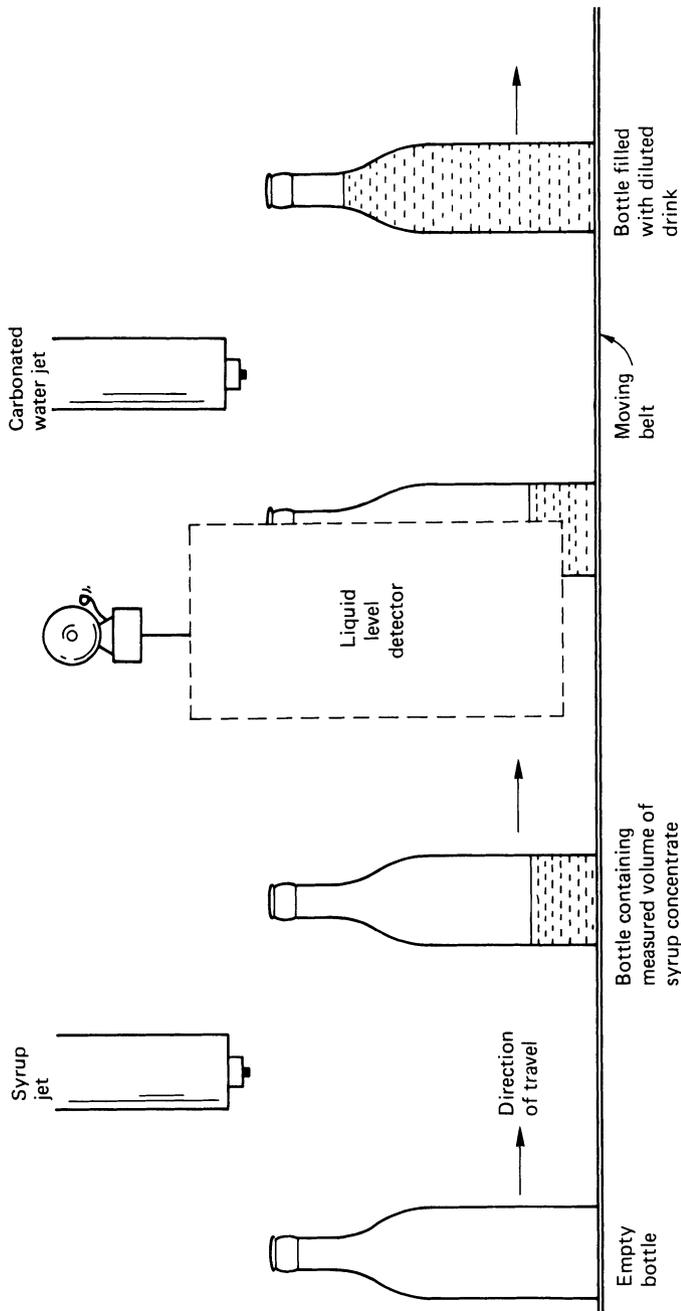


Figure 5.1 Sketch of a bottle filling line

dose of syrup. But if, as in the case of tonic water, the syrup is clear, then, because the bottle is filled to the top with carbonated water, it is not possible to distinguish an incorrectly filled bottle from a correct one. Imagine the dismay of the gin and tonic drinker when he realises that there is no quinine in his cocktail and how low his opinion of the soft drinks firm might sink. Fortunately there is a simple way in which this fault may be detected for tonic water. The quinine present in the tonic water syrup fluoresces when illuminated with ultra-violet light. By shining a small 'black light' lamp over the crate of bottles, prior to dispatch, all the bottles will glow iridescently except any in which there is no quinine present. By sensing the intensity of this fluorescence with a phototransistor and an ultra-violet light mounted on the bottle line just after the filling station, an automatic rejection system could be installed.

But what is really required is an automatic system which will check any soft drink bottles, irrespective of the syrup colour or bottle glass colour, to make sure that the correct amount of syrup has been added. Perhaps the most accurate way would be to install two weighing stations in the conveyor, one before the syrup dosing machine and the other immediately after, so that the empty bottle weight could be remembered and then subtracted from the partially filled weight to obtain the weight of the added syrup. By knowing the number of bottles *in situ* between the two weighing machines, the earlier weight of the empty bottle can be retrieved when the same bottle reaches the second weighing station. This approach can be looked on as the ideal approach but it would require major changes to the line, involve considerable expense as in-line weighing machines are not inexpensive, and have to be carefully designed to work in the damp and dripping environment of a bottle filling line. It would be desirable if a sensor could be found that was relatively cheap and easy to install on the existing line.

Two other ways were examined to see if the height of the liquid in the emerging bottles could be checked. As was mentioned in the introductory chapter (page 6), ultrasonic transducers can be used to obtain an approximate measurement of distance by measuring the time taken for a pulse of sound to travel from the transmitter to the receiver. If this pulse is reflected from a surface and the positions of the transducers are known, then the distance to the surface can be gauged. By placing two such transducers side by side (but not clamped together to avoid interfering, direct vibrations) so that the sound waves travel downwards through the open neck of the bottle, the syrup surface will reflect the sound pulse, sent by the transmitter, back to the receiver. Allowing the circuit to detect a received signal only after a certain time period will prevent the distance to the top of the bottle being measured. Taking the first reflected pulse signal after that time as the one

of interest (because later ones might also feature because of multiple internal reflections) the height of the liquid in the bottle could be estimated. For the purposes of this particular application, the variations in the speed of sound due to changes in temperature or humidity would not generate large enough errors to be significant, even though the bottling line environment can be extremely humid.

There are at least two difficulties involved in implementing the ultrasonic system. The first is in steering the open bottles precisely under the ultrasonic transducers so that a good reflected signal is obtained. A 'bottle present' sensor would also be needed to signal when the sound pulse should be dispatched. The second is that the bottles shake quite a bit as they move along the conveyor and so the surface of the liquid inside a bottle is far from tranquil. Such a choppy sea will only reflect a small proportion of the sound waves directly back to the receiver. However, the most important reason for not implementing an ultrasonic system has not been mentioned yet. Just before the syrup filling machine, there is often a huge ultrasonic cleaning tank through which the bottles pass. The bottles are shaken within the cleaning fluid in the tank at 40 kHz to remove any remaining residue. Unfortunately, low-cost ultrasonic transducers suitable for this measuring application also work at 40 kHz and therefore it would be foolhardy to expect them to work well in close proximity to such a powerful cleaning bath.

The second method considered was an optical one. Initially one might shy away from an optical technique in a damp and humid atmosphere because of the problems which might be caused by condensation on lenses. But provided the atmosphere is not a dense fog which would attenuate the light beams too much, it is possible to keep the sensors slightly warmer than the surrounding air, as was suggested in the section about inspecting corrugated cardboard in chapter 4 (page 62), to prevent condensation.

Looking at a half filled bottle, a human being can immediately see the level of the liquid inside, even if the liquid is transparent and colourless. How? Above the liquid, objects on the far side of the bottle are seen fairly clearly because the outer and inner sides of the bottle are concentric and the rays of light emerge along almost the same path as they went in. But within the liquid, the liquid acts as a cylindrical lens and concentrates the rays of light onto a focal line (see figure 5.2).

Therefore if a source of light is positioned on one side of the conveyor, a vertical, bright line will be projected onto the other side below the liquid's surface and general, slightly dimmed light will illuminate the area above it when the bottle passes by (see figure 5.3). By positioning a phototransistor at the desired height, the bright line will be registered if the syrup has been filled to that height. A second phototransistor could be

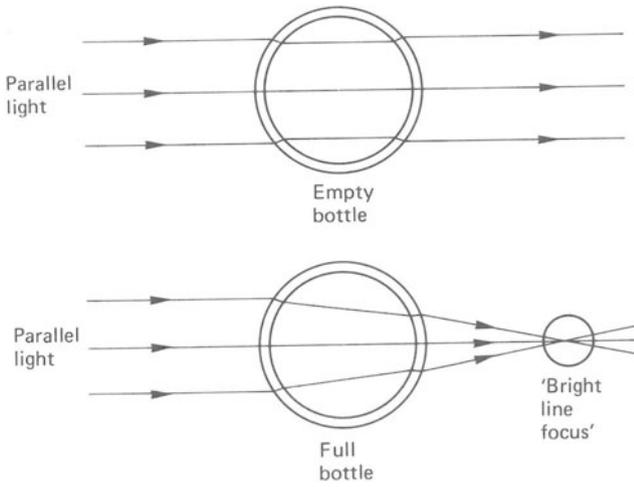


Figure 5.2 *The effect on light rays passing through an empty and a full bottle*

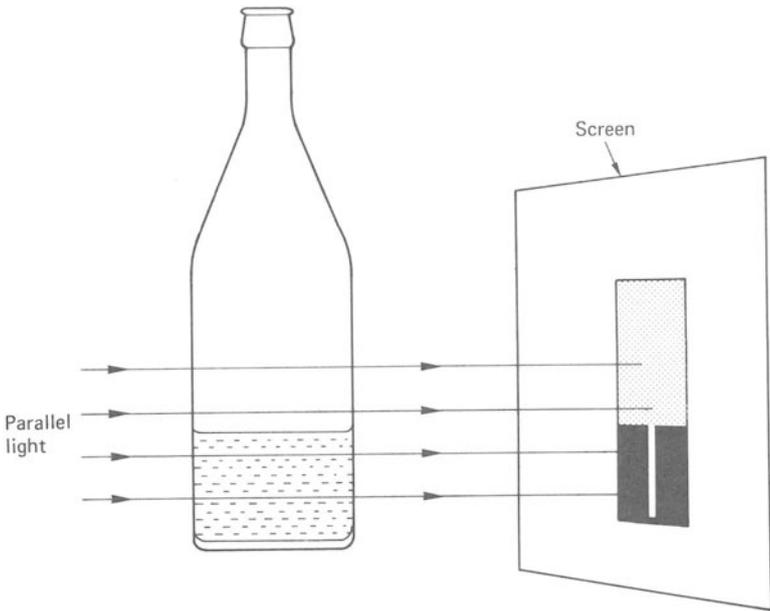


Figure 5.3 *The bright line effect*

placed slightly higher up so that, if the bright line illuminated this, then the system would be aware that the bottle was too full. The bottles would have to pass along a well-defined channel so that the phototransistor remained at the focused point but this is reasonably straightforward to organise.

To cater for a variety of differently coloured glass bottles, another technique can be employed. It is the same technique as was used in the hem width sensor described in chapter 3 (page 48). Rather than having to set a fixed threshold which the signal from the phototransistor must exceed to register a bright line, it is possible to use two phototransistors, one positioned well above the maximum liquid level and the other at the correct height for sensing the liquid, and to use the difference signal from these for selection. Any change in attenuation of the transmitted light through the bottle due to glass colour will affect both sensors equally and therefore will not feature in the difference signal.

When the system was set up, the contrast between the light level at the bright line and the light level above the liquid was so great that most of the syrups were transparent enough for this system to be used without the need to set more than the one threshold level to cater for differing attenuations. The most reliable sensing systems are invariably those in which there is a large margin between the background signal and the signal being sought for. However, the combination of 'dandelion and burdock' syrup and the brown bottle into which it was poured, attenuated the light too much for the above system to work. But the syrup was sufficiently opaque to allow a simple detection arrangement to be used whereby the two sensors were compared when the bottle was in position and the lower phototransistor detected less light than the upper one, if the syrup was present. This was the reverse of the previous technique. It required a separate 'bottle present' sensor and a switch to select the 'dandelion and burdock' rather than the normal arrangement to ensure a reliable performance of the system.

LABEL DETECTOR

All bottles, when filled, have to be labelled to identify the ingredients. Obviously the operators filling the crates at the end of the line will discard any bottle which does not bear a label, but there may be occasions when label absence is not noticed, perhaps at the end of a day or if the operator sees the reflection of an adjacent label in a clear bottle and is deceived into thinking that the clear bottle has been labelled. If the labelling machine ceases to apply labels, perhaps because the glue has run out or the labels

are not being transferred from an intermediate, applying roller, then dozens of bottles may emerge from the machine before the operator's attention is caught. A device is needed to inspect each and every bottle to check that a label has been applied.

In the labelling machine the bottles travel around on a carousel, a sort of merry-go-round, while slowly rotating. Labels, freshly pasted with glue, are projected into the path of the bottles and are applied as each bottle passes by (see figure 5.4). If the application roller becomes accidentally coated with glue, then the label gets stuck to the wrong surface and the next one and the next one and . . . Surely no description is needed for the mess created to be imagined when the bottles are passing through at a rate of ten bottles per second!

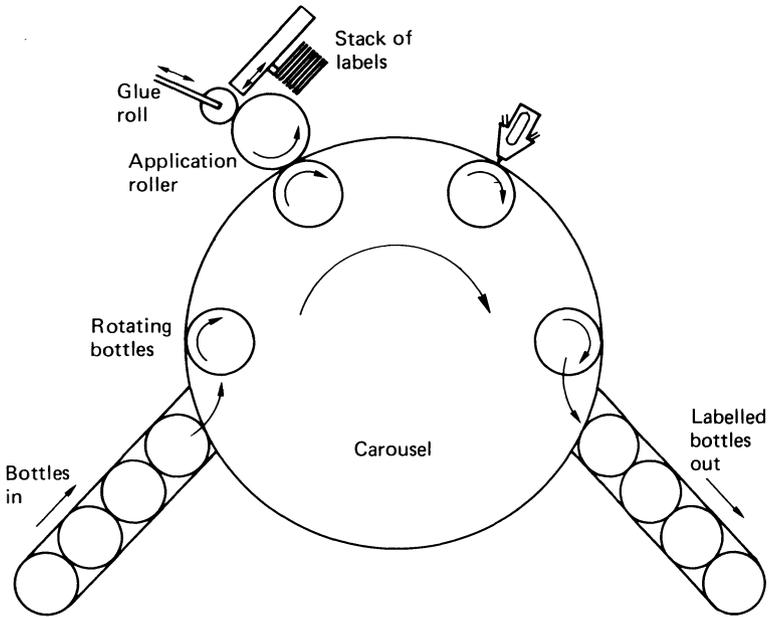


Figure 5.4 *Plan view of label applicator showing position of label sensor*

A reflective opto-sensor, similar to that described for counting the undulations in corrugated cardboard in chapter 4 (page 59), could be placed a short distance after the application roller to check that the label was present on each bottle. If no label were present then the surface of the glass would reflect a certain amount of the light back to the detector and, if there were

a label present, then perhaps less light would be reflected back from the duller surface. Unfortunately the amount of light reflected back from a white label can be greater than that from a glass surface because, for the glass the majority of the light is transmitted through it. How can this problem be overcome?

There is obviously more than one solution, but a simple way is to twist the reflective sensor so that it does not 'look' at the cylindrical surface of the bottle normally to the surface (see figure 5.5). By setting it at say 20° to the normal, there will be no reflection from an unlabelled bottle and most labels will reflect some diffuse light back except those which are all black. Because the labels cannot be all black (otherwise they would communicate nothing!) there is always some area on the label which will reflect enough light. So if the sensor is mounted on a vertical rod, it can be slid up or down to the optimum position for any label. However it is preferable not to install sensors which have to be reset for every type of label. There may be literally hundreds of styles. Because the reflective opto-sensor is a relatively low-cost item, a number of these can be mounted one above the other, on the vertical rod. If the output from each is 'OR-ed', then if any sensor receives a reflected signal there will be a label present and if none receives a signal then no label can be present. In this way the system can cope with all types of label without needing any adjustment.

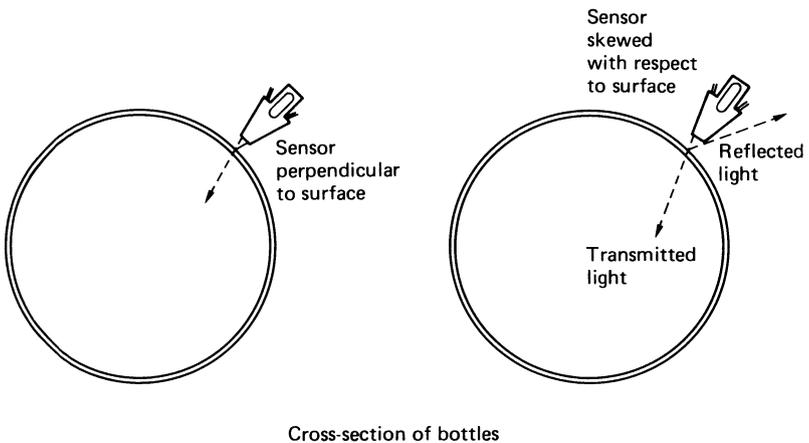


Figure 5.5 *How specular reflection can be avoided by positioning of the sensor*

SOFT FRUIT INSPECTION

At the beginning of this chapter, the problem of specifying impurities in food was mentioned. However, sometimes a food manufacturer is able to specify both the nature of the impurity and the maximum acceptable particle size. A good illustration involves the problems encountered by a confectionery manufacturer who needed to use cherries. These were shipped from Italy to England whole, in barrels. The first process, on arrival at the factory in England, involved cutting the fruit in half and poking out the cherry stone or pit. The destoning and slicing machine was very efficient, in fact so efficient that occasionally it sliced the pit in half too, leaving small broken pieces of pit with the freshly cut cherry halves. In order to prevent these small pieces travelling on with the cherry halves, so that nobody would damage teeth when chewing the final sweet at a later stage, it was necessary to develop an inspection system. The impurity was known – pieces of cherry stone – and the maximum particle size which would be allowed to pass through undetected would be a cube 1.5 mm across. Anything smaller than this was considered unlikely to cause any discomfort to the consumer.

Various methods had been tried to locate these elusive pieces of stone but with no great success. One method used an X-ray scanner in the hope that the pieces of pit would be more impervious to X-rays than the surrounding flesh, but the difference was insufficient to provide reliable detection. Another method relied on computer analysis of television pictures taken of the cherries passing under a camera. Any sharp, pointed objects would be labelled as stone fragments and smooth textured ones as halves of cherry. In order to cope with the requested throughput, it would have been necessary to have about half a dozen computers, each connected to its own separate TV camera, and all these connected to a much larger computer in which the image processing would have taken place. The cost was prohibitive and, of course, whole stones would have been allowed to pass through quite happily.

The technique used in the end was suggested by a micro-biologist. No sooner was the problem described to him than the solution sprang to his mind, even though the implementation took much longer. It would have not occurred to an engineer to think of this method as it is outside the normal engineering province, but to a micro-biologist auto-fluorescence is very commonly used to highlight features under a microscope. Light in one wavelength band (blue) is shone on the specimen and the fluorescent light emitted is observed through a barrier filter (orange) which prevents the incident light being seen. A study revealed that the cherry pit fluoresced far more than the cherry flesh, making the pieces of pit stand out in

contrast against the background (see figure 5.6). Later quantitative measurements established a ratio of 4:1 between the pit fluorescence amplitude and the light emanating from other parts of the cherry.

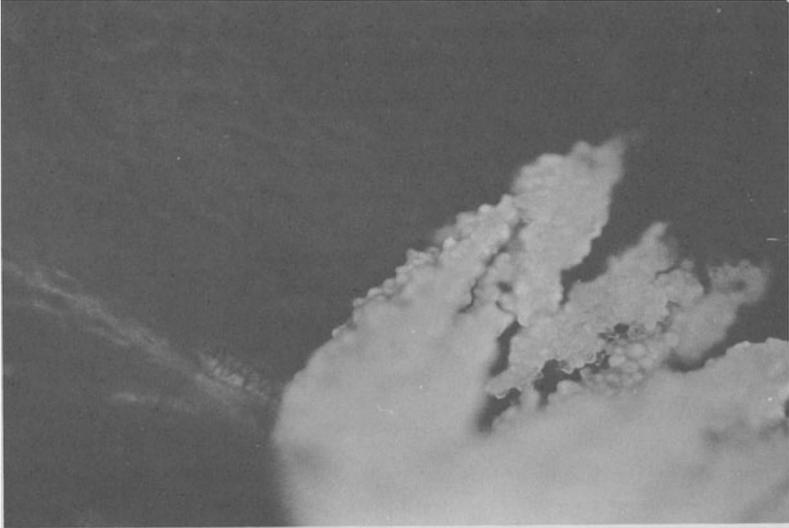


Figure 5.6 *Fluorescent microscope picture of cherry pit*

The next step needed was to see if this very dim light could be detected by a line camera (more detail is given in chapter 7 (page 136)). The line camera could then be positioned overlooking a flat conveyor belt on which the up-turned cherry halves would pass. Unfortunately no line camera could be found with sufficient sensitivity to discriminate between the very weak signal coming from the fluorescing pit and the general background noise when scanning at the rate demanded by the process requirements. In the line camera used for the investigation, this background signal was mainly due to variable reverse leakage from diode to diode in the line array. In order to improve the response of the camera to meet this speed requirement, it was necessary to build a small electronic memory into which this fixed background signal, recorded while the camera was in darkness, was stored. The recorded waveform was then synchronously replayed, every time the camera was scanned, and the old waveform simultaneously subtracted from the new signal coming from the camera (see figure 5.7). Whereas previously the illumination coming from the pit was lost in all this fixed noise, now it was possible to observe the fluorescence signal distinctly.

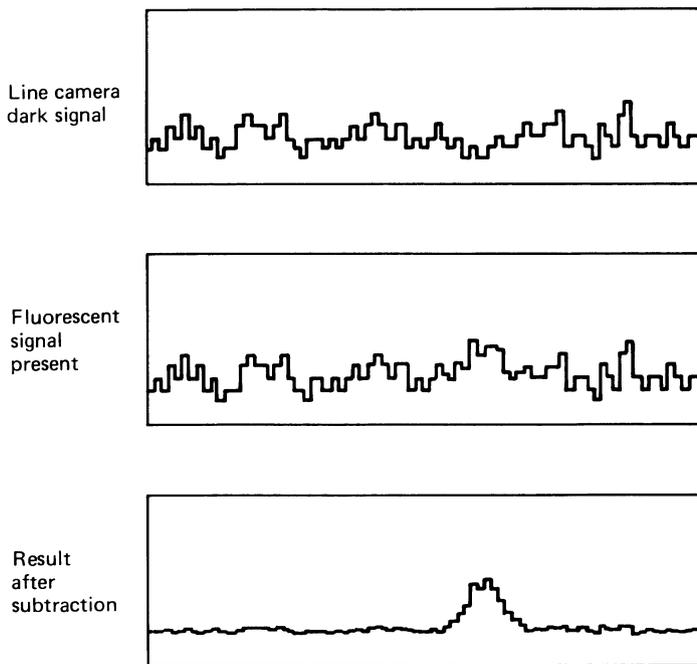


Figure 5.7 *Line camera waveforms indicating signal recovery by subtraction*

It should be pointed out that the fixed pattern noise due to reverse leakage in the diodes of the array varied with temperature. Therefore it was necessary to keep the array at constant temperature so that the stored waveform could be used to cancel out the background unwanted signal. A Peltier cooler (a technique using thermocouples in reverse) was used initially because the fixed reverse diode leakage decreased with cooling, but this method proved expensive and more complicated to apply than a heating method. It was therefore decided to warm up the line camera diode array to a constant temperature above the maximum ambient temperature before the waveform, to be used for subtraction, could be stored. This was achieved by placing a resistor within a small copper block under the array package and, by sensing the temperature of the copper block by means of an embedded diode whose characteristic varied with temperature, controlling the current passing through the resistor. By using a controller to keep the temperature above the maximum ambient temperature, any variation in the ambient temperature did not affect the array or the fixed pattern signal coming from it. While it was a disadvantage that the reverse

leakage diode signal from the array varied with temperature, a similar effect in another diode could be turned to advantage to correct the situation. Roundabouts and swings!

Using the difference waveform, and comparing the level against a fixed threshold, it was possible to detect all the pieces of pit, even those as small as the resolution of the camera would allow. To reach the throughput requested to meet the process requirements, it was necessary to scan a belt width of approximately 600 mm which was divided into fifteen parallel channels. This meant that five cameras had to be used which scanned along one line on the belt. The lines viewed by the cameras overlapped slightly so that no piece of pit would be missed (see figure 5.8).

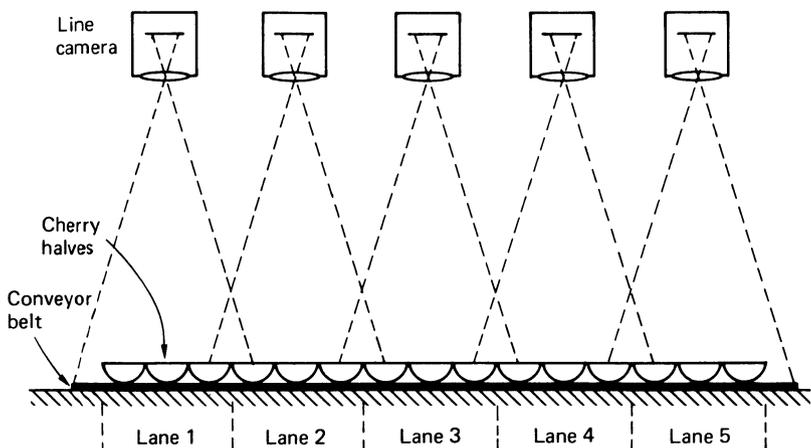


Figure 5.8 *Transverse arrangement of the five line cameras above the conveyor belt carrying cherries*

Because the cameras had to 'see' cubes of pit as small as 1.5 mm across, the resolution of the individual diodes in the cameras' arrays had to be 0.7 mm, referred to the belt, in order to make sure that no piece of stone was missed. Also the repetitive scans had to occur at 0.7 mm intervals of movement of the belt for the same reasons. With a maximum belt speed of 10 metres per minute, the cameras had to scan their particular part of the line in about 4.5 milliseconds. The machine was capable of inspecting 3600 cherry halves per minute.

The faulty items were blown off by air jets when they reached the end of the conveyor belt. To determine when the appropriate pair of jets should be operated, shift registers were used. There were 15 separate shift registers to cover the 15 parallel channels of cherries and there were 16 air jets, off-set so that any two would be activated by the output from any one shift register. The shift register was a long, serial memory into the beginning of which a digital fault indication could be loaded. This indication was then moved through the memory at a rate proportional to the progress of the conveyor. A toothed wheel sensor or shaft encoder, mounted on one of the conveyor's driving rollers, produced an incrementing 'clock' signal for the memory. By choosing a shift register length proportional to the distance between the inspection point and the rejection point, the appropriate air jets were activated just when the faulty item appeared at the end of the belt. Although it has been stated that there were fifteen channels of cherries, the distribution across the belt was fairly random. Because overlapping detection and rejection were built into the design, this spread could be accommodated without error. An ingenious vibratory system was produced for turning the cherry halves the right way up but that used no electronic devices and therefore does not qualify to be mentioned here. Producing an even, brightly illuminated line of light in the inspection area on the belt was far from easy but that is also another story!

BRAZIL NUT INSPECTION

The auto-fluorescence technique can also be used for the inspection of freshly broken out Brazil nut kernels. Here it is important that no part of the shell remains adhering to the kernel. As any one who has endeavoured to crack open Brazil nuts at Christmas will know, it is sometimes difficult to achieve this separation. The nut can be thought of simply as having three separate parts. These are the hard, dark brown shell, the soft, cream coloured kernel and a thin, brown skin which lies between the shell and the kernel. During cracking, some of this skin may remain attached to the shell and some on the kernel. It is not satisfactory to inspect the freshly cracked nuts and reject any dark brown item as shell, for a considerable number of quite edible kernels, with patches of this brown skin on them, would also be rejected. Therefore, to distinguish between the shell on the one hand and the kernel and its skin on the other, would not be feasible using colour inspection at the normal visible wavelengths.

The kernel contains a substantial amount of vegetable oil and this substance fortunately fluoresces well. Because the skin has always been in

contact with the kernel, it is also saturated with the oil. However, the shell, being hard and non-porous, contains very little of this oil. Under suitable excitation conditions, both the kernel and the skin fluoresce but the shell does not (see figure 5.9). Obviously the kernel fluoresces far more than the skin but there is a sufficient margin between the detected light levels from the shell and the skin to enable a system, similar to the cherry inspection machine mentioned above, to be implemented.

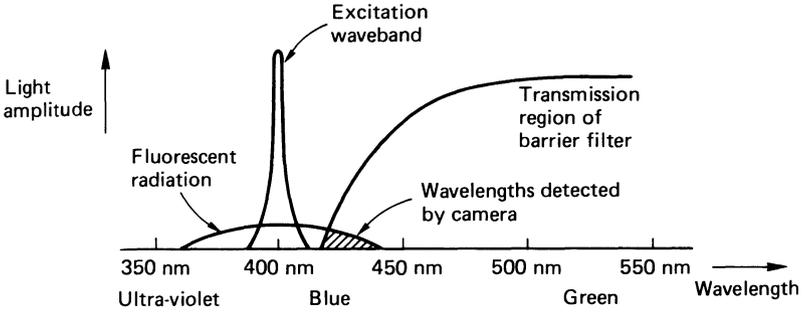


Figure 5.9 *Typical fluorescence spectrum (the shaded area indicates the waveband of light falling on the detector)*

DIRTY BOTTLES

Fluorescence techniques can also be used to inspect washed, returnable bottles. During the holiday period, in the summer particularly, milk bottles may not be returned to the dairy for some considerable time. If the bottles have not been cleaned really well, the residues of milk are an excellent medium on which miniature plant forms, such as algae, can grow. These may be very tenacious and difficult to remove from the bottles during the washing process. Whereas lumps of concrete and splashes of mud may be easily seen on the sides of bottles, the algae are often fairly translucent and difficult to spot. If left in the bottle when it is refilled with a natural food such as milk, the algae could rapidly develop making the milk at best undrinkable.

Although algae do not exhibit significant auto-fluorescence, they will readily absorb a fluorescent dye. Such a dye is commonly used in washing powders to convert the ultra-violet rays from the sun into light in the visible wavelengths so that washing hanging on the line appears 'whiter than white'. These dyes are non-toxic and so can be used safely in milk

bottles. By rinsing the bottles in a dilute solution of the dye and exposing the bottles to ultra-violet light, the algae literally glows and may be detected by an electronic sensor. This might be an external camera or a probe which passes down through the neck of the bottle while it is rotating on a carousel. Because the bottle rotates as the probe descends, a helical scan of the inside of the bottle is taken (see figure 5.10).

The ultra-violet light is transmitted to the end of the probe from a ultra-violet source by quartz optical fibre (which attenuates the ultra-violet wavelengths less than ordinary glass) and reflected sideways onto the inner surface of the bottle by a small surface-silvered mirror (again surface-silvering rather than back-silvering to avoid the attenuation produced by passing through glass twice). A phototransistor, selected with good sensitivity at the blue end of the spectrum rather than just at the usual red end, is

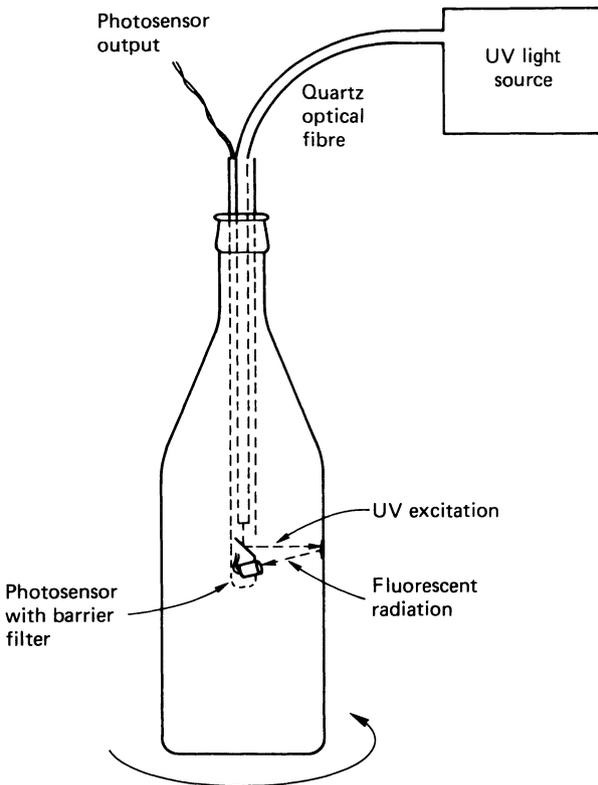


Figure 5.10 *Algae inspection probe*

positioned adjacent to the mirror to scan the area illuminated with ultra-violet light. On detecting fluorescing algae, the bottle is then rejected and destroyed. This arrangement means that the ultra-violet light is not attenuated by the bottle glass, which would be necessary for an external camera system, and also that the ultra-violet light is concentrated on just one small area. As the bottle rotates around the probe, while it is on the carousel, the probe can be positioned so that the radiated light is projected towards the centre of the carousel. With suitable screening, any danger to passers-by from ultra-violet light is therefore avoided.

EGG QUALITY INSPECTION

Making sure that eggs are of the highest quality and kept in prime condition on their way to the consumer is most important for the poultry industry. To ensure this, samples of eggs are taken regularly from an egg packing house to a laboratory. There the shell colour and weight are recorded and then the eggs are broken out onto a flat plate and the height of the egg white (albumen) near the yolk is measured for each egg. It has been found that freshness of an egg is directly related to the way an egg spreads on a flat surface. The further it spreads, the less fresh it is. As it is often the appearance of an egg, when broken out in a frying pan, by which the consumer will judge its quality, this is very relevant. The breakdown in the firmness of the albumen can also be affected by the post-laying storage temperature and the age of the bird.

The height of the albumen can be measured by lowering a calibrated probe down until it just makes contact with the albumen and then reading off the distance remaining between that position and the flat plate. Not only does this reading process take a significant amount of time and is open to the danger of misread data but also the albumen jumps up onto the probe on contact to form a meniscus, making it difficult for the observer to be sure of the actual height of the albumen.

A relatively simple electronic system has been produced to overcome these difficulties. A manually operated, vertical probe is still used, because it is important that the probe comes down in the right part of the albumen and does not spike the yolk. To the probe is attached a linear potentiometer. As the probe is lowered, the sliding contact travels along the resistance track so that the proportion of the voltage applied across the resistance track, available at the terminal connected to the slider, reduces as the slider proceeds towards the end of the track. The resulting voltage is directly proportional to the distance travelled by the probe and can be displayed by a digital voltmeter suitably calibrated by scaling resistors to

indicate the distance in millimetres. The stainless steel probe is electrically isolated from the supporting tripod but connected to a circuit which measures the resistance between the tripod and the probe. Because the legs of the tripod are also made of stainless steel and at least one of them is in contact with the egg, when the probe touches the albumen the circuit is closed and the resistance drops below 2000 ohms. Immediately this is detected, the digital voltmeter display is frozen at the current value. Therefore there is no need for the operator even to look at the probe tip and because the electronic circuit works so fast, the probe can be brought down rapidly into the albumen. A spring return is provided for the probe to ease the operation. The instrument shown in figure 5.11 will record this height and egg weight automatically on a printer so that no errors can be made as a result of misreading the display.

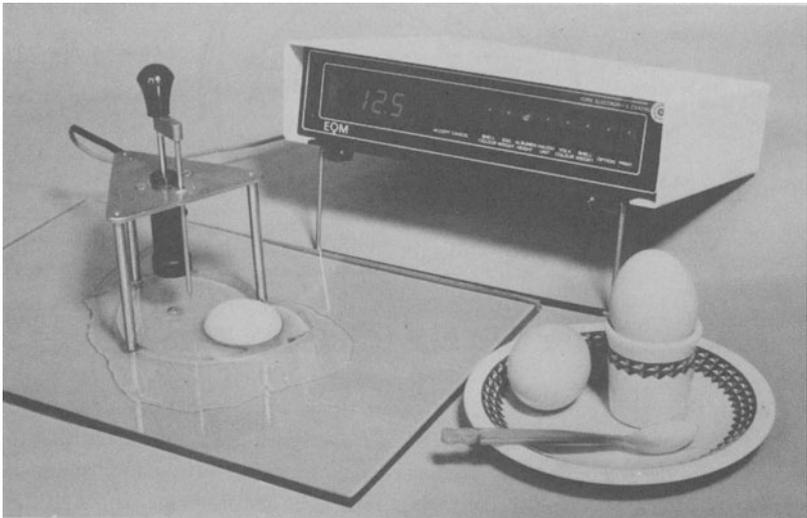


Figure 5.11 *Albumen height gauge and egg quality instrument*

INTACT EGG INSPECTION

The above measurement system may work very well but it still means that samples of eggs have to be taken from the packing house and destroyed during testing. Only a minute fraction of all the eggs is tested and although the sample is statistically large enough to be valid, this still means that

none of the eggs which actually go to the consumer has been tested for freshness. To be able to measure the albumen consistency of intact eggs, on the packing line or even in the laboratory, would be very desirable.

A number of methods were tried to measure the firmness of the albumen, such as measuring the egg's rotational damping factor when twisted about its vertical axis and trying to measure the natural resonance of the yolk when subjected to an external sinusoidal vibration over a range of frequencies. But the most promising one turned out to be a method which measured the position of the yolk in the egg when in various orientations and from this determined the consistency of the albumen. The internal structure of an egg is shown in figure 5.12.

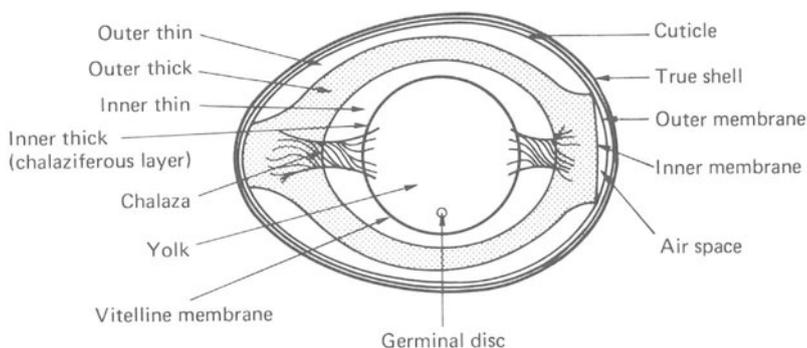
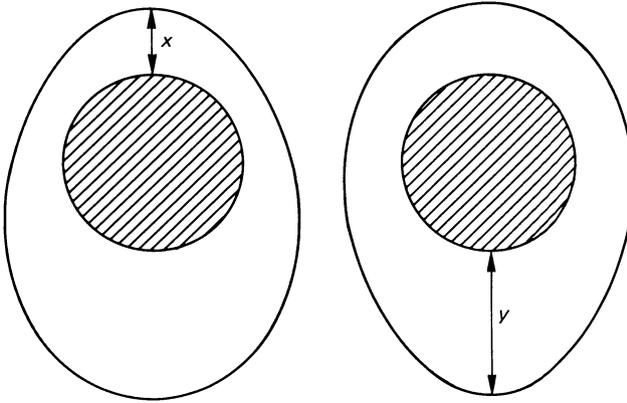


Figure 5.12 *Internal structure of an egg*

When the egg is newly laid, the outer thick white and the chalazae are in a firm condition. The air sack, shown in figure 5.12 at the right-hand end, forms as the egg cools because the contents shrink and the sack gradually increases over the following days as moisture is lost through the porous shell. Over a period of time the thick white and the chalazae disintegrate, allowing the yolk to move around the egg more freely. Although the air sack grows with the age of the egg and therefore could be used to estimate the age of the egg if the storage humidity and temperature conditions were known, there is no simple relationship between albumen consistency and air sack size. As was mentioned earlier, the age of the bird and hereditary factors also play a part.

To determine the albumen firmness it was decided to measure the position of the yolk from the same end of the egg, but firstly with it point uppermost and secondly point downwards. Because the yolk contained a significant fat content which the albumen did not, it tried to float upwards

in the egg, pulling at the lower chalaza and squashing the upper chalaza and thick white. It was hoped that the yolk displacement would correlate with the broken-out, albumen height measurement. Figure 5.13 shows the measurements (x and y) which were needed to determine the yolk displacement.



$$\text{Displacement of yolk} = y - x$$

Figure 5.13 *Diagram showing the displacement of the yolk with the egg upright and inverted*

To locate the yolk in a white shelled egg is relatively straightforward. Rear illumination of the egg with a bright light, preferably most intense towards the blue end of the spectrum, will enable an observer to see a blurred shadow of the yolk on the shell. The reason for suggesting a bluish light is because Rayleigh scattering from the particles in the yolk causes the transmitted light through the yolk to be attenuated more as the wavelength decreases, so creating a darker shadow. Unfortunately, blue light is the worst colour to use for the much more common, brown-shelled eggs because brown shells are almost completely opaque to blue light. To see a yolk shadow in a brown egg is therefore very difficult.

Ultrasonic sensors are used a lot in industry to detect sub-surface cracks in metal components. Their use in scanners for pre-natal examination of the foetus in pregnant women shows their versatility. It should be possible to obtain a good picture of the yolk in an egg with an ultrasonic scanner, but the machine cost is very high and the ultrasound would need to pass into the egg without going through air first as this would attenuate the

signal far too much. A non-air contact can be achieved by immersing the egg in a tank of liquid or by using a contact jelly but as this might dissolve the natural protective film around the shell, it is not an acceptable practice.

Returning to the optical approach, the problem was coping with the attenuation of blue light by the brown shell. If white light was used then at least some of it would be transmitted but the amount stopped by the yolk would be less. The indistinct shadow would still be difficult to observe on a mottled and often speckled shell. The following arrangement was devised to sharpen up the projected shadow so that it could be observed more distinctly.

Instead of illuminating the rear of the egg over its whole surface, a spot of very bright light was projected onto the rear surface. Inside the egg, light shone onto the yolk from just one point on the shell, so casting a clean shadow on the opposite wall. On moving the spot of light along the surface of the egg, the shadow cast travelled in the opposite direction. When the light spot and the shadow were opposite each other, it was known that the edge of the yolk was on the same line. Therefore the position of the upper and lower edges of the yolk could be pin pointed accurately (see figure 5.14).

To measure this yolk position automatically, two phototransistors were placed close to the egg on the opposite side from the spot of light. One of these was positioned diametrically opposite the spot of light and the other a short distance further along the path of travel. In this particular case the egg was moved and the sensors remained still, but identical results would have been obtained if the egg had been static and the sensors and light source had moved. The difference signal derived from the two sensors could be used to indicate when the light seen changed to shadow and back again (see figure 5.15).

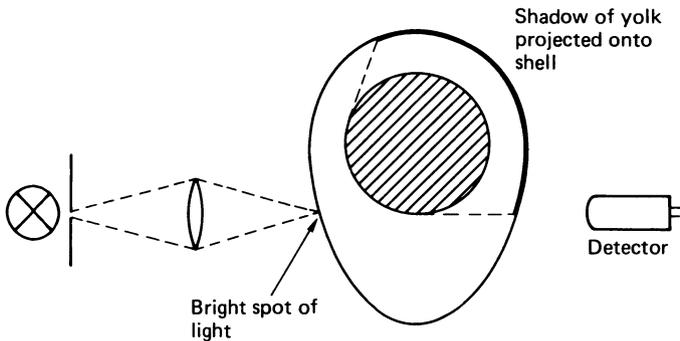


Figure 5.14 *How the internal shadow is generated*

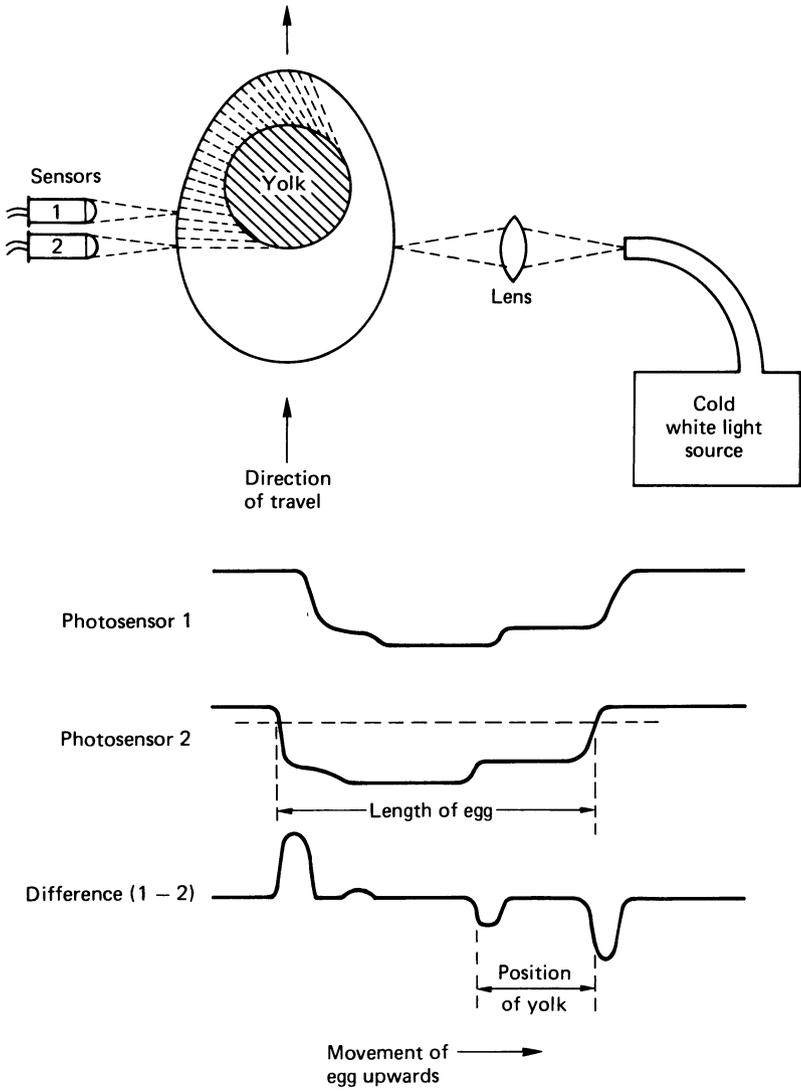


Figure 5.15 Sketch of yolk position measuring system with timing diagrams

In this implementation only the change from shadow to light was used as the egg passed upwards because the shadow was much more distinct at the centre of the egg than near the point where the sides sloped in rapidly. The egg was then inverted and again raised past the sensors so that a second measurement of yolk shadow could be made in the centre of the egg. Using one of the sensors also to measure the total length of the egg and assuming that yolk size variations from egg to egg were minimal, an answer relating to yolk displacement was found.

When these measurements were compared with the broken-out albumen height recordings for the same eggs, there was a large scatter of results but a clear area on the graph where the displacement was small and the albumen height was satisfactory. Although the intact egg inspection technique could not replace the other testing system, it could be used to make sure that no egg had an albumen firmness less than the normally accepted level.

EGG SHELL COLOUR

The poultry breeders are also interested in monitoring the brownness of eggs so that, by intermixing the flocks, they may breed a strain of hen which will lay a uniformly brown egg. Strange as it may seem, the average consumer is said to prefer a box of eggs to be all of the same colour. A hand-held instrument was therefore designed to give a reading of brownness so that statistical information could be accumulated. By taking objective readings of shell colour rather than relying on subjective judgement, the information gathered could be used to determine the optimum breeding programme so that uniform brown eggs would be produced in due course after a few generations of hens had come and gone. Fortunately it was found empirically that reflection measurements in green light correlated well with subjective groupings of the brown eggs by humans. It was therefore possible to use a number of green light emitting diodes (LEDs) as the light source, thereby minimising the power drain on any battery and avoiding the disadvantages of deterioration and occasional replacement needed for a tungsten lamp. The LEDs were arranged in a circle to shine down on an aperture at 45° so that no specularly reflected light would fall on the photodiodes (see figure 5.16). Using a black and a white tile, the unit was calibrated before use so that the reading obtained was zero for black and 100 for pure white. The blunt end of each egg was placed in the circular aperture, the photodiode measured the diffuse reflected light and the display indicated percentage brownness.

In its simplest form (see figure 5.17) the unit worked well on brown eggs but when it was checked on very pale eggs it appeared to be affected

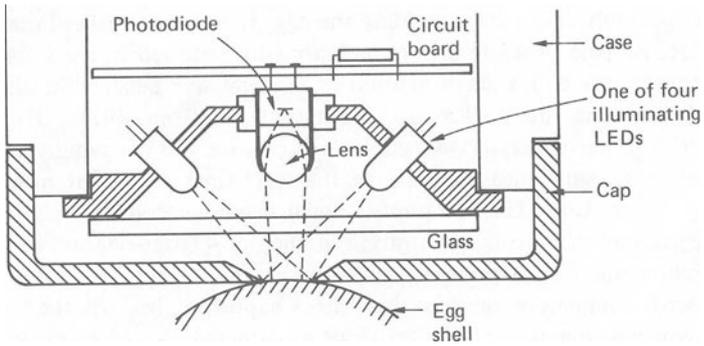


Figure 5.16 *Cross-section of reflectometer head*



Figure 5.17 *The egg reflectometer*

by the position of the hand holding the egg. It was then realised that this was because pale or white eggs (which are still preferred in the USA) are semi-translucent and a small amount of daylight was penetrating the egg and illuminating the shell area being monitored, from within. To overcome this it was necessary to switch the LEDs on and off rapidly and to subtract the signal measured during the 'off' time from that measured during the 'on' time. This technique, known as modulation, was mentioned in the section on printing registration in chapter 4 (page 68) and a couple of circuits and a description are given in chapter 7 (page 132). Although the user is completely unaware that this is happening because the switching frequency is much higher than can be detected with the human eye, the unit is now quite impervious to the lighting conditions surrounding it.

6 Chiropody, Dentistry and Other Applications

Very sophisticated electronic equipment is now available in medical fields to help in the diagnosis and treatment of disease and illness. People now readily accept the use of body scanners, kidney dialysis machines, electrocardiographs and heart pacemakers without always knowing that in each are electronic sensors and complex circuitry which are essential for the equipment to function. The applications mentioned in this chapter will be far more mundane but at least the mixture will be unusual!

INSTRUMENT FOR TREATING TOE NAILS

Ingrowing toe nails are a subject which appeals to few. However there are many people who suffer considerable pain from ingrowing toe nails and therefore an improvement in the treatment available has been welcomed. Small elasticated braces can be applied to restrain the nail from ingrowing but these are clumsy and not always very effective. At present, most serious cases have to undergo amputation of the offending nail in order to obtain relief from the pain. This is an unpleasant business, expensive and also there is always the risk of an infection as a result of the operation.

Human nail is a thermoplastic. When heated it can be bent, without changing its composition, to a new form and, if retained in that position during cooling, will remain there. A chiropodist, working every day with toes and feet, felt that there must be some way in which an instrument could be designed using this property, which would enable him to correct his clients' ingrowing nails without their having to undergo nail amputation. He produced a pair of pliers with a coil of heating wire wrapped round the upper jaw with which he was able to prove the technique. The nail could be bent and it stayed where it was put.

In order to make the instrument safe for use on patients, it was necessary to arrange for the temperature of the heating element to be controlled precisely, to make all the items so that they could be easily cleaned and sterilised without damage, and to isolate the electrical system, which would be in close contact with the patient, from the mains electrical

supply. A set of standard, chiropodist's, stainless-steel cutters was used for the prototype, and the upper jaw was replaced with a heat-resistant part in which was incorporated a single wire heating element, insulated from the rest of the instrument. The single wire was chosen so that the whole length would be in contact with the nail to achieve good conduction of heat and also to keep the mass as small as possible for a fast cooling rate. The lower jaw was thinned so that it could slide under the nail but was still large enough to act as a heat barrier between the heated nail and the rest of the toe. To control the temperature of the heating element precisely, a miniature thermistor was incorporated in the insulated housing, above, but in thermal contact with, the wire. The control circuit for the heater measured the resistance of this thermistor, which varied inversely with temperature, to maintain the pre-set temperature. A timer was also included so that the duration of the heat pulse was limited. See figure 6.1.

When in use, the instrument was applied to the offending nail, the heating initiated and after the set time the nail was bent to its new position without any pain to the patient either from the heating or from the bending operation. Because the heating system allowed the nail to cool down

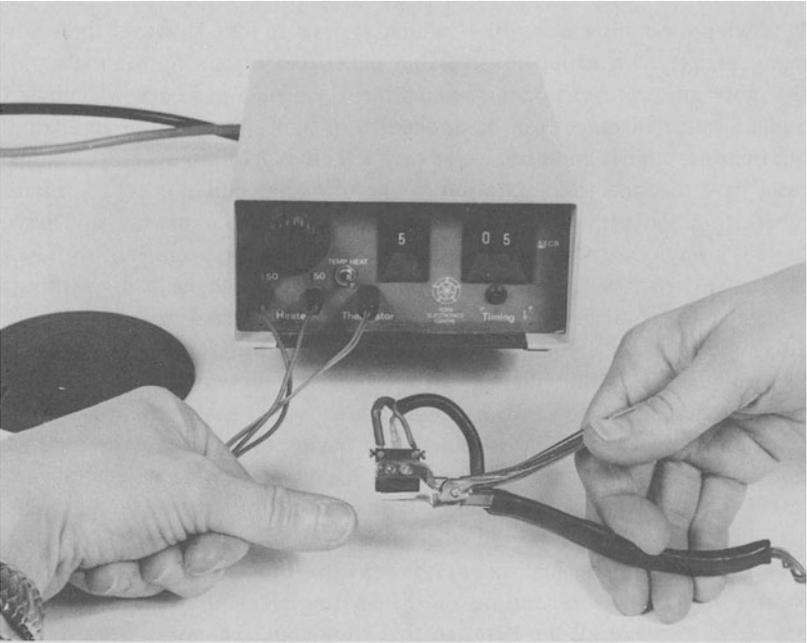


Figure 6.1 *Instrument for treating ingrowing toe nails*

quite quickly, the instrument did not have to be kept for long in the new position to establish the new shape. The sequence was started by a foot switch, because the hands would have been otherwise engaged and a couple of LEDs on the front panel of the control unit indicated to the chiropodist when the pre-set times had elapsed. It now looks as if this instrument could cure many of the problems which previously required surgery, for the results from field trials have been very successful.

PERIODONTAL PROBE

If treating ingrowing toe nails seemed unattractive, then dealing with gingivitis (inflammation of the gums) will appeal even less! Before treatment and as the treatment progresses, it is necessary for the dentist to be able to measure the gap or pocket which has developed between the tooth and the gum. This has been done by inserting a small wire-ended probe into the pocket, around which has been engraved graduated lines, and by counting the number of lines still visible, estimating the depth of the pocket (see figure 6.2). Looking into the back of a patient's mouth and

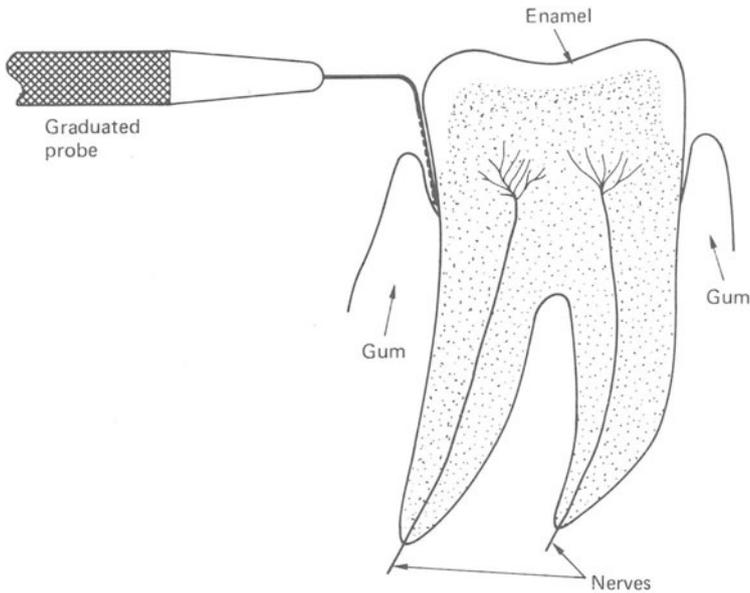


Figure 6.2 *Sketch of tooth and gum showing the standard pocket depth probe*

counting a number of fine lines accurately is neither easy nor particularly pleasant. The process needs to be repeated each time the patient returns, during the treatment, to see what progress has been achieved.

An electronic probe has been designed which will make this task much easier and less prone to reading errors for the dentist and also indicate to the patient the extent of the problem. After all, the patient has an interest in the situation too! This instrument uses a wire probe but, instead of being graduated, the wire can retreat into the instrument so that the only part protruding is that which is penetrating into the pocket. The wire runs in a sleeve and, during use, the front edge of the sleeve rests upon the gum's upper surface. The other end of the wire presses up a hinged beam which is located within the handle of the instrument. By measuring the movement of this beam, the penetration of the probe within the pocket between the tooth and the gum can be determined (see figure 6.3).

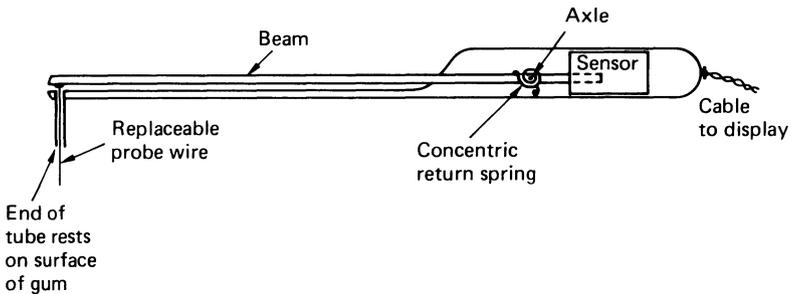


Figure 6.3 *Diagram of probe tip and beam*

In order to keep the instrument as small as possible, it would be satisfying to develop a sensor to measure the wire's movement right at the tip, but it is important to remember that with all medical instruments they have to be regularly sterilised and with the advent of the AIDs virus, this may mean autoclaving at 140°C. Therefore any electronic sensor would have to withstand this temperature. It must also be remembered that the probe must be designed so that parts, such as the probe wire, can be easily replaced by the dentist, without the need for special tools, if they are damaged or bent. For these reasons it was decided to divide the instrument into two parts: the front part consisting of the probe wire, sleeve and beam so that this entire unit could be autoclaved without fear of damage, and the rear part consisting of an electronic sensor which would monitor the movement of the beam when the two parts were interlocked. Only the

rear part needed any electrical connections, therefore avoiding electrical connecting pins between the two sections of the probe.

The beam's movement could be measured in a number of ways: rotation of the axle by a rotary potentiometer, linear movement by a potentiometer or by varying the mutual coupling between two coils as was alluded to in chapter 1 (page 3), variation of capacitance, etc. All these methods would have involved mechanical or electrical connection to the beam and so it was decided to use a slotted opto-sensor. A vane is mounted on the beam which passes through the slot between the phototransistor and the light emitting diode. As the beam moves, the vane obscures a larger cross-section of the optical path between the phototransistor and the LED; the received signal therefore reduces accordingly but not in a linear fashion. In order to correct for this non-linearity and to increase the sensitivity of measurement, the slotted sensor can be positioned so that the vane slices the beam. This is best illustrated by a sketch rather than a description – see figure 6.4.

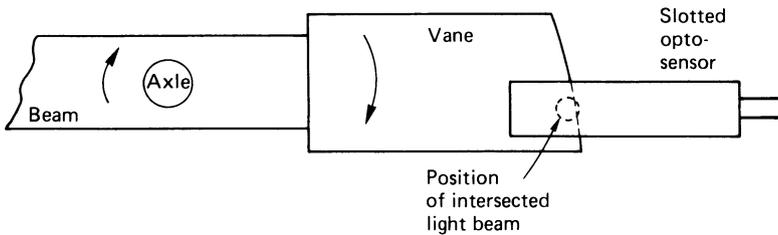


Figure 6.4 Sketch of vane and slotted sensor

By fashioning the outer edge of the vane so that the voltage across the phototransistor varies proportionally with the distance moved by the wire probe, a direct reading of penetration can be obtained. However all is not quite as splendid as it might appear. Such a system would require very accurate relocation of the removable part of the instrument to obtain the same result every time. The slightest crack between the two parts of the unit would give an appreciable error. To overcome this difficulty and to keep the advantages of non-linear correction and angle magnification by the slicing or wedge action, it was necessary to develop a vane with multiple wedge-shaped apertures in it like a comb (see figure 6.5).

There need to be as many apertures as possible in the optical path to minimise change in the attenuation of the light path for horizontal movement, but there is a limit to how fine these apertures can be made. For-

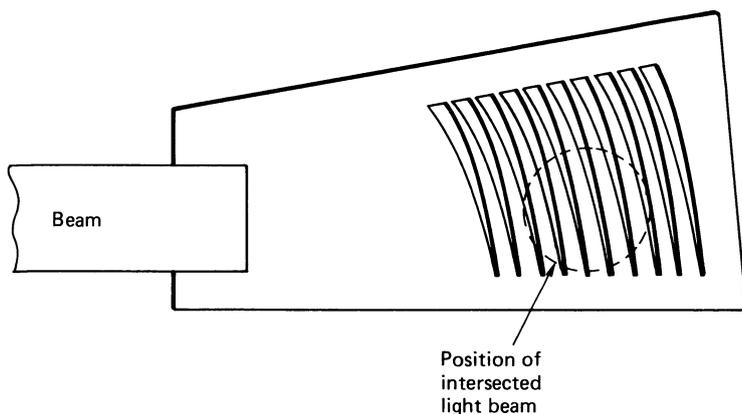


Figure 6.5 *Comb styled vane*

tunately for this application, the accuracy needed did not require more than about five in the path at any one time and so fabrication was straightforward. The vane, if made correctly, should give an insignificant change in the signal for movement in either of the two horizontal axes. The vane was made by drawing the required form on paper, photographing the drawing and reducing it to the appropriate scale, and then etching the photographic image through thin stainless-steel sheet. The vane, together with the beam to which it was attached, could then be autoclaved without danger. The intermediate photographic film was used in a prototype to test that the calculated curves had been drawn correctly and that a linear response would be produced.

The prototype equipment consisted of the probe and a display unit. The circuitry inside the display unit retained the maximum reading after each operation so that the reading could be recorded at leisure and it automatically reset the zero of the display when the probe was withdrawn, after a suitable time interval, so that any offset in the vane's position, when at rest, would not affect the reading obtained. The production version (called the Pocket Depth Recorder and made by Dextrodent Diagnostics Ltd) has a colourful, illuminated bar-graph display to impress potential purchasers and their patients, but the sensing technique remains the same (see figure 6.6).

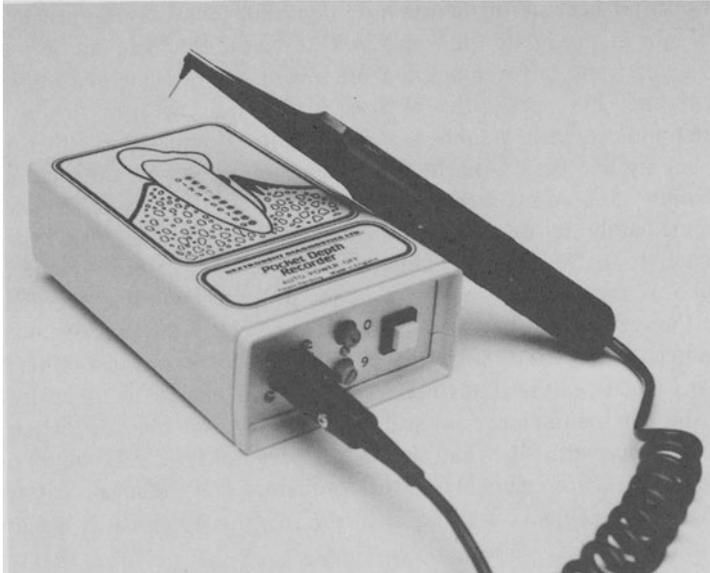


Figure 6.6 *Pocket depth recorder*

PHARMACEUTICAL TABLET INSPECTION

Pills come in all sorts of different shapes and sizes. Those which are meant to be swallowed rather than chewed in the mouth often have a soluble protective coating which prevents the pill disintegrating until it reaches the stomach, so making the tablet palatable. A brightly coloured sugar coating is often used. The inner part of the pill is usually made by compacting the ingredients together in powder form under great pressure. Unfortunately, with varying atmospheric conditions, there may be times when the particles of the compacted material do not adhere properly and cracking may develop later in the sugar-coated surface. Although this does not cause any medicinal problems, the cosmetic appearance of the pills is unsatisfactory and it is necessary for such a batch to be sorted so that any cracked tablets may be removed. This is a tedious and time-consuming task.

There are a number of expensive image analysis systems available on the market which could be used to inspect these tablets. But the first and most important problem to be tackled when considering any such system is to identify the means by which the required feature can be isolated from the remainder. Image analysis systems provide an excellent way of testing

ideas out but because of their in-built flexibility, they are not usually able to operate at production line speeds. One method, which can be used at quite a fast rate, is to compare a pre-recorded television picture with a current one. For speed, the picture can be split up into tiny squares (pixels) and stored in a solid-state frame store. Comparison is then made on a line by line basis with the current picture. By storing the picture of a good tablet and comparing every new tablet with it, any difference can be immediately spotted and remedial action taken. The snag with this approach is that every new tablet must be located in exactly the same position as the recorded one or a major difference will be recorded. To make the system adjust for misplacement would slow the process down far too much. So to use this approach, the inspected item must either have regular, precise physical features which would enable it to be located accurately, or the tolerance on the inspection resolution must be sufficiently broad to cope with slight misplacement. Because the cracks which occur in these tablets are invariably on their 'equators' and the sugar coatings do not have the accuracy of a machined surface, this approach is unsuitable for this application.

Some interesting work was done in Japan (by Otani and Urabe in 1980) on inspecting ceramic tiles for surface flaws using ultrasonic sensors (see figure 6.7). An ultrasonic beam was reflected off the tile's surface as it passed at a steady rate under the transducers. If the surface was smooth, then there was no change in the received signal. However, if a flaw in the tile appeared the signal was altered. By differentiating the amplitude signal derived from the ultrasonic waveform, an indication of the flaw could be detected.

This method was evaluated on the tablets. The tablets were placed on a turntable so that the 'equator' was on end and at right angles to the direction of travel (that is, in line with the radius of the turntable). As the tablets went around, the ultrasonic beam moved up one smooth side, across the 'equator' and down the other side of each tablet. If a crack were present, it was hoped that this would give a much larger differentiated signal than the other more slowly changing surfaces. Unfortunately the cracks were not discernible in the resulting signal. Because the crack caused a change in the phase relationship between the reflected signal from the crack and that reflected from the smooth adjacent surface, in order for a significant difference to have appeared in the amplitude of the received waveform, the distance travelled by the waves from the two surfaces needed to be a substantial fraction of the sound's wavelength or the crack would have had to have had a large area. In this case, with a frequency of 40 kHz, the wavelength was approximately 7.5 mm and so even a fairly large crack in the tablet, with a width of say 0.5 mm, would have pro-

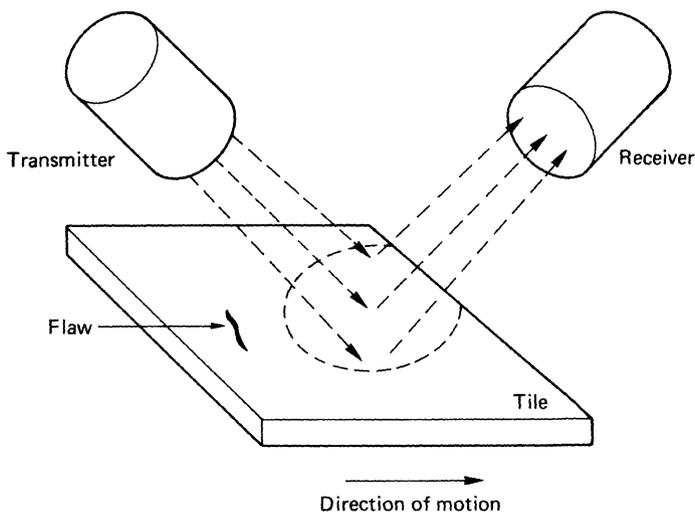


Figure 6.7 *Ultrasonic tile inspection arrangement*

duced a minimal effect on the returning signal. To obtain a significant signal change from a crack width of 0.1 mm, an ultrasound frequency of about 1 MHz or higher would have been necessary. Such transducers were certainly not readily available and would have been difficult and expensive to produce.

Back to optical inspection techniques again. What could be done with a line camera? The tablet was rotated on its 'equator' under the line camera with the camera scanning at right angles to the 'equator'. For a good tablet, a fairly constant picture was obtained but for a tablet with a crack in it, there was a notch or bump in the top of the waveform (see figure 6.8).

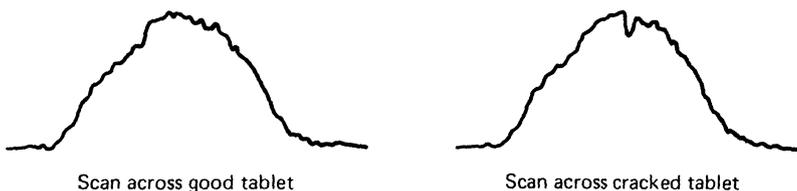


Figure 6.8 *Line camera waveforms of a good tablet and a cracked one*

As discussed earlier, a direct comparison between a stored perfect picture and a present one would have rejected far too many if it was necessary to detect a crack width of 0.1 mm. The tablet had only to joggle slightly for the new image to differ considerably from the stored one. But if one scan from the camera was compared immediately with the next and the difference signal was differentiated to accentuate the sudden appearance of a crack then, because there were many scans per revolution of the tablet, the variations due to vibration and gradual irregularities in the sugar coating would have been much less significant. The waveforms in figure 6.9 show a cracked tablet profile and the differentiated difference signal resulting from it. Two fixed thresholds were set, one just above the normal signal amplitude and the other just below, so that if the signal exceeded either threshold, the tablet was then deemed faulty.

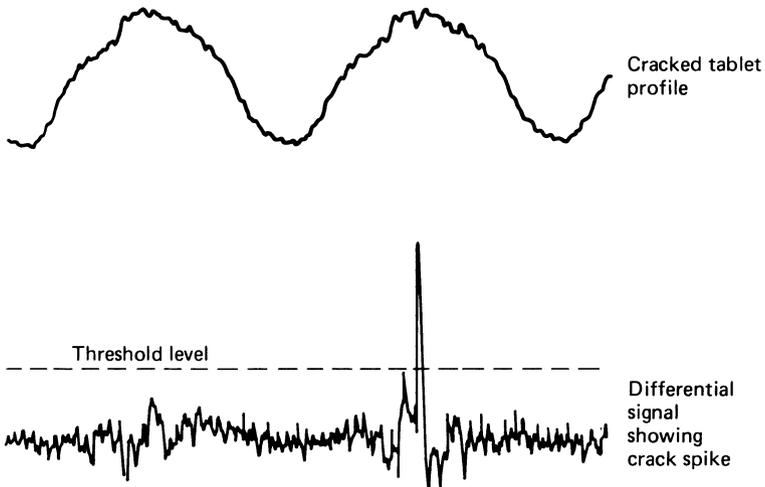


Figure 6.9 Waveforms from successive scans of the tablet showing how the sudden appearance of a crack generates a large spike in the differentiated waveform

Although a full system is only being constructed at the time of writing, the laboratory prototype (see figure 6.10) showed that the technique could be used to inspect tablets at production rates and it was estimated that it could resolve cracks ten times smaller than those seen by the naked eye. Much of the work was carried out by an undergraduate, Julian Martin, in his final year project at the University of York and received a commendation in the Design Council's Molins Prize the following year.

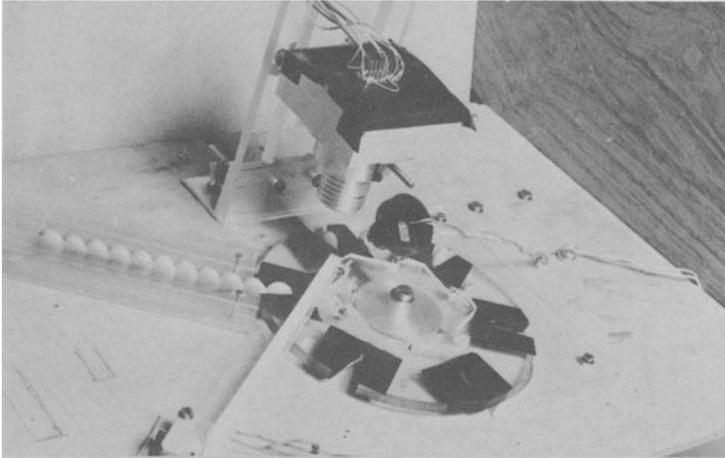


Figure 6.10 *The tablet inspection prototype*

CRYOMETER

This is the name given to an instrument which measures the rate of cooling of biological specimens. The equipment could measure the rate of cooling of almost anything (or even the rate of heating for that matter) but it was developed for biological laboratory use to assist sample preparation for electron microscopy. Briefly, in order for the microscope to ‘see’ the cell structure in a sample, the electrons have to be absorbed or reflected by the constituent parts of the surface in different ways. For organic matter, a very thin layer of gold is applied to the surface to be observed so that the cell wall structure is accentuated. To achieve a successful application of the gold the sample needs to be freeze-dried first. This is done by plunging a tiny sample of the specimen into liquid nitrogen which has a boiling point at -196°C ; hence the ‘Cryo-’ bit in the name of the instrument. As the sample cools, ice crystals grow in the specimen (see figure 6.11). If the cooling rate is too slow, the formation of these ice crystals can destroy the cellular structure of the specimen making the sample useless for observation.

Therefore it is very important that the samples are cooled very rapidly to only allow very small ice crystals to form. The cooling rates may be as fast as $10\,000^{\circ}\text{C}$ per second! The cryometer was developed to record these rates of cooling so that precious time on the electron microscope (and precious gold as well) was only spent on worthwhile samples of the original specimen. By making sure that the required rate of cooling had

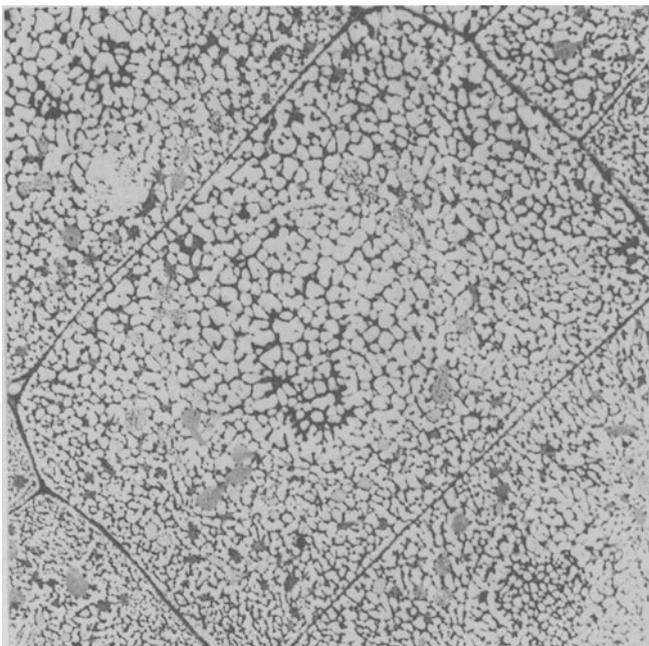


Figure 6.11 *Electron-microscope photograph of a cellular structure showing the deformation of the cells by the growth of ice crystals*

been achieved for each sample taken, the frustration of finding that the samples were unsatisfactory at the electron microscope stage was considerably reduced.

To measure rapid rates of cooling of minute objects, it is necessary that the sensor should be very small, not only to correspond in size with the sample of the specimen but also so that its heat capacity is minimal. For this application the thermocouple junction of two dissimilar metals is the most appropriate contender for such an electronic sensor. Because the difference in voltage generated at the junction is not proportional to the contact area between the two metals but to the nature of the two metals and the temperature difference between the hot and cold junction, the thermocouple can be made with fine wires just welded together at their extreme ends. The junction at the tip of these wires is then fixed in very close proximity to the sample to be cooled so that a best estimate of cooling is obtained as the assembly is dropped into liquid nitrogen. Being fine wires they do not impede the fall of the sample. A choice has to be made from a number of different metals which make good thermocouple

junctions to suit the range of temperatures over which the cooling takes place. There are four or five standard thermocouple metal pairs which cover the temperature ranges normally required and for this low temperature application the metals chosen were copper and copper-nickel alloy (Type T) because this pair gives the most linear response from -200°C to 25°C .

In scientific experiments the other thermocouple junction (in this case the hot junction) would have been placed in some constant temperature enclosure, for instance a beaker of melting ice. However this would be far from convenient for a laboratory instrument and therefore in the Cryometer a special circuit was used to simulate the other (hot) junction. The compensation circuit, with an amplifier, was all included within a special integrated circuit made by Analog Devices. It was necessary to choose the correct compensation to suit the type of thermocouple selected.

In order to calculate the rate of cooling, the voltage coming from this amplifying circuit was sampled as quickly as possible and the resulting numbers stored away in quick succession in a digital memory. After the



Figure 6.12 The Cryometer

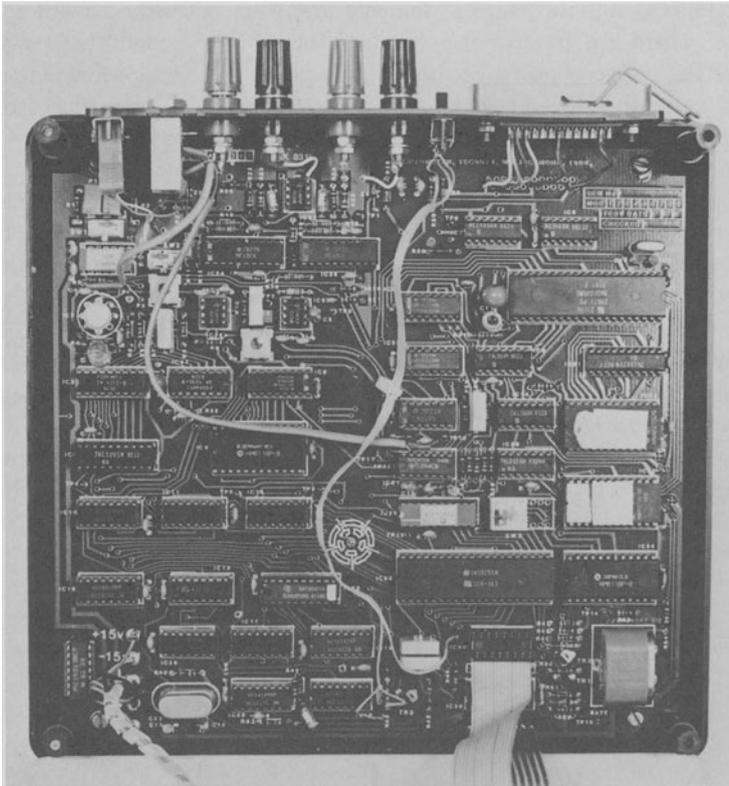


Figure 6.13 *Internal electronic circuitry of the Cryometer*

sampling was finished, a miniature microcomputer (if that is not tortology) interrogated all the locations in the memory and calculated the average rate of cooling between set limits. The microcomputer was not nearly fast enough to calculate the rate of cooling in real time, partly because of the number of operations involved and also because of the slight non-linearity in the thermocouple characteristic which had to be corrected first by the microcomputer, using a look-up table, before the rate calculations were made. At the fastest sampling rate, 2048 separate samples were recorded within a fifth of a second. The built-in microcomputer was used to set the temperature limits for the rate calculations, the sampling period and to play back the recorded data through digital-to-analogue converters so that a trace of the cooling effect could be recorded on a chart recorder. It could also send all the stored data to another computer for further pro-

cessing if required. Modern electronic packaging enabled all this to be contained within a neat plastic enclosure so that it could be used conveniently in a biological laboratory (see figures 6.12 and 6.13).

ELECTRICAL POWER MEASUREMENT

Obviously this topic does not come under a medical heading, except perhaps when trying to economise on the power consumption in a hospital. But this and another sensing application need to be fitted in somewhere and none of the other chapter titles seem more appropriate.

In large institutions, such as hospitals, the electrical energy usage is not only considerable but also fluctuates considerably during a working day. Sudden demands on the electricity supply can create problems for the electricity provider and so a tariff is charged, on top of the ordinary total kilowatt consumption, for the maximum peak usage in any 30 minute period. Equipment for monitoring power usage can be fitted by the user to monitor the demand and temporarily, automatically switch off in-essential loads if the peak demand is about to exceed a tolerable pre-set level. Such loads as heaters or air conditioning plant may be turned off for a few minutes with little effect being noticed in room temperature. The equipment needs to monitor the current being drawn from the supply and the voltage available in order, by multiplication, to calculate the total power being consumed.

Devices, called current transformers, are used to measure the large alternating currents involved rather than resistors, mainly because resistors could get extremely hot. These transformers consist of a magnetic core, shaped like a doughnut, which encircles the cable carrying the load current. Around the core is a secondary winding of many turns. The current in the winding, generated by the alternating magnetic flux in the core, flows through a sensing resistor. The voltage across the sensing resistor is proportional to the current flowing through it which is proportional to the current flowing in the main cable divided by the number of turns in the secondary winding. It is assumed that the main cable only passes through the core once. The current transformer provides complete isolation from the mains supply and a convenient low voltage suitable for processing by electronic circuitry. But to install such a device retrospectively would mean that the main electricity cables would have to be disconnected and threaded through the current transformer.

To avoid the above problem, which would mean interrupting the supply to the hospital during installation, split core transformers could be employed so that the two halves could be opened and then reclamped around

the cable without disturbing it. However these are not recommended because oxide films build up with time on the mating surfaces, increasing the magnetic reluctance of the core and therefore reducing the maximum flux capacity of the core. The core has to have a large enough cross-sectional area and permeability to be able to transform the maximum peak current.

An alternative solution can be provided by using a silicon, integrated circuit Hall effect probe, positioned in an air-gap in the core which will measure the magnetic flux passing round the core. This probe is then used to control the current via a power amplifier fed back to the winding round the core (see figure 6.14). The Hall probe balances the flux due to the main single cable and the flux due to the feedback winding so that they are exactly equal and opposite. The condition for zero total flux around the core is

$$I_{\text{main}} = NI_{\text{feedback}}$$

so the main current is transformed down by the factor N , the number of turns in the feedback winding. A voltage proportional to the feedback current and hence main current is available across the feedback resistor R for use in further power measuring circuitry.

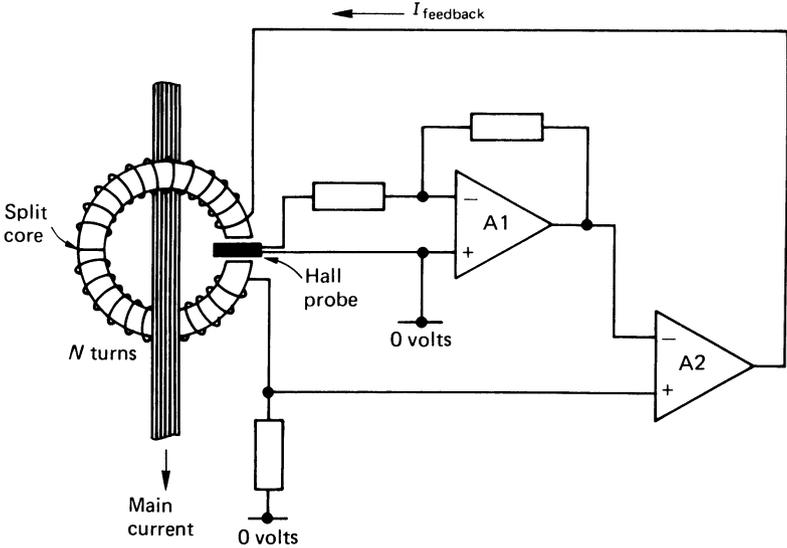


Figure 6.14 Circuit diagram of flux nulling current transformer

This technique has the significant advantage that as the flux is nulled to zero, under normal conditions the magnetic material of the core is in no danger of becoming saturated and so it can be made with a small cross-section and minimum physical size. An air-gap has to be deliberately included to take the Hall probe so oxide films (which will be hundreds of times thinner than this gap) will have little effect. Because the flux is nulled, any change in reluctance over a period of time will have no effect.

FUEL COMBUSTION MONITOR

While talking about regulating energy usage, there is another application of an electronic sensor which has produced substantial energy savings for schools, hospitals and other large institutions. The combustion efficiency of a boiler can be measured by monitoring the oxygen content in the flue gases. The more oxygen remaining in the flue, the poorer the combustion process

An oxygen sensor was developed at the City University in London and is now made by City Technology Ltd (an offshoot company from City University). This sensor (see figure 6.15) produces a current directly proportional to the concentration of oxygen in the gas being monitored. By arranging for a small pump to draw off a continuous sample of the flue gases through a tube and then through the cell at a constant rate, the

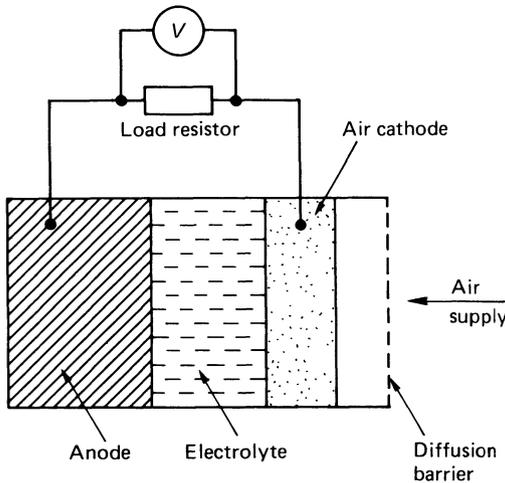


Figure 6.15 Schematic diagram of oxygen sensor

oxygen content and hence the boiler's efficiency is measured. The air-inlet flap to the boiler can then be controlled by this signal so that, irrespective of the heat output required, the boiler always operates at maximum efficiency. The sensor is based on fuel cell construction techniques with the rate at which the gas enters the sensor being controlled by a gas diffusion barrier.

It contains an anode, electrolyte and an air cathode. At the air cathode, oxygen is reduced to hydroxyl ions which in turn oxidise the metal anode. The current is proportional to the rate of consumption of oxygen (Faraday's Law). Because the cell is operated in the current limiting region, the oxygen is consumed as fast as it reaches the electrode. Because of the diffusion barrier, there is a direct relationship between the oxygen concentration and the limiting current. By placing a resistor of known value across the sensor, the oxygen concentration can be read off as a voltage signal.

SHOP WINDOW SECURITY

Current transformers may be ideal for measuring large currents but standard diodes were used in a current sensor for a security alarm unit. Unfortunately electrical equipment on display in a shop window or on the shelves within the shop is very vulnerable and theft of such items accounts for many millions of pounds each year. It is common to see a single wire security system used which is looped by the shop assistant through the carrying handle of each item on display. Should the wire be broken or unplugged, then the small current flowing in it is interrupted and the circuit monitoring the current flow causes an alarm to sound. This system is cheap and reliable but the presence of the wire detracts from the display and should an item be required for sale, the wire has to be unthreaded back to that item and then rethreaded after legitimate removal.

The following sensor circuit was devised to monitor continuously the mains current flowing to any item of electrical equipment so that, if the current ceased, an alarm could be sounded. By using this circuit on each mains outlet and linking the signals to a common alarm, each piece of equipment could be protected from unorthodox removal without any obtrusive security wiring. However the normal appliance load current could vary from about a milliamp for the supply-on neon indicator to at least 4 amps for a 1 kilowatt electric fire. Therefore if a resistor had been used, the resistance value would have had to have been large enough for a significant voltage to have been developed across it for detection purposes when 1 milliamp was flowing and yet with sufficient surface area to handle

the heat dissipation when loaded by an electric fire. The range involved, of 4000, is enormous. The diode, which has already appeared in different guises in earlier chapters, provides an excellent solution for this requirement. The exponential relationship between voltage and current (see chapter 7 (page 120)) means that a significant voltage is developed across it even when a minute current is flowing through it, and the voltage only increases by a small amount when the current is large. As the dissipation from the diode is proportional to the voltage across it times the current going through it, the power radiated is not proportional to the square of the current as in a resistor but only directly proportional to the current. A single outlet sensing circuit is shown in figure 6.16.

The circuit works as follows. The current for the appliance flows from the live terminal of the mains supply, through the fuse to the live terminal for the appliance. The current from the appliance returns through the neutral terminal, through diodes D2 and D3 and across to the mains neutral supply terminal. Because the mains supply provides an alternating current, the current direction reverses every 10 milliseconds and therefore diode D1 carries the reverse component.

For the following description it is assumed that the switch SW1 is closed and the 9 volt rechargeable battery is fully charged. During the current's positive half cycle, a voltage of approximately 1.3 volts is developed across D2 and D3. A small current flows through R2 into the base of transistor TR1 and turns it on. Therefore, during this time, a current flows down through R4 and R3 and because R3 is very much smaller than R4, the capacitor C1 remains discharged. During the negative half cycle the capacitor only charges fractionally and therefore the transistor TR2 is not allowed to turn on as the base-emitter threshold voltage is not exceeded. The transistor TR3 is also held off because no base current can flow through R6 and TR2 and the alarm unit AUW1 remains silent.

If the appliance is removed or turned off, then the voltage across the diodes D2 and D3 will not be sustained and so the base of transistor TR1 will no longer be supplied with current. Therefore no current will flow down through the resistor R3 and the capacitor C1 will slowly charge up, the power coming from the 9 volt battery through resistor R4. As soon as the voltage across the capacitor reaches the base-emitter threshold voltage of TR2 (0.6 volts) this transistor will start to turn on. Current will now start to flow through the base of TR3 and resistor R6. As TR3 turns on, the voltage across the sounder will rise. After it has reached approximately 1.3 volts, current will flow through the diode D6 and resistor R5 to reinforce the current coming down from the supply through resistor R4. Because R5 is very much less than R4, the transistors TR2 and TR3 will then turn on rapidly. The diode D6 and the resistor R5 provide a latching

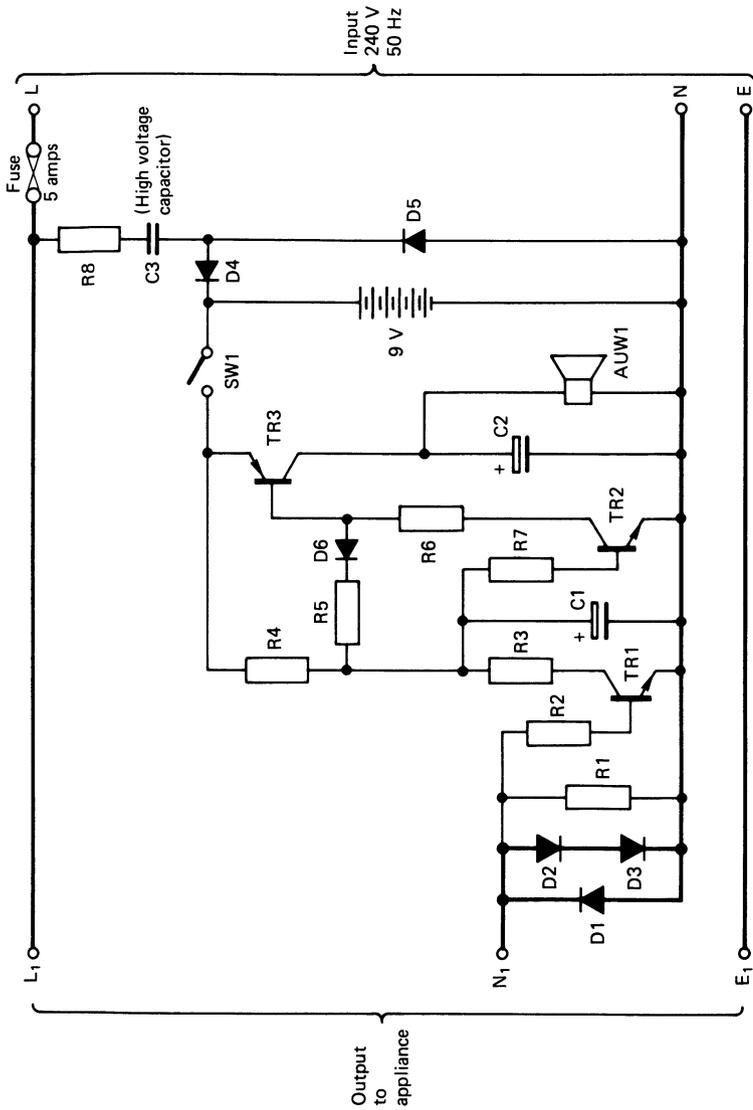


Figure 6.16 Circuit diagram of appliance current sensing circuit

arrangement so that the current continues to flow through the sounder even if the appliance is reconnected and the sound can only be stopped by turning off the keyswitch SW1. The rechargeable battery enables the unit to function if the power is disconnected from the security unit. See figure 6.17.

For use in a shop, the sensing part of the circuit can be replicated for each socket and all connected to a single sounder, battery and key switch. Dummy plugs, with a 220 kohm resistor fitted between the live and neutral terminals inside, may be inserted into any unused sockets to make them inactive. In the home, one of these circuits may be connected in the supply to a freezer so that the owner can be alerted if the equipment is accidentally turned off. Gold fish tanks and incubators could also be similarly protected. It is all possible, at a reasonable price, because of the exponential characteristic of the diode!

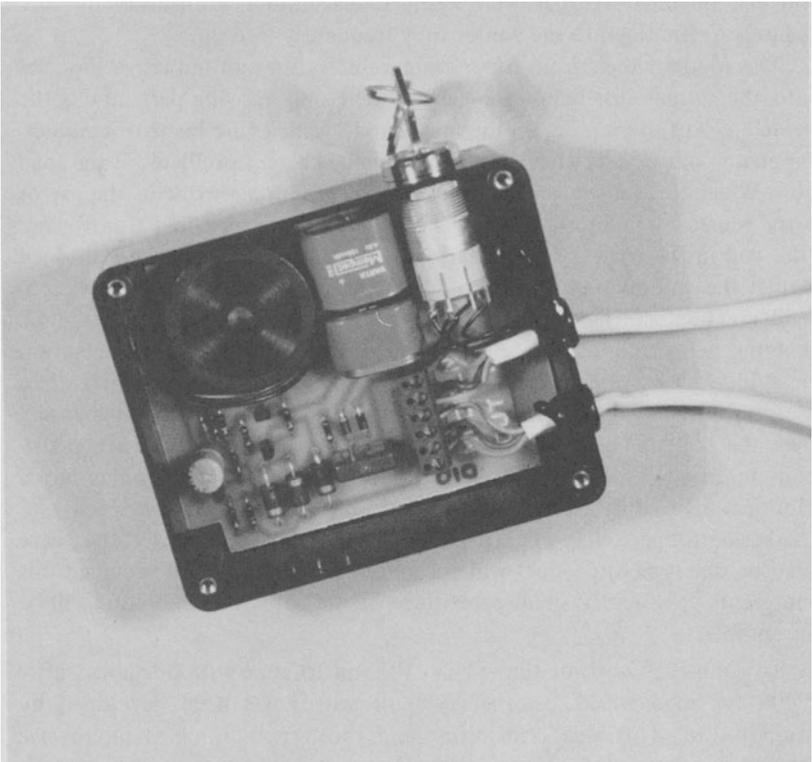


Figure 6.17 *The single way security unit*

TRAFFIC CONTROL

When the number of motor cars on the roads increased to such an extent that serious congestion occurred at busy road junctions, lights were installed to regulate traffic flow. These lights were switched on and off by a rotating drum, in the circumference of which pegs were fixed to operate the lights' switches on a cyclical basis. Because the drum rotated at constant speed, the green and red illumination times were fixed and no allowance was made for the variations in traffic density.

Later on, rubber tubes were set in the road's surface to detect the pressure exerted by the tyres of cars and lorries approaching the junction. At the end of each tube a diaphragm switch detected a sudden change in air pressure (first differential) as a wheel passed over. The controller, in which the drum had now been replaced by timers and relays, could respond more closely to traffic conditions. This was a considerable improvement but the pneumatic tubes were easily damaged and worn away by continuous traffic flow. In the winter they frequently iced up.

The modern technique for sensing vehicles uses an inductive loop set into the tarmac just below the surface. The only moving part now is the vehicle. The system relies on the fact that all vehicles are made of conducting metal and usually steel. A high-frequency current oscillates in the road coil. When the vehicle passes over the coil, the metalwork of the car or lorry represents a shorted secondary winding of an air-cored transformer (the coil in the road is the primary winding). Therefore energy is drained out of the coil circuit and this is detected to trigger the traffic light controller. The fact that the metalwork of the vehicle is also a magnetic material helps to concentrate the magnetic flux and increase the detection reliability. However the system does not work well for cyclists, unless they are prepared to get off their bicycles and lay them down flat on the road over the coil! (The flux linkage between the primary and the secondary coils in an air-cored transformer is proportional to the overlapping cross-sectional area.) Just as in the hem width sensor (chapter 3 (page 48)) and the swede topper (chapter 2 (page 24)), with many sensing systems there may be one type of product which cannot be catered for but provided this represents only a very small percentage of the total, the technique will be acceptable.

To calm the wrath of the cyclists (?) and to cope with portable traffic lights for road works, another type of sensor has been developed by Mullard Ltd. This is a transmitter and receiver, working at microwave frequencies, mounted in a suitably designed enclosure on top of each traffic light and pointing towards the oncoming traffic. The transmitted beam is so weak that it will not cause any harm but strong enough to be

reflected by any conductive object, even a human being. The ingenious sensor responds to changes in position of the oncoming object. A tiny part of the transmitted energy is diverted onto the receiver so that the reflected wave is mixed with the outgoing wave. If the object is moving, the frequency of the reflected wave will be shifted because of the Doppler effect and the resulting beat frequency, between the emitted and reflected waves, will be proportional to the object's speed. Although the microwave frequency is extremely high, the beat frequency conveniently lies within the audio spectrum and therefore can be easily amplified by common electronic components and circuits. The system can respond to a man approaching at two kilometres per hour at up to ten metres away! So the sensor will detect cyclists as well as all the other vehicles; it has no moving parts and does not need to be replaced every time the road is dug up. The only snag is that on temporary lights installed at roadworks, the microwave sensors so often seem to be pointing at the sky!

Vehicle sensors for traffic lights have evolved and taken advantage of developments in electronics. The number of moving parts used in the equipment has been gradually reduced with a corresponding improvement in reliability. All road users can now be catered for. The evolution through drum switching, timers, pneumatic wheel pressure switches, inductive loops and the Doppler microwave module indicates how the designers were able to think laterally and resist confining themselves to perfecting previous techniques.

7 More Facts about Sensing Elements

This chapter is meant to add a few details which were deliberately left out in the earlier chapters as such facts might have caused a distraction from the application being described. Even so it is not intended to explain the operation of semiconductors, such as transistors, using Solid State Physics but only to consider them in their simplest form as current controlled switches and amplifiers. For a more rigorous description, some references to other suitable books are provided in Further Reading (page 143) at the end of the book. The information given is therefore only intended to assist the reader to understand how the sensors and circuits describe previously operate and is not meant to be a comprehensive guide to all electronic sensors.

DIODE

The diode is primarily a rectifier which permits an easy flow of charge in one direction but restrains the flow in the opposite direction. Diodes can be made from a variety of materials but the most common one, used in modern electronics, is the silicon diode. When the diode is conducting a small voltage is sustained across it. This voltage will increase slightly as the current through the diode goes up. The volt/ampere characteristic looks like that given in figure 7.1.

The 'cut-in' voltage for a silicon diode is 0.6 volts and from there on the relationship obeys this equation, approximately:

$$I = I_0 (e^{eV/kT} - 1)$$

where I_0 is the reverse saturation leakage current, V is the voltage across the diode, k is a constant and T is the absolute temperature. When V is very small then $I = I_0$, and as V increases the current shoots up. Soon the -1 in the equation becomes insignificant and the equation can be considered in logarithmic form as

$$\ln I = \ln I_0 + kV \text{ [at constant temperature]}$$

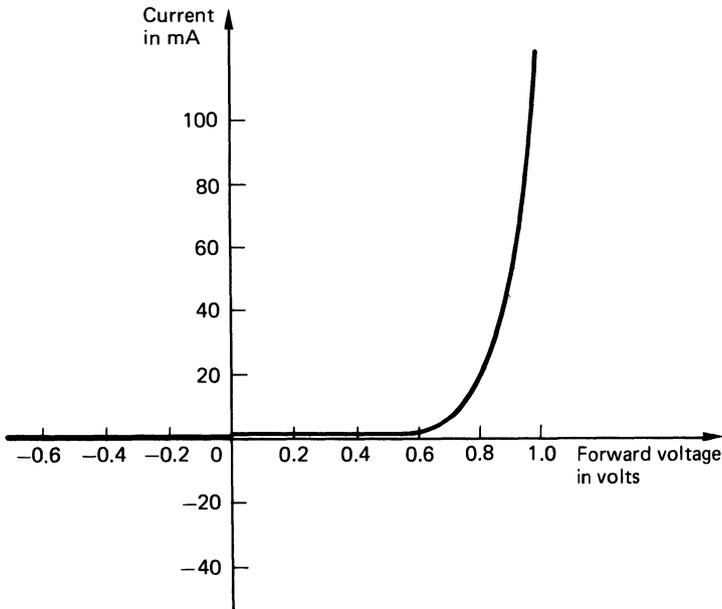
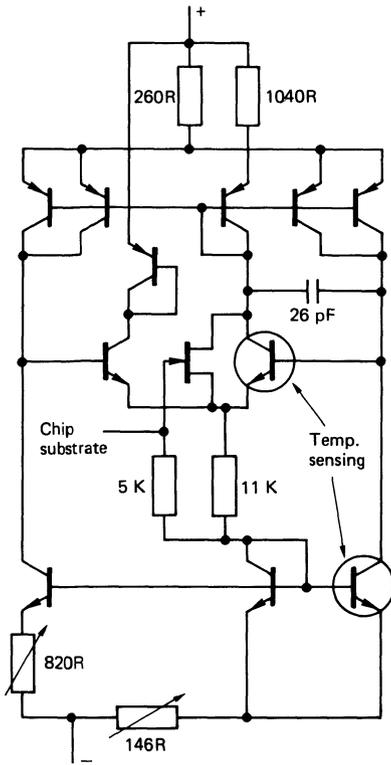


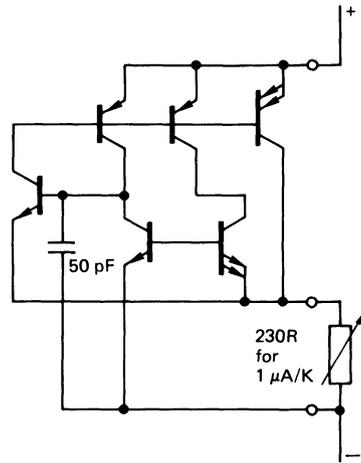
Figure 7.1 The volt/ampere characteristic of the silicon diode

Therefore for reasonable values of V , the diode can be used to produce a natural logarithmic characteristic. Although the plot of $\ln I$ against V produces a nice straight line for small currents, it starts to bend over at higher currents as the voltage drop, because of resistance in the diode, becomes more significant. However the exponential relationship between the voltage and the current can be exploited at low currents as has been demonstrated in some of the applications described.

The diode's temperature characteristic can also be used. The voltage across a silicon diode varies inversely with temperature by about -2.5 millivolts per $^{\circ}\text{C}$. As the base-emitter junction of a transistor is a forward-biased diode, the transistor exhibits a temperature characteristic as well. This effect is exploited in the temperature sensor mentioned in chapter 2 (page 22). In such a sensor, a circuit is devised in which two identical silicon transistors, situated in an integrated circuit, are operated at a constant ratio of collector current densities (r). The difference in their base-emitter voltages will be $(kT/e) (\ln r)$. As both k , Boltzmann's constant and e , the charge of an electron, are constant, the resulting voltage is directly proportional to absolute temperature. The circuits of figure 7.2 are of two makes of



(a) AD590 (Analog Devices)



(b) LM 334 (National Semiconductors)

Figure 7.2 Circuit diagrams of two temperature sensing circuits: (a) AD590 (Analog Devices); (b) LM334 (National Semiconductor)

remote temperature sensor which both produce a current directly proportional to absolute temperature. One has been calibrated at the factory with laser-trimmed resistors in it to give 1 microamp per K and the other requires an external variable resistor which is then set to give the current to temperature ratio required.

TRANSISTOR

Only the bipolar transistor has been mentioned in the previous chapters. There are two types of this silicon transistor, the *n-p-n* and the *p-n-p* (see figure 7.3). These letters refer to the construction of the transistor and

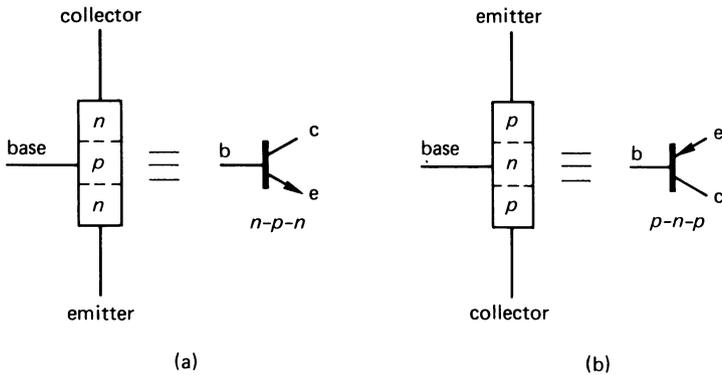


Figure 7.3 *Symbolic diagrams of transistors: (a) n-p-n; (b) p-n-p*

specify the type of doping applied to the internal layers. (Doping is the addition of minute amounts of impurities in pure silicon to create donor and acceptor atoms; *n*-regions have one type and *p*-regions have the other; the junction between a *p*-region and an *n*-region forms a diode.)

The middle layer is called the base and in the *n-p-n* transistor, when a small amount of current flows from the base to one of the *n*-regions, called the emitter, a much larger current is allowed to flow from the top *n*-region (the collector) through to the bottom one (the emitter). The reason why the names seem to be around the wrong way is because the electrons, being negatively charged, actually flow in the opposite direction to conventional current. The amplification ratio between the base current (I_b) and the collector current (I_c) is often labelled as h_{FE} . Therefore $I_c = h_{FE}I_b$ and as the base current and the collector current both emerge from the emitter, $I_e = I_b + I_c$. Because the base-emitter *p-n* junction represents a forward-biased diode, a voltage (V_{be}) of approximately 0.65 volts is required across it before any appreciable current will flow. If more than sufficient current flows into the base (I_c/h_{FE}) for a given collector current, then the transistor is said to be saturated and there will be a very low voltage between the collector and the emitter. (Surprisingly, this voltage (approximately 0.1 V) is much less than V_{be} .) When the transistor is used as a switch, it is usually provided with enough base current to ensure saturation so that the power dissipation in the transistor is minimised.

The *p-n-p* transistor works in the same way as the *n-p-n* transistor except that the currents flow in opposite directions. This description has left out many of the subtler characteristics of the transistor as there are many textbooks available which cover the transistor in great detail.

OPERATIONAL AMPLIFIERS

The operational amplifier (op-amp) is used to perform many mathematical functions and has become a basic building block for electronic systems (see figure 7.4). Within it are many transistors which combine together to provide a unit with a high, predictable amplification in a very small package. It is usually shown in symbolic form and the power supply connections are often omitted so as not to distract from the main circuit arrangement. Equal positive and negative supplies are usually required and the signal being operated upon is referred to 0 volts, being half way between the two supply rails. The output voltage range cannot exceed the supply voltages and usually can only reach about 90 per cent of either voltage.

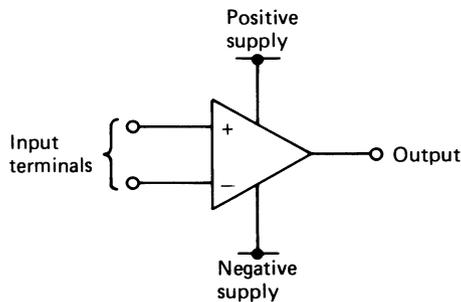


Figure 7.4 *Symbolic diagram of the operational amplifier*

The standard op-amp has two input terminals. If a voltage V_1 is applied to the positive terminal and the negative terminal is connected to 0 volts, then the amplification between the output V_0 and the input voltage V_1 will be positive (non-inverting).

$$\text{Amplification} = V_0/V_1$$

Alternatively, if the positive terminal is connected to 0 volts and a voltage V_2 is applied to the negative terminal, then the amplification (or voltage gain as it is sometimes called) will be negative (inverting).

$$\text{Amplification} = -V_0/V_2$$

If neither input is connected to 0 volts but they are connected to V_1 and V_2 , then the amplification will be proportional to the difference between the input voltages.

$$\text{Amplification} = V_0/(V_1 - V_2)$$

The operational amplifier is nearly always used with feedback around it. In simplest terms, when using feedback to the negative terminal, the operational amplifier always tries to keep the voltage between the two inputs to a minimum by changing the voltage on its output. The most straightforward case is the voltage follower (see figure 7.5) which has a wire connected from the output to the negative input.

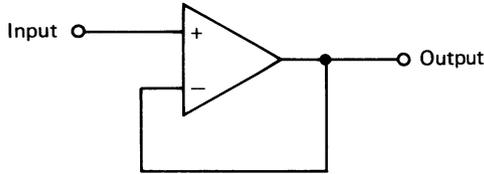


Figure 7.5 *The voltage follower*

As the voltage on the positive input increases, positive amplification causes the output to rise so that the negative input, which is directly connected to the output, also rises. But the output voltage will not go above the input one because the amplification would become negative. So the output follows the input voltage exactly and the amplifier keeps the voltage between the two input terminals to a minimum. At first sight this circuit may seem completely unnecessary but the resistance of an operational amplifier's input terminals is very high and the output of the op-amp can supply quite a few milliamps of current without its behaviour being affected. The circuit can therefore be used to monitor a voltage, say across a high value resistor, without drawing appreciable current from the resistor which might have affected the voltage being measured.

SUMMING AMPLIFIER

If the positive input terminal of an operational amplifier is connected to 0 volts and a resistor is connected from the output to the negative input terminal (negative-feedback), then the amplifier can be used to multiply or divide an incoming voltage by a fixed ratio. As the amplifier always tries to keep the two input terminals at the same voltage and in this case the positive terminal is earthed (0 volts), the negative input terminal will also be effectively at earth potential and so is known as a virtual earth. This concept is very useful when working out arrangements of components around the op-amp to carry out particular mathematical functions. For

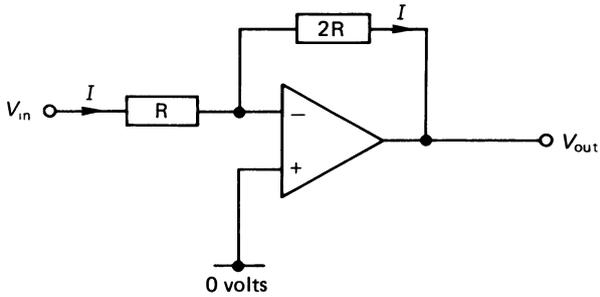


Figure 7.6 *Circuit for an amplification of -2*

instance, if the amplifier is to be used to double the incoming voltage, the circuit shown in figure 7.6 could be used.

It is important to remember that although the negative input terminal is almost at 0 volts, effectively no current will flow into it because of the very high input resistance. Therefore all the current flowing through the first resistor (R) will flow also through the second feedback resistor ($2R$). If the voltage across the first resistor is $+V$, then the voltage across the second resistor will be $-2V$.

$$V_{\text{in}} = IR, V_{\text{out}} = -2IR, \text{ therefore } V_{\text{out}} = -2V_{\text{in}}$$

The same effect can be produced without involving a change of sign at the output but the inputs are not held at 0 volts. However the amplifier still aims to keep the voltage between the two inputs to a minimum. The circuit looks like that given in figure 7.7.

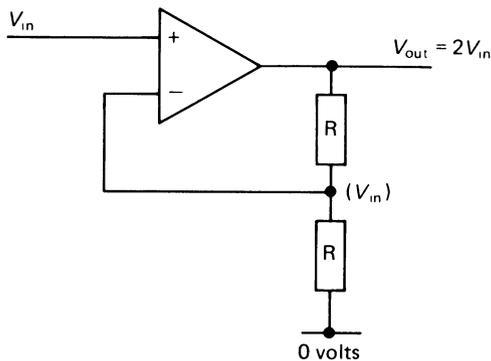


Figure 7.7 *Non-inverting amplifier with amplification of 2*

The first inverting version can be used to add or subtract signals. This is done by summing currents into the virtual earth. In the circuit of figure 7.8, the sum of the input currents must equal the feedback current.

Because the resistors all have the same value, then the output voltage will equal the sum of the input voltages except with a change of sign. If some of the input voltages are negative then a subtraction effect is produced for these inputs.

$$I_+ = I_1 + I_2 + I_3$$

$$\text{so } V_{\text{out}}/R = -(V_1/R + V_2/R + V_3/R)$$

$$\text{therefore } V_{\text{out}} = -(V_1 + V_2 + V_3)$$

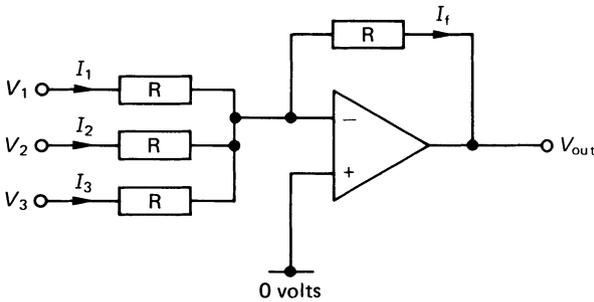


Figure 7.8 A summing amplifier

INTEGRATOR

By replacing the feedback resistor, shown in figure 7.8, with a capacitor, the circuit will perform the mathematical operation of integration (see figure 7.9).

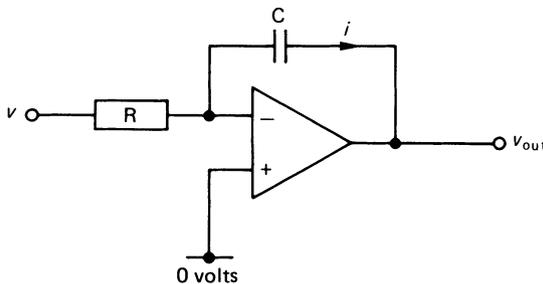


Figure 7.9 The integrator

The input current is constant because the op-amp creates a virtual earth at the negative input terminal and so the voltage across the input resistor is constant. Therefore a constant current flows into the capacitor. If Q is the charge and the current is i , then in a time interval t , as $Q = Cv$ and $Q = it$, the change in voltage at the output will be equal to it/C . Alternatively as $i = v/R$ then

$$v_{\text{out}} = \frac{-1}{C} \int i \, dt = \frac{-1}{RC} \int v \, dt$$

Such a circuit can be used to generate a ramp waveform which could be used in a voltage-controlled oscillator because the time taken for the ramp to reach a pre-set level will be controlled by the input voltage. Unlike a single resistor-capacitor network, the ramp is linear rather than exponential. The time-base generator in an oscilloscope uses this type of circuit to pull the spot across the screen repetitively at a constant rate.

DIFFERENTIATOR

If the resistor and the capacitor exchange places, then the circuit becomes a differentiator (see figure 7.10).

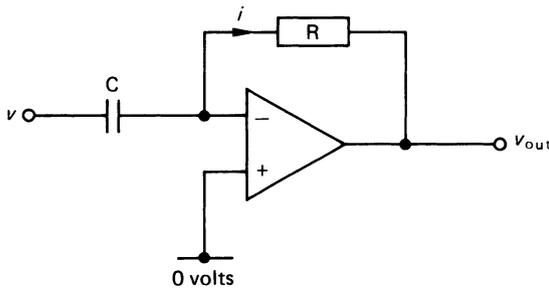


Figure 7.10 A differentiator circuit

$$i = C \, dv/dt, \text{ and so } v_{\text{out}} = -Ri = -RC \, dv/dt$$

Because the voltage across a capacitor cannot change instantaneously, a step change of voltage applied to the circuit will cause the output of the amplifier to move immediately to the positive or negative extreme. The output voltage will then ramp back to 0 volts at a rate set by the feedback resistor. This particular differentiation circuit is rarely used in practice because any small disturbance on the incoming line, such as the inevitable

electrical noise which will be present in any system, will be amplified enormously, obliterating the true signal. It is usually necessary to limit the response of the amplifier at high frequencies to minimise noise amplification.

COMPARATOR

The circuits mentioned above all use negative feedback – that is, the feedback component is connected from the output to the negative input terminal of the amplifier and the amplifier tries to minimise the difference in voltage between its input terminals. The comparator (see figure 7.11) uses positive feedback so that the output of the amplifier switches over rapidly as soon as the voltage difference between the input terminals changes sign.

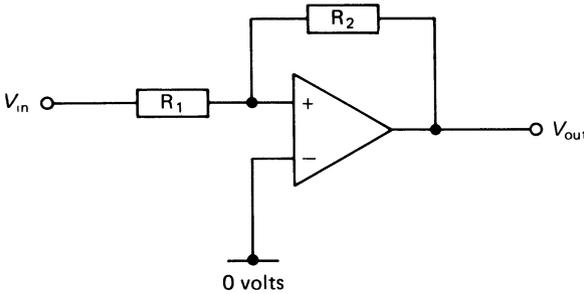


Figure 7.11 A comparator circuit using positive feedback

In the circuit, if the input voltage is slightly positive then the output voltage will be at the maximum positive voltage allowed by the power supply, because of positive amplification. Therefore the voltage on the positive terminal of the amplifier will be slightly higher than the input voltage to the circuit. If the input voltage is V_{in} and the output voltage is V_{out} , then

$$V_{+term} = V_{in} + [V_{out} - V_{in}] [R_1 / (R_1 + R_2)]$$

If the voltage on the input now descends and goes negative, no change will occur in the amplifier until the voltage difference between the input terminals changes sign. Therefore the change will only occur when

$$V_{+term} = V_{-term} = 0 \text{ volts}$$

$$\text{therefore } V_{in} = -iR_1 = -V_{out}R_1/R_2$$

This is a small negative voltage set by the ratios of the resistors. At this point the output voltage immediately switches from positive to negative. The positive terminal is therefore pulled down to a lower voltage than the input voltage. If the input voltage rises again, it will have to rise above zero before the comparator reverts to its previous state. For a circuit fed from symmetrical power supply rails, the switching point will be at a similar voltage above zero to the negative one. The difference between these two voltages is known as the hysteresis of the comparator and this hysteresis effect can be very useful in preventing false switching, due to noise, on a slowly changing signal. See figure 7.12.

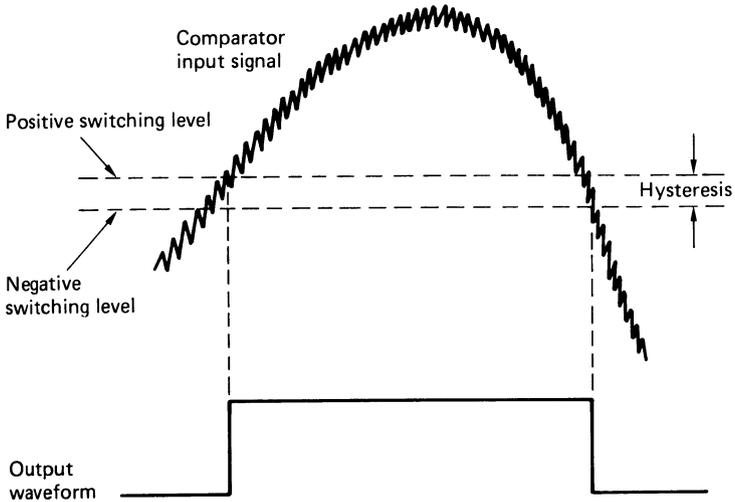


Figure 7.12 *How positive feedback can be used to avoid multiple output switching on noisy signals*

PEAK DETECTOR

Sometimes it is necessary for a circuit to follow the maximum value of a waveform or even to store the peak value reached over a certain time. This can be easily achieved by the operational amplifier circuit shown in figure 7.13.

The amplifier behaves like a voltage follower except that the diode prevents the capacitor discharging. Because of the feedback connection, the forward voltage across the diode is taken care of by the amplifier and

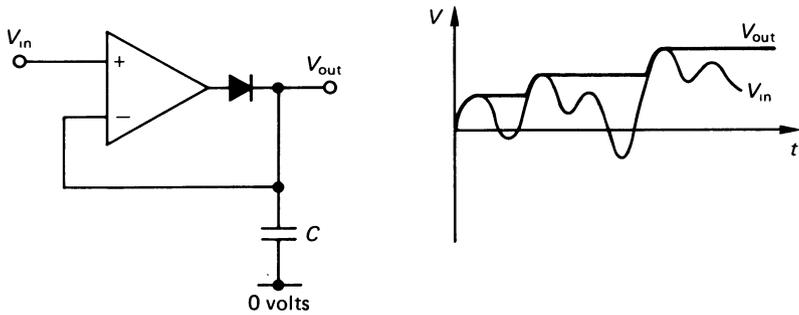


Figure 7.13 Peak detector circuit and illustrative waveform

does not affect the resulting output. When the input voltage exceeds the output voltage, the voltage at the positive terminal exceeds the voltage at the negative terminal and the output of the amplifier goes positive so that the diode conducts. The capacitor is then charged through the diode to the value of the input. To reset the circuit for another attempt, a mechanism for discharging the capacitor is required, such as a transistor used as a shorting switch. The circuit following should have a high impedance input.

SAMPLE AND HOLD CIRCUIT

A logical extension to the peak detector is the sample and hold circuit (see figure 7.14). There are a number of applications in which it is convenient to sample the current value from a waveform and store it temporarily. For

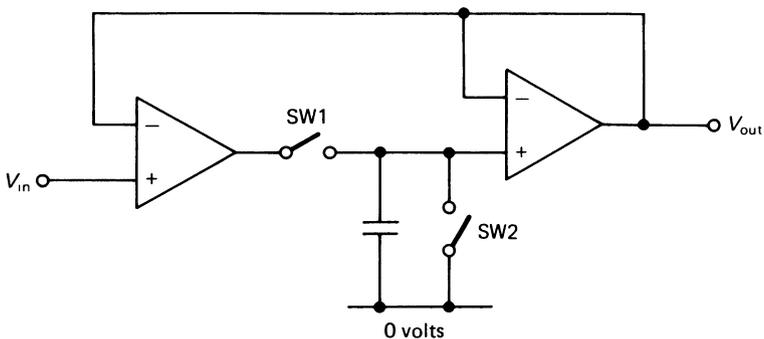


Figure 7.14 Sample and hold circuit

instance, in the pocket depth gauge mentioned in chapter 6 (page 100), the maximum extension of the probe is held while the information on the display may be recorded by the dentist (peak detector). The voltage coming from the sensor, when the gauge is at rest, is stored as well so that it may be subtracted from the reading when the probe is being used (sample and hold).

Figure 7.14 shows the simplest form of sample and hold circuit. Normally the switches would be solid-state versions but to ease the explanation, conventional switches are shown. If initially SW1 is open and SW2 is closed then the capacitor is discharged and because the second amplifier is a voltage follower, the output voltage from the circuit is at 0 volts. When a sample is to be taken, SW2 opens and SW1 closes. The capacitor is then charged in the appropriate direction until the output voltage and the input voltage, as compared by the first amplifier, are equal. The output impedance of the first amplifier and the size of the capacitor govern the time required for the new voltage to be reached. When the sampling period is complete, the switch SW1 opens but SW2 does not close. Because the second amplifier has a very high input resistance, the capacitor retains its charge and the output voltage from the second amplifier remains at the voltage selected during the sample period. Some leakage of charge will occur and this may be noticeable if the hold time is long. The size of the storage capacitor is always a compromise between making it small enough to charge fully during the sample period and large enough so that the leakage is insignificant during the hold period.

MODULATION TECHNIQUES FOR COPING WITH AMBIENT LIGHT

In the earlier chapters a couple of applications required circuits to eliminate the effects of ambient light. The simplest way is to use a transmission wavelength outside the normal visible range, such as in the near infra-red, and then to place a filter which is impervious to the visible wavelengths in front of the detector. This may work well for applications in which 'invisible' beam detection is appropriate, such as for machine guards and lift doors, but for colour measurement and for applications where the beam's position must be checked, it is not suitable.

A common solution offered is to switch the light source on and off rapidly and then subtract the amount of light measured during the 'off' time from the light present during the 'on' time. Modern light emitting diodes lend themselves to this technique very readily because they can respond almost instantaneously to changes in current. An oscillator is used to control the switching of the light source and, depending on the type of

detector circuit chosen, this switching signal may be used to regulate the receiver.

The system for inspecting graduation marks on a measuring tape, mentioned in chapter 4 (page 67), used the type of circuit shown in figure 7.15.

The signal from the receiving phototransistor is fed to two solid-state switches which are controlled by another 'clock' signal so that they turn on and off alternately. When S1 is on then S2 is off. S1 is on when the light emitting diode (LED) is illuminated and S2 is on when it is extinguished. The signal emerging from S2 then passes through an amplifier with an amplification of -1 (because the two resistors are equal). The final stage is a summing amplifier with an extra integrating capacitor around it. When the LED is on and S1 is closed, the phototransistor detects both the LED light and any other illumination falling upon it. The output of the summing amplifier gradually changes to an equal but opposite negative voltage to the incoming signal (because the feedback resistor and the input resistor to this amplifier are equal and the negative input terminal is used). When the LED goes off, the inverted output from the phototransistor is fed to the summing amplifier and the output gradually changes to a positive level equal to the light remaining when the LED is off. However the switching frequency of the light is very fast, so the capacitor averages out the transitions between the 'on' and 'off' states. The inversion of the 'off' signal means that this signal is subtracted from the 'on' signal to give a final negative result proportional to only the LED light. The values of the resistor and capacitor around the final amplifier have to be chosen so that the ripple due to the on/off cycle is minimal, but the total response of the circuit is not too slow to detect items passing between the LED and the phototransistor. Therefore using a high switching frequency is advantageous. The waveforms in this circuit have the form shown in figure 7.16.

There is another way of deciphering the modulated light signal which is slightly more complicated but does not need the synchronising 'clock' signal. This was used in the egg shell colour reflectometer described in chapter 5 (page 94), and the circuit could be used in applications where the LED transmitter and the receiver are a long way apart making it inconvenient for them to be connected together with a wire (for instance, across a farm gate). It works on the principle of first connecting the signal through a capacitor so that no DC component is present and the signal is therefore symmetrical about zero. Then the signal is half wave rectified and fed into a summing amplifier in a similar manner to the previous circuit. But the true signal is also fed in as well and so the same result as in the previous method is achieved. The circuit looks like that shown in figure 7.17.

The first amplifier is a half wave rectifier; it inverts the positive going signal but ignores the negative one. When the signal is positive the current

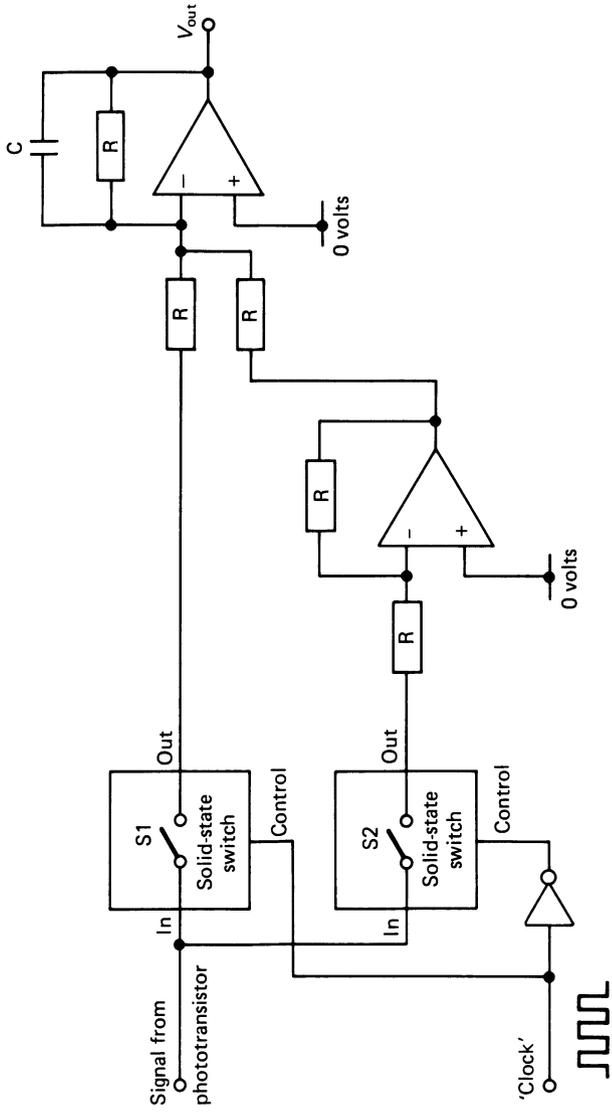


Figure 7.15 Switched or 'clocked' modulation circuit

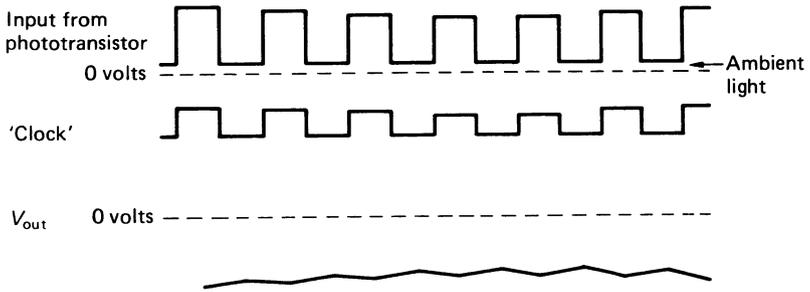


Figure 7.16 Waveforms for the circuit in figure 7.15

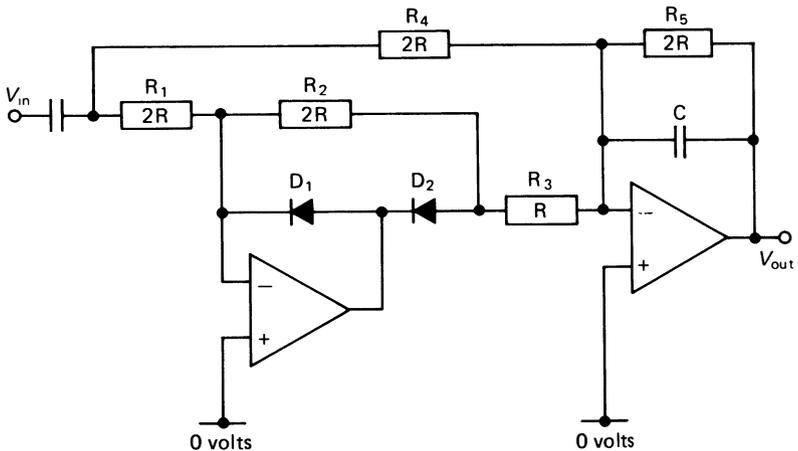


Figure 7.17 Rectifying modulation circuit

flows down through R_1 (to the virtual earth), then through R_2 and D_2 and into the output of the amplifier. Therefore, because the two resistors are equal, the voltage applied to R_3 is equal and opposite to the input voltage. When the incoming signal is negative, current flows from the output of the first amplifier through D_1 (to the virtual earth) and through R_1 to the input. Therefore the diode D_2 is reverse-biased because the other

end of R_2 is at 0 volts (the virtual earth) and the resistor R_3 is connected to 0 volts through R_2 .

The second amplifier produces an output proportional to just the combined LED light. For the positive half cycle the circuit conditions are (see figure 7.18):

$$V_{in}/2R - V_{in}/R + V_{out}/2R = 0$$

$$\text{therefore } V_{out} = V_{in}$$

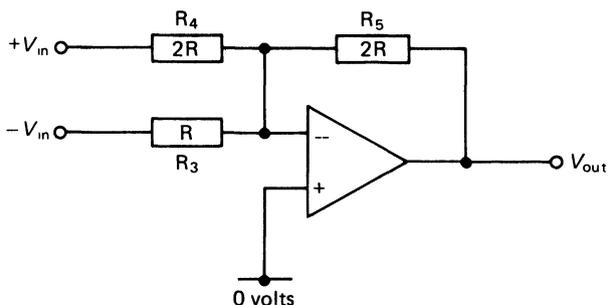


Figure 7.18 *Situation in the right-hand half of the circuit of figure 7.17 when the input is positive*

For the negative half cycle the circuit conditions are (see figure 7.19):

$$V_{in}/2R - V_{out}/2R = 0$$

$$\text{therefore } V_{out} = -V_{in}$$

The circuit will therefore produce a signal which is proportional to the light from the LED only. The capacitor is needed to eliminate the switching transitions.

THE LINE CAMERA

In a line camera the image of a scene is focused onto a linear array of photodiodes. There are a number of sizes available, from 64 up to 4096 diodes long. The longer arrays used charge coupled technology to transfer the information from the array but the description given here will be only for the smaller arrays. Each diode in the array has an inherent capacitance

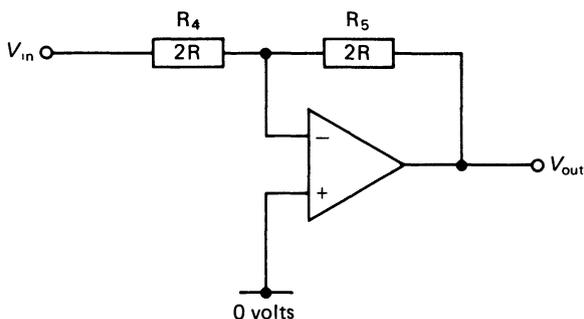


Figure 7.19 *Situation in the right-hand half of the circuit of figure 7.17 when the input is negative*

in parallel with it. The discharge rate of the capacitor is dependent on the diode reverse leakage current. This reverse leakage current is in turn dependent on the light intensity falling on the diode. See figure 7.20.

The diodes in the array are sequentially addressed by the propagation of a pulse signal through a shift register so that a voltage level, dependent on each diode capacitor, is available in serial form at the output. After the voltage across each diode has been read out, the diode is then temporarily connected to a negative recharging supply so that the light sensing process may recommence. The first scan pulse to be propagated through the register causes each diode in turn to be charged to the negative supply potential. During the period (defined as the integration time) before the next scan pulse, the diode loses an amount of charge proportional to the total amount of light received. During the next scan the voltage across each diode may be read out as explained above or the amount of charge required to recharge the diode may be measured externally as an alternative means of obtaining a light-dependent signal. This second method gives a slightly better responsivity from the diode array but the voltage sampling mode, used in the cherry stone sorter described in chapter 5 (page 81), allows the subtraction of the fixed background pattern from the present signal to be implemented.

The array may be scanned at different rates by altering the shift register clock frequency. If the rate is increased then the time available for accumulation of the image projected onto the array is shortened. This means that if the picture has to be taken rapidly (the object may be moving along on a conveyor) then the illumination of the object will have to be more intense. Conversely, if the light intensity is very low (as in fluorescence applications) then the scan rate has to be as slow as possible to allow for

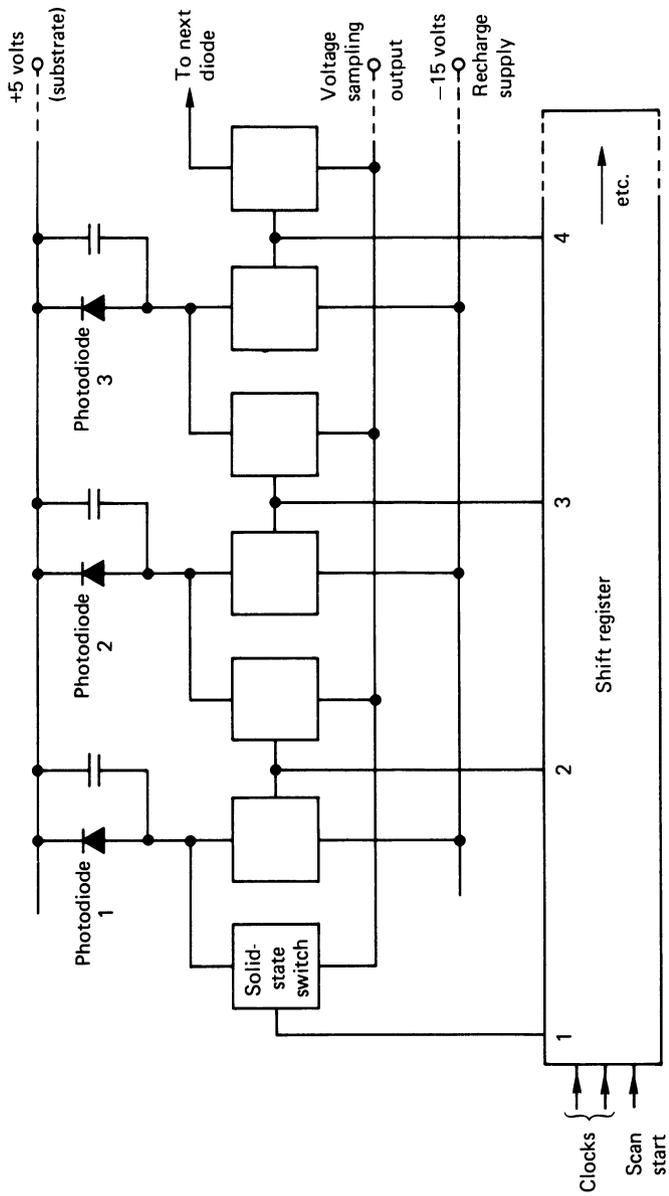


Figure 7.20 Schematic circuit diagram of photodiode line camera in voltage sampling mode

the maximum integration time. Unfortunately the residual leakage current, usually measured under dark conditions, also goes up with increased integration time so there is a limit on how slow the scan can take.

This chapter has only touched on a few of the many techniques available to an electronic engineer. There are many books describing the basic devices and potential applications. Most component data books usually have a number of application circuits adjacent to each device and some suggestions for further reading are given at the end of this book.

8 Conclusion

The applications of electronic sensors described in the previous chapters have come from a wide variety of sources, some in manufacturing industry, some in agriculture and others in medicine. These sources illustrate the extraordinary range of possibilities for electronic applications. One of the delights of being an electronic engineer is the daily contact with many interesting people from different disciplines and diverse backgrounds. Another delight is that a solution to one problem may well prove applicable in another apparently quite different area: it has been shown how a capacitance probe can be used to detect potatoes or felt tip pens; the electronic techniques needed to size potatoes or diamonds are almost identical.

In searching for a solution to a sensing problem, it is always essential to grasp how a process works in detail and to discover what its salient features are. It is very easy to make false assumptions right at the beginning which can then lead to major errors at a later date. One has to swallow one's pride and ask what may seem basic questions of those who know the process well so that the detailed requirements can be established. What is obvious to one person may not be to another and nothing may be taken for granted.

To help in the selection of a sensor, a list could be drawn up of all the types of electronic sensor. This would prevent the chance of one type being left out of consideration. This is fine if the possibilities are restricted to commercially available sensors used in the manner for which they are designed. However, some of the applications covered in this book have shown how unconventional use of a sensor can occasionally be the key to success. Even if a list were compiled of all the known applications of electronic sensors (and that would be enormous) it would still not be comprehensive as it would not allow for the inventive step which a human being is sometimes capable of making. The process of lateral thinking, which sidesteps the logical progression through a list of possibilities, cannot, by its very nature, be defined but is a vital part of seeking a solution to a sensing problem. Sometimes, as in the case of the fabric texture sensor (chapter 3 (page 51)), the searching for a suitable technique went through many

alternatives before returning to a solution quite closely related to the earlier ideas. In the case of the button crescent detector (chapter 3 (page 46)), the eventual solution was very different from the initial thoughts. In the cherry stone detecting system (chapter 5 (page 81)), the lateral thinking occurred right at the beginning by involving people in separate disciplines.

There are a number of common threads running through many of the applications mentioned in this book. The use of 'feedback' and the 'null-effect' always occur in operational amplifier circuits and have been described in types of weighing machine, pressure gauges and electrical power monitors. It is hoped by mentioning some practical applications, the power and elegance of this technique has been hinted at. This book has demonstrated how comparing the difference between two sensors to eliminate an unwanted effect, such as temperature or general variations in light intensity, can lead to a successful result in quite a few of the applications. Even comparing the response from a sensor temporally to distinguish changing features (crack detector – chapter 6, page 103) or to remove background effects, be they camera imperfections or ambient light penetration gave effective results.

Non-contact inspection is much preferred, especially in the food industry. The popularity of electronic cameras, with or without microcomputer image processing, stems from this. But simpler sensors, like the capacitance probe, the inductive loop and the microwave module, can be used very effectively in many non-contact applications at far lower cost. The amount of post-camera or post-phototransistor signal processing required can be minimised if the lighting and the general optical arrangement is optimised. This is often known as structured lighting. Examples were given in the sections about potato sizing (chapter 2 (page 16)) and finding cherry stones (chapter 5 (page 81)). If the difference between the wanted signal and all the other signals from the background must be in the ratio of about 4:1 to give a high standard of inspection reliability, then starting with the best signal from the initial sensing device is essential. The concept of looking for something added to, rather than missing from, the inspected scene was referred to in the section about crescent-shaped notches in buttons (chapter 3 (page 46)) but also applies to the cherry stone sorter (chapter 5 (page 81)) and the web break monitor (chapter 4 (page 61)). The Brazil nut fluorescence technique, as it was described in chapter 5 (page 85), would need to be built in a form in which the shell signal contrasted with the signal emanating from the conveyor in order to satisfy this concept.

Real applications of electronic sensors are numerous and only a very few have been described here. The potential for their use is enormous. I was tempted to put a list in this chapter of potential applications waiting for electronic sensor solutions as a challenge for the reader, but a mere

title for each would be quite inadequate. No explanation in a book will ever replace seeing the real thing. For any problem there will always be more than one solution and each will have its pros and cons. The steps described in the preceding chapters by which solutions were eventually reached, have illustrated ways in which sensor design can progress and some of the pitfalls awaiting the unwary. Hopefully the applications outlined in this book will illustrate, to those with a developing interest in Engineering, how problem solving can be approached when the engineer is equipped with a knowledge of the physical laws, a familiarity with available devices and an ability to think laterally.

Further Reading

Microelectronics, Millman and Grabel (McGraw-Hill)

The Art of Electronics, Horowitz and Hill (Cambridge University Press)

Lateral Thinking, Edward de Bono (Penguin Paperback)

The Burr-Brown Electronics Series (McGraw-Hill)

Operational Amplifiers, Tobey, Graeme and Huelsman

Applications of Operational Amplifiers, Graeme

Designing with Operational Amplifiers, Graeme

Function Circuits, Wong and Ott

Feedback Circuits and Operational Amplifiers, Horrocks D. H. (Van Nostrand Reinhold)

Electronic Components and Technology, Sangwine S. (Van Nostrand Reinhold)

Basic Electromagnetism and its Applications, Compton A.J. (Van Nostrand Reinhold)

Transducers and Interfacing, Bannister B. R. and Whitehead D. G. (Van Nostrand Reinhold)

Electronic System Design, Barnes J. R. (Prentice-Hall)

Engineering Instrumentation and Control, Haslam J. A., Summers G. R. and Williams D. (Edward Arnold)

The Open University text books for T291 on Instrumentation

The Institute of Physics publishes in their *Journal of Physics E: Scientific Instruments*, special editions on their two yearly conferences on Sensors and their Applications.

Index

- Absorption 6, 36
- Air jet 85
- Alarm 114-15
- Albumen 88-94
- Amplifier 12, 41, 47, 50, 109, 112, 120, 124-33, 135-6
- Analogue gate 66-7
- Angle measurement 31, 101-2
- Aspect ratio 19
- Autoclaved 100
- Auto-fluorescence 81-2, 85-6

- Battery 115, 117
- Beam splitter 4
- Bellows 29
- Boltzmann's constant 121
- Bottle filling 73-8, 86
- Bottle labelling 78-80
- Bourdon tube 29
- Bowl feeder 18, 47
- Brake 68
- Brazil nut 85, 141
- Brine 1

- Capacitance 2, 7, 8, 9, 35-6, 48, 70, 137
- Capacitance probe 8, 9, 10, 11, 35, 70, 72, 140-1
- Capacitor 1, 2, 3, 9, 41, 67, 71, 115, 127-8, 130-3, 137
- Carousel 79, 87-8
- Centre of gravity 47
- Ceramic 5, 6, 104
- Cherries 81-5, 137, 141
- Chiropody 97-9
- Cloth 48
- Cockle 48
- Combustion 113-14
- Communication 6

- Comparator 41, 47, 129-30
- Concave mirrors 4
- Condensation 62, 76
- Contra-rotating rollers 18-20
- Conveyor 4, 7, 9, 11, 75-6, 82, 85, 141
- Cooler 5
- Corrugated cardboard 57-62
- Counter 13, 38-40, 43-4, 59, 65, 71
- Crack 103-6, 141
- Crescents 46-7, 141
- Crisp 22, 27
- Crop spraying 29-33
- Cryometer 107-10
- Current transformer 111-13
- Cylindrical lens 4, 25, 76

- Diamonds 18-20, 140
- Difference measurement 49-50, 78, 83-4, 92, 96, 104, 106, 108, 124, 132-3, 137, 141
- Differentiating 104, 106, 118, 128
- Diffraction grating 4
- Digital voltmeter 88-9
- Diode 3, 4, 23, 32-3 41, 47, 82-4, 114-17, 120-2, 130-1, 135, 137
- Distance measurement 6, 49, 57-60, 70, 75, 88, 101
- Doctor blade 61-2
- Doppler effect 6, 119
- Drilling 35-6 42, 46
- Drinks 73-8
- Dyes 86-7

- Eggs 88-96
- Electrical noise 129

Electrical power measurement 111-13, 141
 Electron microscopy 107
 Emitter coupled oscillator 9
 Exponential 3, 32, 47, 120-1, 128

 Fabric texture 51-6, 140
 Farm 7, 14, 29
 Feedback 29, 112, 125-30, 133, 141
 Felt tip pens 72, 140
 Fibre lean 51-6
 Fluorescence 75, 81-8, 139, 141
 Fluorescent lamps 57, 62
 Food inspection 73-96, 141
 Force balance 29
 Frame store 104

 Half-silvered mirror 4
 Hall effect device 4, 112-13
 Heat 2, 5, 27
 Holes (buttons) 34-45
 Hopper 7, 9, 36
 Hydraulic ram 11, 24
 Hysteresis 130

 Ice crystals 107-8
 Image 4, 27, 43, 45, 68, 81, 103, 136, 141
 Impedance 7, 131-2
 Inductance 3, 118
 Inductor 2, 9, 141
 Infra-red light 132
 Integrated logic circuit 39
 Integration 127, 133, 137, 139

 K prism 45

 Lateral thinking 47, 119, 140-2
 Lens 4, 16, 18, 25, 43, 62, 68, 76
 Light emitting diode (LED) 9, 14, 17, 24, 29, 38-9, 41, 58, 63, 68, 94-6, 99, 132-3, 136
 Line array 4, 5, 18, 82, 101, 136-7
 Line camera 4, 16, 18, 27, 43-5, 62, 82-4, 105-6, 136-9
 Linear displacement transducer 3, 88
 Logarithmic amplifier 3, 47

 Magnet 29
 Magnetic flux 3, 4, 111-13, 118
 Magnetic reluctance 3, 63, 71, 112-13
 Make ready 68, 71
 Measuring tape 67-9
 Memory 82, 85, 109-10
 Microcomputer 19, 21-2, 110, 141
 Microprocessor 17, 42
 Microscope 107
 Microwave 6, 118-19, 141
 Mirror 4, 52
 Modulation 68, 96, 132
 Mutual inductance 3, 101

 Non-contact inspection 4, 29, 36--45, 52, 72, 81-8, 90-4, 103-6, 141
 Null effect 29, 112-13, 141

 Optical filters 4, 71, 81, 132
 Optical sensing 4, 49, 58-71, 76, 87, 92-4, 101-2, 105-6, 132-9
 Oscillator 8, 9, 118, 128, 132
 Oxygen monitor 113-14

 Pallet box filler 11
 Paper 57-72
 Peak demand 111
 Peak detector 130-2
 Peltier effect 5, 83
 Periodontal probe 99-102
 Permeability 112
 Pharmaceutical tablet 103-6
 Photodiode 3, 5, 16, 18, 19, 43-4, 62, 68, 94, 136
 Phototransistor 3, 14, 17, 24, 29, 36, 38-9, 41, 49-56, 58, 63, 71, 75-8, 87, 92, 101, 133, 141
 Piezoelectric effect 5, 6, 47
 Pixels 103
 Platinum resistance 6, 22, 24
 Pneumatics 18, 118
 Potato grading 7-13, 141
 Potato storage 21-4
 Potentiometer 9, 49, 88, 101
 Pressure 29, 141

Printing 27, 63-71
 Prism 4, 45
 Proximity 2, 7, 9, 35, 108
 Pulse generator 39
 Punch 46
 Pyroelectric 6

Rate of cooling measurement
 107-10
 Rayleigh scattering 91
 Receiver 75, 105, 118-19, 133
 Record player cartridge 6, 47, 52
 Rectification 120, 133
 Reflective opto-sensor 58-60,
 65-6, 79-80
 Registration 63, 65-8, 71
 Reluctance 3, 63, 71, 112-13
 Resistance 1, 2, 22-3, 27, 29, 66,
 88-9, 98, 114, 121, 125
 Resistor 1, 2, 67, 83, 88, 111-12,
 114-17, 122, 125-30, 133,
 135-6
 Resonance 3, 6
 Roller table 12, 15-18
 Rotation 38, 45, 47, 52-6, 71,
 87-8, 90, 101, 104-5

Salt 1
 Sample and hold 131-2
 Sampling 23, 110, 137
 Security 114, 117
 Seebeck effect 5
 Semiconductor 3, 120
 Sewing hems 48-51
 Shadow observation 49
 Shaft encoder 63, 85
 Shell colour reflectometer 94-6,
 133
 Shift register 85, 137
 Ship 1
 Shirt buttons 34-48
 Sizing 13-20, 24-6, 73
 Slotted opto-switch 17, 42, 65-7
 Soft fruit 81
 Solid state switch 66, 132-3
 Sorting 14, 42, 44
 Sound 6, 47, 52, 75-6, 114-17
 Spark 6
 Spectrum 36-8, 91, 119
 Specular reflection 20, 94

Speed control 11, 58
 Speed measurement 26, 31, 63
 Sprocket 17
 Strain gauge 6, 27-9
 Structured lighting 141
 Sugar 22
 Summing 125-7, 133
 Superheterodyne detection 9
 Surveyor's tape 67-9
 Swedes 24-6

Tachometers 63
 Tachoratiometer 63, 71
 Tangent 31-3
 Television 4, 16, 18, 45, 81, 104
 Temperature 2, 5, 21-4, 28-9,
 63, 76, 84, 88, 90, 97-8, 100,
 108-11, 120-2, 141
 Tension control 63
 Texture measurement 51-6
 Thermistor 2, 22, 98
 Thermocouple 5, 6, 22-3, 83,
 108-10
 Thermometer 21
 Thermoplastic 97
 Threshold 50, 78, 84, 106, 115
 Tiles 104
 Toe nails 97-8
 Tooth 99
 Tractor 24, 26, 29-31
 Traffic lights 118-19
 Transducer 75, 104
 Transformer 3, 111-12, 118
 Transistor 2, 3, 9, 115, 120-4,
 131
 Transmitter 75, 105, 118, 133
 Triboelectric effect 12

Ultrasonic 6, 75-6, 91, 104-5
 Ultra-violet light 75, 87-8

Vane 101-2
 Velvet 51-6
 Virtual earth 125, 127-8, 135-6
 Voltage follower 125, 130
 Volume measurement 17

Wastage 68-71
 Web break detector 61-2, 141

Weighing 14, 27-9, 73, 75, 88,
141
Wheatstone bridge 23,29

X-rays 81

Zero crossing detection 59-60