AN INSTRUMENTATION SYSTEM FOR THE MEASUREMENT AND DISPLAY OF THE DYNAMIC FORCE DISTRIBUTION UNDER THE FOOT DURING LOCOMOTION

by

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ABSTRACT

The clinical assessment of the weight bearing foot during locomotion is normally based on subjective judgement rather than on quantitative measurement. The techniques which have been proposed for recording the dynamic forces acting on the foot are either too complex for clinical practise or there is difficulty in relating the measured force distribution to the physical surface of the foot. The system that has been developed measures the vertical foot/ground forces during gait and immediately displays the data in a manner which can be readily assimilated.

The instrumentation system consists of a segmented force plate constructed from 16 transparent beams mounted so that the total load as well as the centre of pressure on any beam can be ascertained. When the foot contacts the plate, its plantar surface is photographed through the transparent force plate by a television camera while a second television camera photographs a lateral aspect of the legs and feet.

A composite video display is then generated consisting of (i) a lateral view of the legs and feet (ii) a view of the plantar surface of the planted foot with centre of pressure lines superimposed (iii) a bar chart display of the load carried by each beam.

The system output is recorded on a video tape recorder which has a stop motion facility. This enables a frame by frame analysis to be made subsequently and selected stills to be photographed as a permanent record. Three series of photographs are presented which clearly show the differences between normal and abnormal gait.

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CHAPTER 1

INTRODUCTION

The foot is a complex mechanical structure of twenty-six bones which, braced by associated muscles and ligaments, can carry full body weight and the dynamic forces imposed by gait, yet contour itself to all types of terrain. (See Appendix A)

Although studies of the biomechanics of locomotion can be traced back as far as Aristotle and Leonardo da Vinci, the foot has been traditionally viewed as a static tripod or at best a semi-rigid support for body weight. In this conception, the weight-bearing legs of the tripod were assumed to contact the ground at the heel and the first and fifth metatarsal heads, while the integrity of the tripod was supposedly maintained by the longitudinal and lateral arches of the foot. This traditional viewpoint loses sight of the fact that the foot has evolved primarily for walking and must be studied as a dynamic mechanism which forms an integral part of the human locomotor system. The body requires a flexible foot to accommodate the variations in the external environment, a semi-rigid foot which can act as a spring and lever arm for the push off during gait, and a rigid foot to enable body weight to be carried with reasonable stability.

The normal gait or walking cycle can conveniently be divided into two distinct phases: the stance phase, during which the foot is weight bearing, and the swing phase during which the limb is swinging forward. The swing phase is concerned with preparing and aligning the foot for heel strike and also ensuring that the swinging foot clears the ground. The stance phase, which occupies about 60% of the total gait cycle, is concerned with weight bearing and body stability.

The clinical assessment and analysis of the abnormal or diseased weight bearing foot is usually based on the subjective judgement of a physician or surgeon. Although anatomical abnormalities are often apparent at examination, the accurate assessment of an abnormality of function is more difficult, particularly if the malfunction is only apparent under dynamic loading conditions. Also the increased professionalism in sport and the growth of running and jogging in the wider population has caused a dramatic increase in sporting injuries to the foot over recent years, stimulating a greater interest in the analysis of foot function.

The numerous studies into the biomechanics of locomotion reported in the literature have tended to concentrate on the lower limb (particularly the resolution of gait forces through the hip and knee) and the foot has been rather ignored. Most of these studies use monitoring systems consisting of a floor mounted force plate together with high speed cine or television cameras. Synchronous recordings of the forces applied by the foot to the plate and high speed film records of the position of the limbs in space allow the forces acting through the segment of interest to be computed for any instant in the stance phase. Consequently the biomechanics of limb motion is now well understood.

Unfortunately an analysis of the biomechanics of foot function is almost impossible using a system of this type, as it is difficult to see the subtle movements occurring in the foot during the stance phase and therefore difficult to relate the gross reaction forces measured by the plate to specific anatomical sites on the foot. A better approach is to record the dynamic interface force distribution over the plantar surface of the foot and relate this force distribution to the spatial position of the weight bearing and swinging legs.

Attempts to measure the foot/ground interface pressures for diagnostic purposes stretch back as far as the nineteenth century. An early researcher in this field was Beely (1882) who attempted to relate interface pressures with the depth of a foot impression in a thin bag filled with plaster of paris. Later researchers such as Elftman (1934) and Morton (1935) used the deformability of rubber projections on a walk-path mat to measure localised loads. A similar method has been proposed recently, although here an optical technique is used to display the localised loads as a set of circular interference fringes (Arcan and Brull, 1974). All of these methods allow an easily assimilated visual display of the loading patterns on the standing foot to be displayed, however the rapidly changing loading patterns produced during gait make data recording and interpretation very difficult.

In order to reduce the data handling problems, some investigators have measured the load on various strips of the foot by using a number of parallel load measuring beams set into a walkway (Hutton and Drabble 1972), or by attaching pressure transducers to selected anatomical sites on the sole of the bare foot (Schwartz and Heath 1949) or by mounting the transducers in specially constructed shoes (Holden and Muncy 1953).

Although these techniques reduce the amount of data produced, the interpretation of these measurements is extremely difficult as there is no longer a visual display of the loading pattern, making it difficult to relate the measured loads to the physical surface of the foot.

All of the above techniques are rather awkward to use and are therefore suitable for research only with little application in day-to-day clinical routine. The novel instrumentation system described in this thesis is intended for clinical use and uses a combination of parallel load measuring beams with the addition of two television cameras to record visual information. The results of the load measurements are processed and combined with the visual images to produce a complete and easily interpreted visual display.

CHAPTER 2

INSTRUMENTATION SYSTEM DESIGN

The intention of this research was to design and construct an instrumentation system which would measure the dynamic force distribution acting on the plantar surface of the foot during the stance phase of gait with adequate spatial and temporal resolution. In order that this information be clinically useful, it is essential that the data obtained from these measurements be presented in such a way that they may be simply interpreted by medical personnel.

2.1 SYSTEM DESCRIPTION - GENERAL

During the stance phase of gait, the foot is subjected to one vertical and two in-plane components of force as well as associated torques and moments. The vertical component is the largest of the linear forces acting on the foot during gait (Paul 1967) and it was therefore decided that the instrumentation system could be greatly simplified by measuring this component only, without seriously degrading the recorded data.

The force measuring apparatus consists of a segmented force plate comprising a number of transparent beams mounted in a walkway transverse to the direction of walking. Each end of each beam is supported by a force transducer in order to measure the vertical reaction forces there as shown in figure 2.1.a.

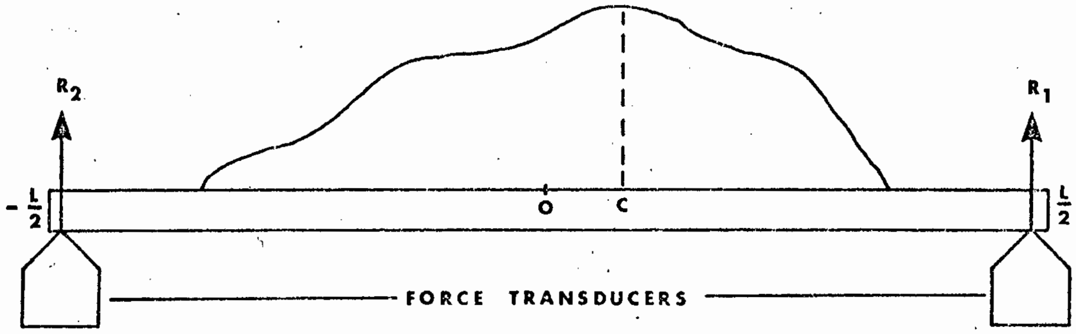


Figure 2. 1. a   Schematic diagram of single force plate beam.

Consider a vertical force distribution over the beam. The total vertical force downwards is clearly equal to $R_1 + R_2$. In Appendix B it is shown that the position of the centre of moment of the vertical force distribution is given by C, where

$$C = \tfrac{1}{2}L\ (R_1 - R_2)/(R_1 + R_2)$$

This implies that the given vertical force distribution is equivalent to a single force of magnitude $R_1 + R_2$ acting vertically downwards at C.

In this way it is possible to ascertain not only the total vertical force on any beam but also the point of application of that force.

Two television camera are used in conjunction with the force plate system to provide simultaneous visual data. When the foot contacts the force plate, its plantar surface is photographed through the transparent beams by camera 1 beneath the plate while its lateral aspect and the position of the swinging leg is photographed by camera 2 mounted adjacent to the walkway. The arrangement of the force plate and cameras is shown in figure 2. 1. b.

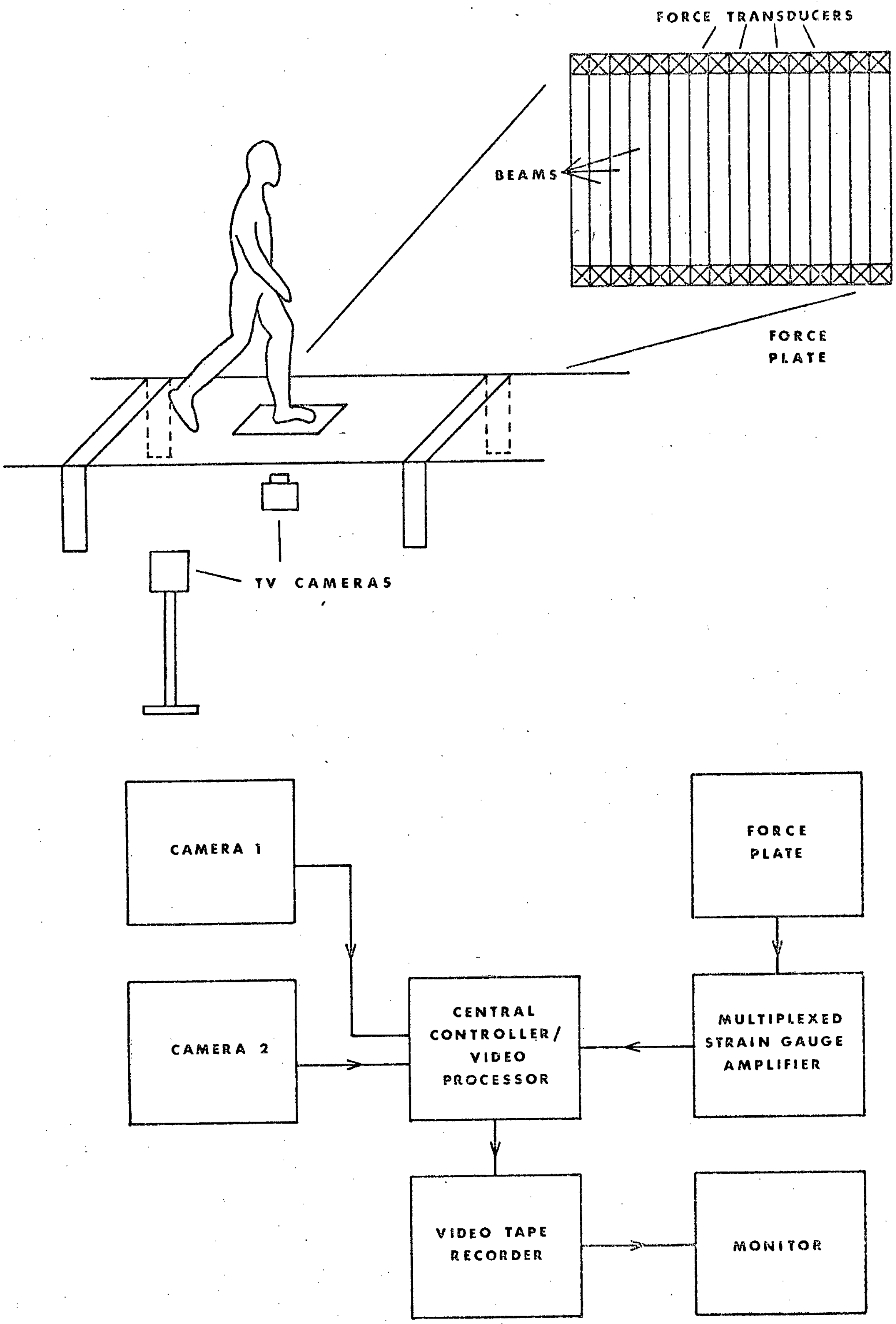


Figure 2.1.b General system configuration.

The outputs from the force transducers and television cameras are, by means of the multiplexed strain gauge amplifier and central controller/ video processor, used to generate a composite video picture on a television monitor which shows (i) a lateral view of the planted foot and swinging leg, (ii) a view of the plantar surface of the weight bearing foot showing the boundaries between the beams with lines of centre of pressure superimposed, (iii) a bar chart type display of the load carried by each beam.

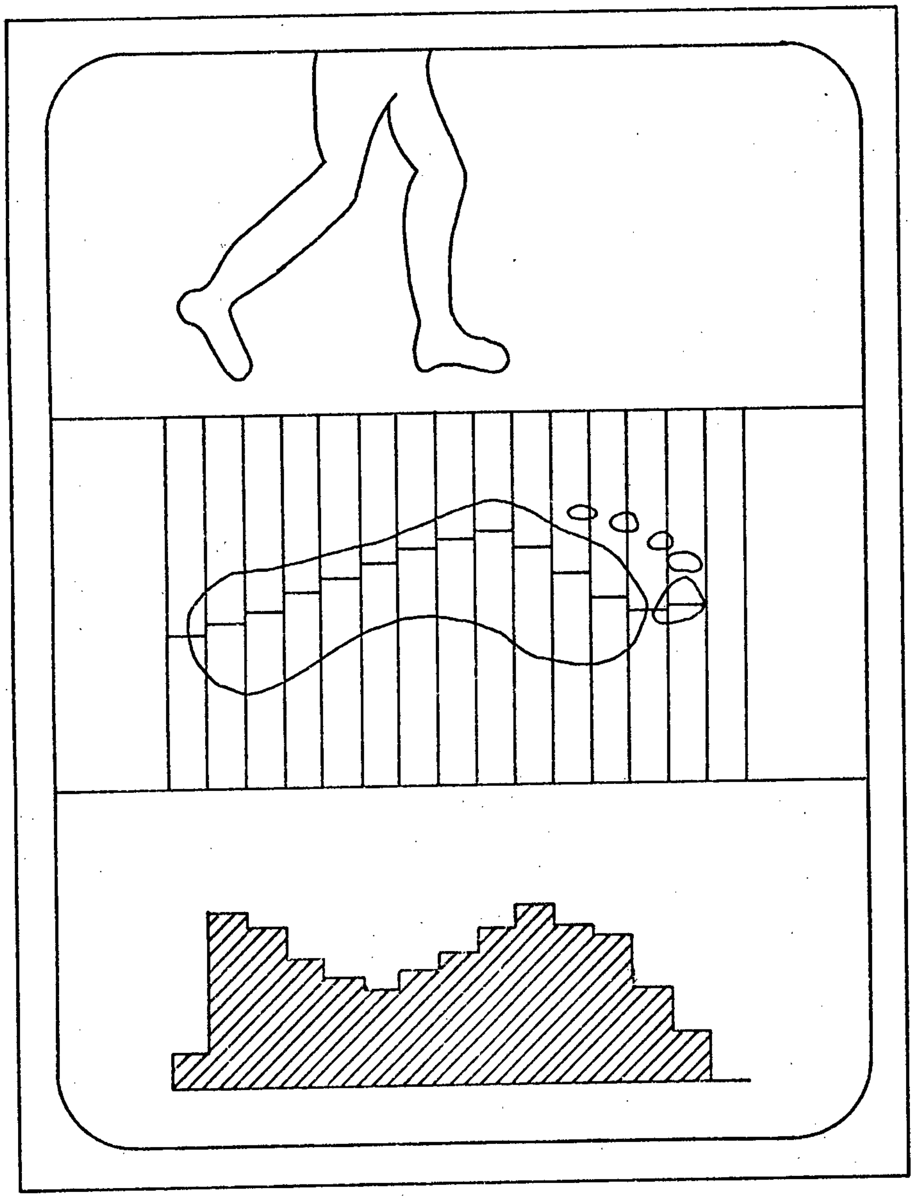


Figure 2.1.c System output.

A schematic representation of the output of the system at an instant in the stance phase is shown in figure 2.1.c . When a load is applied to a beam, the magnitude of the load is reflected by the height of the respective bar in the bar chart. The centre of pressure of the load on the beam is superimposed upon the image of the beam and thus upon the image of the plantar surface of the foot as an electronically generated white line. A lateral shift of load is therefore reflected as a lateral shift in the centre of pressure lines relative to the foot, while a longitudinal shift of load (i.e. from hind foot to forefoot) will be shown as a change in the shape of the bar chart display. It is possible to see at a glance not only the magnitude of the load carried by different section of the foot, but also the pattern of loading applied to the plantar surface. Quantitative results can be obtained by calibrating the bar chart.

The output of the system is recorded on a video tape recorder which has a "stills" facility thus enabling a frame by frame analysis to be made subsequently and selected stills to be photographed as a permanent record.

The television monitor and both cameras are operated on their side so that the electron beam in the monitor now scans its lines from bottom to top and its fields from left to right. This simplifies matters considerably as the visual image of each beam, together with its associated section of bar chart and centre of pressure line, is drawn sequentially by the monitor during a complete field scan.

In order to produce this type of composite video pictures it is necessary that the two cameras be synchronised. In addition, the multiplexer of the strain gauge amplifier is synchronised with the cameras so that while camera 1 is visually scanning a force plate beam, the strain gauge amplifier measures the force at each end of that beam in order to generate the section of bar chart and centre of pressure line corresponding to that beam.

Since the multiplexer is synchronised with the cameras, the sampling rate for the force transducers is dictated by the 50 Hz field frequency of the television system. One complete field is produced every 20 msec during which period each force transducer output is sampled once.

With the monitor on its side, the electron beam scans at a fixed rate from bottom to top across the monitor screen making it relatively simple to produce the bar chart by generating a white level video signal from some fixed time after the start of a line and for a period proportional to the total load on a force plate beam. Similarly the centre of pressure lines are produced by generating a white level video signal of very short duration at a time determined by the relative magnitudes of the forces at each end of the beam.

Camera 2 is not directly associated with the force measuring system, its function being to record any additional visual information. In this arrangement it photographs the subject from the side as the swinging leg provides a convenient timing reference within the gait cycle.

2.2 THE SEGMENTED FORCE PLATE

2.2.1 Mechanical details

The segmented force plate consists of a number of parallel transparent beams supported at each end by a force transducer. The force plate must be large enough to accommodate the average sized foot, consist of beams narrow enough to provide sufficient spatial resolution and yet comprise a minimum number of beams in order to reduce the cost and complexity of the force plate and associated electronics. In addition, the force plate must be stiff enough to appear as a flat surface to the foot to avoid altering the loading pattern. High transducer stiffness is also required so that the natural resonant frequency of the beams be high in comparison to the frequency components of the applied loads to avoid mechanical amplification of certain of these components due to resonances. The beams must nevertheless be capable of resolving small changes in load.

The force plate consists of 16 transparent 'Perspex' beams, each 260 mm long, 20 mm wide and 25 mm thick. Allowing a small gap of 1 mm between beams to avoid cross-talk, this gives a total force plate area of 335 mm long and 260 mm wide. This is large enough to accommodate the average sized foot while even a child's foot will span at least 10 beams thus dividing the foot into at least 10 sections which gives sufficient spatial resolution for clinical data. 16 beams are used in the plate construction as this simplifies the electronics somewhat by virtue of the fact that 16 is a power of 2.

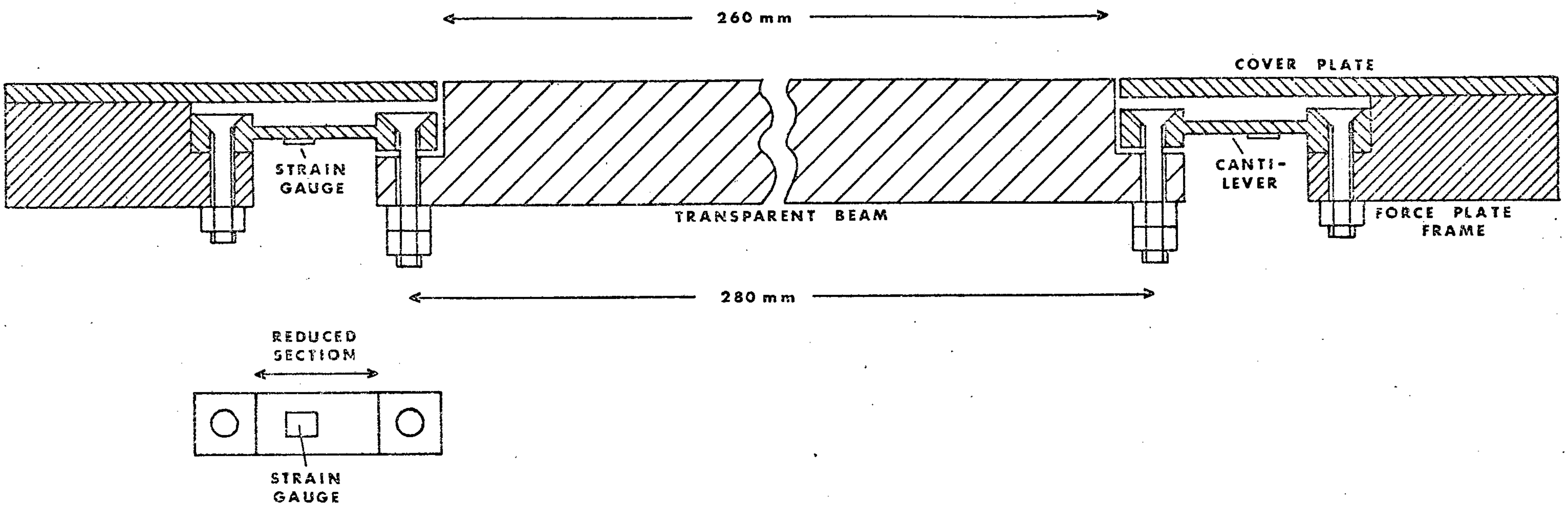


Figure 2.2.a Cross-section through a force plate beam and associated force transducers.

The general construction of a single beam and associated force transducers is shown in figure 2. 2. a.

The force transducers consist of strain gauged stainless steel cantilevers. The load applied to a beam produces a force at each end which tends to bend the cantilevers. Most of this bending takes place over the reduced section of the cantilever, the maximum surface strain in bending occurring at a distance of 1/3 of the length of the reduced section from the fixed end. As the strain gauge experiences a strain directly proportional to the force at the end of the cantilever, the transducer can be calibrated to give force data although, due to inaccuracies in the machining of the cantilevers and in the positioning of the strain gauges, the sensitivities of the transducers are not all the same.

The stainless steel chosen for the cantilevers has a nominal elastic limit of 2000 micro-strains ($\mu\varepsilon$). In order to avoid permanent set in the cantilevers it was necessary to choose the cantilevers dimensions so that under normal operating conditions, this elastic limit is not exceeded.

The plate was designed for children with a body mass of up to 50 kg. This mass corresponds, statically, to a foot/ground reaction force of about 500 newtons. During locomotion, however, this force may be as large as three times its static value (Paul 1967). Each force transducer is therefore designed to withstand a force of 400N without permanent set. The mechanical sensitivity of each cantilever is then 2000$\mu\varepsilon$ for 400N or 5$\mu\varepsilon$/N. Each beam can therefore support a nominal load of 800N at its centre without transducer damage.

A point load of 100 newtons at the centre of a beam produces a displacement of 0,4mm, which was considered small enough to minimize modification to the foot/plate loading pattern. This displacement is due almost entirely to the bending of the beam and not the cantilevers. The natural resonant frequency of the beam was measured to be about 300 Hz, which is considered adequate for gait studies (Hutton and Drabble 1972).

2.2.2 Electrical details

Each of the 32 force transducers consists of a single foil type strain gauge bonded to a stainless steel cantilever, and a dummy resistor. The circuit, as shown in figure 2.2.b was chosen for its simplicity of construction, low cost and the fact that, as the system measures dynamic forces, long term drift is unimportant.

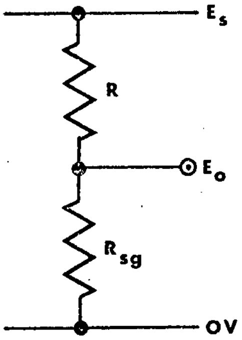


Figure 2.2.b Force transducer circuit diagram.

In Appendix C it is shown that for a given supply voltage E_s, dummy resistor R and strain gauge resistance R_{sg}, the output voltage E_o is given by the relation

$$E_o = E_s R_{sg}/(R + R_{sg})$$

and the variation of this voltage for small changes in the resistance of the dummy resistor and/or strain gauge is given by

$$\Delta E_o = E_o(1 - E_o/E_s)(\Delta R_{sg}/R_{sg} - \Delta R/R)$$

For a given strain gauge voltage E_o, the sensitivity is maximised by maximising E_s. Thus for $E_s \gg E_o$

$$\Delta E_o \doteqdot E_o(\Delta R_{sg}/R_{sg} - \Delta R/R)$$

which is the same sensitivity as a bridge configuration using two strain gauges, one in compression, the other in tension as derived in Appendix C.

In practice, however, E_s cannot be made too large as this increases the power dissipated in the dummy resistor to a point where the self-heating causes its resistance drift to be unacceptably large. The final design therefore uses $E_s = 5V$, $R = 510\Omega$ and $R_{sg} = 120\Omega$.

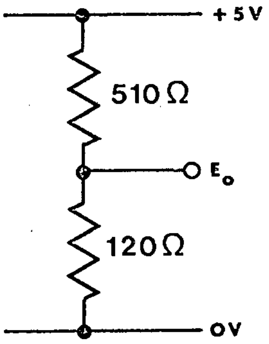


Figure 2.2.c Force transducer circuit used.

$$E_o = E_s R_{sg} / (R + R_{sg})$$

$$= 5 \times 120 / (510 + 120)$$

$$= 0.952V$$

$$\Delta E_o = E_o (1 - E_o/E_s) (\Delta R_{sg}/R_{sg} - \Delta R/R)$$

$$= 0.952 (1 - 0.952/5) (\Delta R_{sg}/R_{sg} - \Delta R/R)$$

$$= 0.771 (\Delta R_{sg}/R_{sg} - \Delta R/R)$$

In this circuit $(1 - E_o/E_s)$ is equal to 0.81 which means that it has a sensitivity of 81% of its maximum theoretical value.

The strain gauges used are Kyowa gauges, type KFC-5-C1-11, which have a gauge factor of 2.10. The electrical output of the complete cantilever/strain gauge force transducer is given by

$$\begin{aligned} \Delta E_o &= 0.771\,\Delta R_{sg}/R_{sg} \\ &= 0.771 \times \text{gauge factor} \times \text{strain} \\ &= 0.771 \times 2.10 \times \text{mechanical sensitivity of cantilever} \\ &= 0.771 \times 2.10 \times 5\mu\varepsilon/N \\ &= 8.1 \times 10^{-6} \text{ volts/newton} \\ &= 8.1\ \mu V/N \end{aligned}$$

There are 32 of these force transducers plus a similar circuit in which the strain gauge is bonded not to a cantilever but to the steel frame of the force plate. This circuit is used as a reference for all the force transducers.

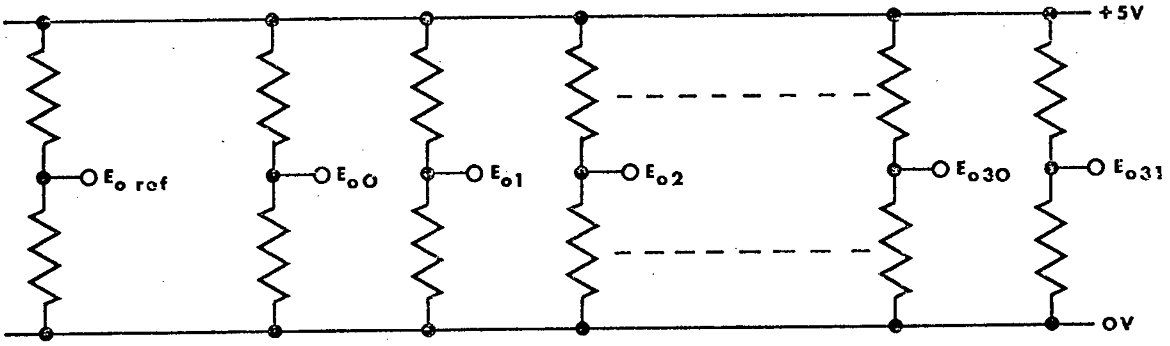


Figure 2.2.d Force plate circuit diagram.

Consider the offset voltage between the reference circuit and any selected force transducer.

Ideally, with no load on the force transducer, the offset voltage E_{os} should be zero. However, due to the tolerances of the resistance of the dummy resistors and strain gauges, this will seldom, if ever, be the case.

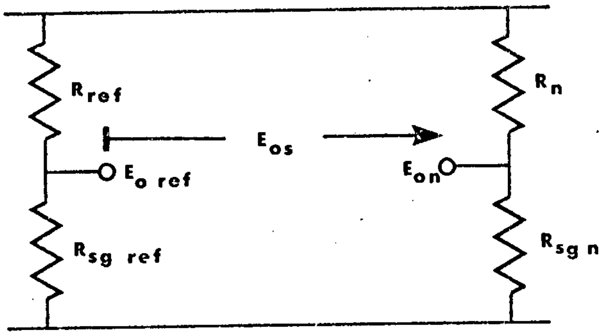


Figure 2.2.e Force transducer offset voltage.

$$E_{os} = E_{on} - E_{oref}$$

$$= E_o(1 - E_o/E_s)\,(\Delta R_{sgn}/R_{sgn} - \Delta R_n/R_n - \Delta R_{sgref}/R_{sgref} + \Delta R_{ref}/R_{ref})$$

The worst case offset occurs when the resistance errors are at their respective maxima and the signs of these errors are such that they add together

$$E_{osmax} = 0.771\,(|\Delta R_{sgn}/R_{sgn}|\,max + |\Delta R_n/R_n|\,max + |\Delta R_{sgref}/R_{sgref}|\,max + |\Delta R_{ref}/R_{ref}|\,max)$$

The dummy resistors have a tolerance of 1% and the strain gauges 0,25%.

$$E_{osmax} = 0.771\,(0.0025 + 0.01 + 0.0025 + 0.01)$$

$$= 1.93 \times 10^{-2} V$$

$$= 19.3\ mV\ .$$

The maximum offset voltage between the reference circuit and any force transducer or between any two force transducers is therefore 19.3mV.

2.2.3 Summary

The force plate consists of 16 parallel transparent beams making up a force sensitive area of 260 mm by 335 mm. The natural resonant frequency of the beams together with their associated cantilevers is approximately 300 Hz and their stiffness such that a 100 newton point load at the centre of a beam produces a 0.4 mm deflection. Each of the 32 force transducers can support a maximum load of 400 newtons and has a nominal sensitivity of 8.1 μV/N when energised by a 5V supply. The maximum offset between the reference circuit and any of the force transducers is 19.3mV.

2.3 THE STRAIN GAUGE AMPLIFIER

2.3.1 Basic requirements

The multiplexed strain gauge amplifier is required to be capable of energising the force transducers, of selecting a particular transducer and producing an output voltage which is directly proportional to the force exerted on that transducer.

In order to eliminate the tedious job of manually balancing each strain gauge bridge before use, the strain gauge amplifier must incorporate an automatic bridge balancing circuit which, when activiated, will balance the selected channel. Thus before a test, with the force plate unloaded, each channel can be selected and balanced. This selection and balancing routine is performed by the central controller/video processor (See section 2.4).

In addition, as the force transducers have slightly different sensitivities, it is necessary to have some means of scaling each channel in order to standardise the output from each transducer.

2.3.2 Block diagram

The block diagram of the multiplexed strain gauge amplifier is shown in figure 2.3.a. Although the force plate has only 16 beams and hence 32 force transducers, the amplifier is designed as a 64 channel unit so that the number of beams can be increased to a maximum of 32 in order to produce a longer force plate and/or greater spatial resolution, should this be desired.

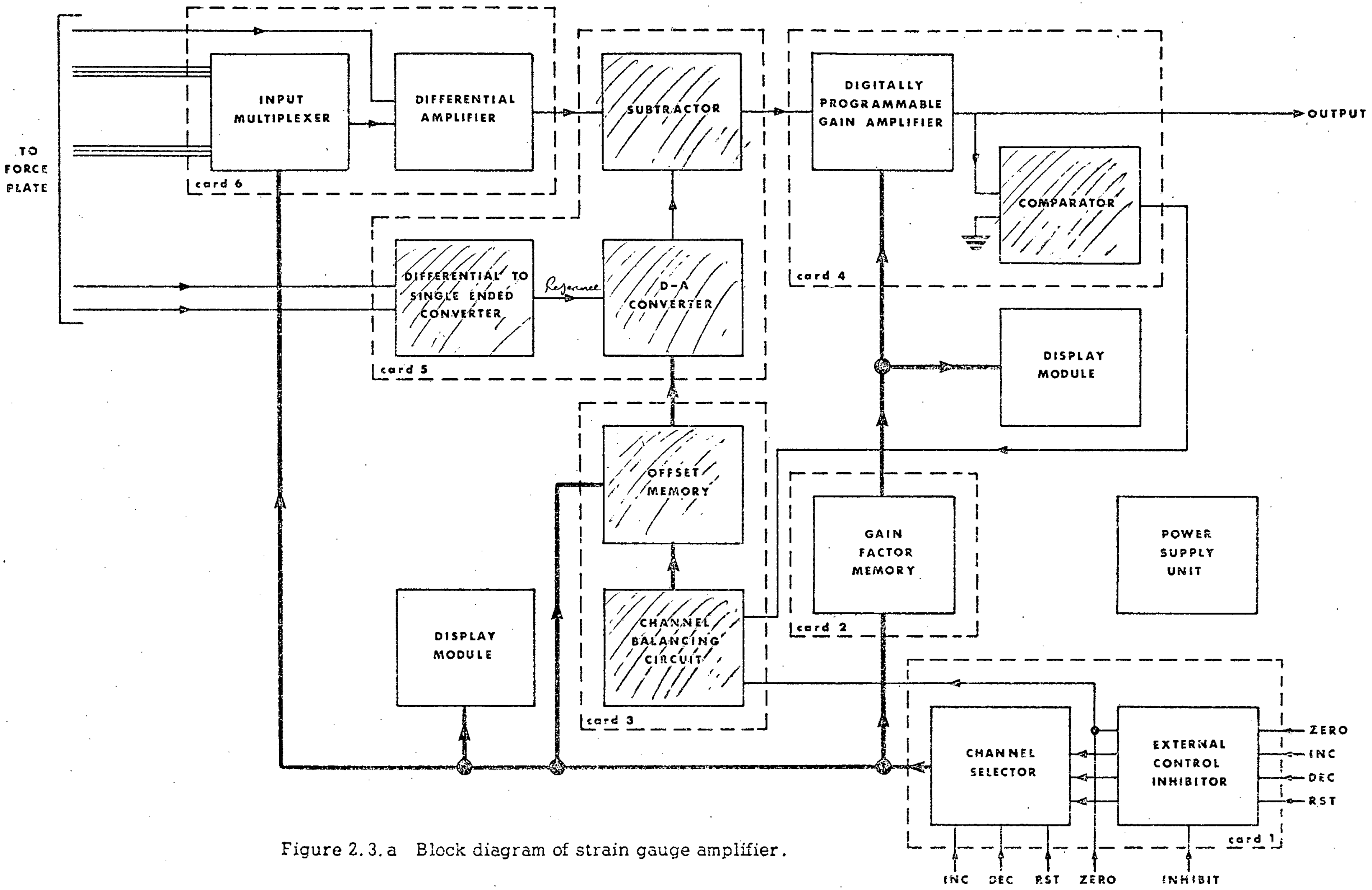


Figure 2.3.a Block diagram of strain gauge amplifier.

The operation of the complete strain gauge amplifier may best be understood by considering each block in figure 2.3.a in turn.

The POWER SUPPLY UNIT provides the necessary power for the electronics as well as a separate 5V supply for the strain gauge force transducers.

The CHANNEL SELECTOR is a 6-bit binary up/down counter which may be reset to zero, incremented or decremented. These instructions may come from front panel switches or from the external control inputs.

The EXTERNAL CONTROL INHIBITOR may be used to disable all four external control inputs by means of a front panel switch when the amplifier is to be used manually only.

The INPUT MULTIPLEXER, under the control of the channel selector, feeds the output of the required force transducer to the input of the differential amplifier.

The DIFFERENTIAL AMPLIFIER amplifies the output from the selected force transducer.

The OFFSET MEMORY is a 64 x 16 bit random access memory which contains a digitally stored voltage for each channel which corresponds to the offset from that channel's force transducer.

The DIFFERENTIAL TO SINGLE ENDED CONVERTER senses the strain gauge bridge energising voltage at the force plate and converts it to a ground referenced potential which is used as the reference for the D - A converter.

The D - A CONVERTER produces an output voltage digitally stored in the offset memory which corresponds to the offset from the selected force transducer.

The SUBTRACTOR subtracts the output of the D - A converter from the differential amplifier output.

The GAIN FACTOR MEMORY is a 64 x 6 bit read only memory which contains a scaling factor for each channel to standardise the outputs from the force transducers.

The DIGITALLY PROGRAMMABLE GAIN AMPLIFIER, under the control of the gain factor memory, scales the output from the selected force transducer to a standard sensitivity.

The COMPARATOR senses the output voltage and produces a single bit output whose state depends on whether the output voltage is positive or negative.

The CHANNEL BALANCING CIRCUIT is a 16-bit successive approximation register which zeros the amplifier output by driving the D - A converter to produce a voltage equal to the output of the differential amplifier. The 16-bit word required to do this is stored in the offset memory.

The DISPLAY MODULES accept a 6-bit binary input and produce a corresponding two digit display. Two of these units are used, one to display the number of the channel selected and the other to display the gain factor of that channel.

2.3.3 The differential amplifier

The differential amplifier used is a conventional instrumentation amplifier configuration using three operational amplifiers as shown in figure 2.3.b. The dual amplifier first stage is a high input impedance differential input amplifier which also has a differential output. The second stage is a differential to single ended converter or subtractor.

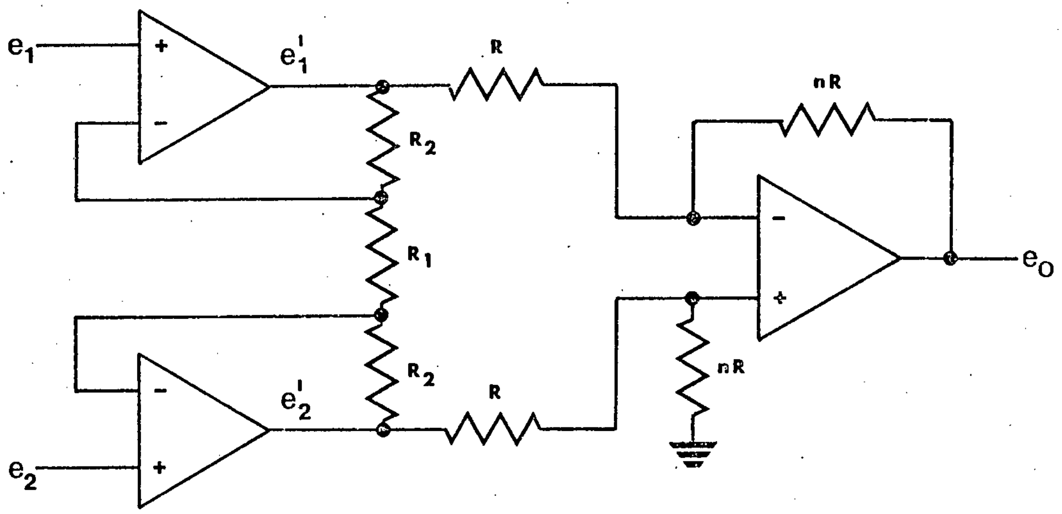


Figure 2.3.b Differential amplifier circuit diagram.

Assuming that the operational amplifiers have zero input current and zero input offset voltage, the output voltages e_1', e_2' and e_o are given by

$$e_1' = (1 + R_2/R_1)\, e_1 - R_2/R_1\, e_2$$

$$e_2' = (1 + R_2/R_1)\, e_2 - R_2/R_1\, e_1$$

$$e_1' - e_2' = (1 + 2R_2/R_1)\, (e_1 - e_2)$$

$$e_o = n\,(e_2' - e_1') = n\,(1 + 2R_2/R_1)\, (e_2 - e_1)$$

The first stage has a gain of $G_1 = 1 + 2R_2/R_1$ and the second stage a gain of $G_2 = n$.

2.3.3.1 Noise considerations. From a noise point of view, each operational amplifier may be replaced by a noise free amplifier and an equivalent noise voltage source as shown in figure 2.3.c. As the source resistances are low, the effects of current noise are minimal and have therefore been ignored.

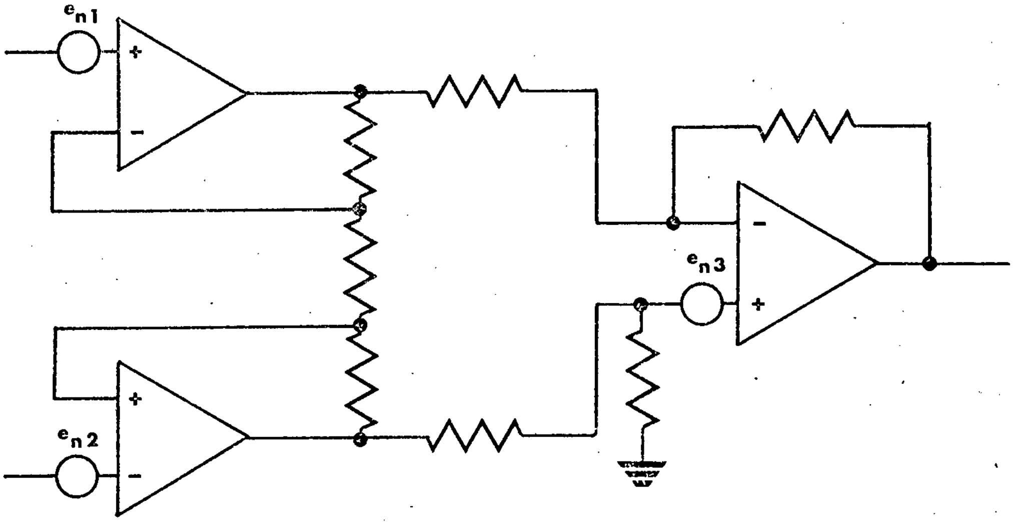


Figure 2.3.c Differential amplifier noise sources.

With a first stage gain of G_1 and a second stage gain of G_2, the output noise voltage due to the noise sources e_{n1}, e_{n2} and e_{n3} are $e_{n1}G_1G_2$, $e_{n2}G_1G_2$ and $e_{n3}(1 + G_2)$ respectively. Since the noise sources are uncorrelated, the total output noise voltage is the square root of the sum of the squares of the individual output noise voltages.

$$e_{no} = \left((e_{n1}G_1G_2)^2 + (e_{n2}G_1G_2)^2 + (e_{n3}(1 + G_2))^2 \right)^{\frac{1}{2}}$$

For a given total gain of G_1G_2, it will be seen that the output noise voltage may be minimised by maximising G_1 and minimising G_2. There are, however, two possible limitations to the increase of G_1. Firstly, the offset voltage between the reference circuit and the selected force transducer combined with a large value of G_1 may saturate one or both of the input operational amplifiers. Secondly, as each of the operational amplifiers has a fixed gain-bandwidth product, increasing the gain reduces the bandwidth accordingly which increases the amplifier settling time.

2.3.3.2 Gain requirements. In order to prevent the amplifier from saturating with the combined offset voltage and signal from the selected force transducer, it is necessary to limit the gain of the differential amplifier.

Since the amplifier operates from ± 15V supply rails, the output should be limited to nominally ± 10V. As shown in section 2.2.2, the maximum offset between the reference circuit and any selected force transducer is 19.3mV. The sensitivity of the force transducers is 8.1 µV/N with a maximum force limit of 400 newtons. The maximum possible input to the amplifier is therefore

$$19.3\text{mV} + 400 \times 8.1\ \mu\text{V} = 22.5\text{mV}$$

It therefore follows that

$$22.5\text{mV} \times G_1 G_2 \leq 10\text{V}$$

$$G_1 G_2 \leq 444$$

It is also necessary to limit G_1 to prevent either of the two input operational amplifiers from saturating.

$$e_1' = (1 + R_2/R_1)\, e_1 - R_2/R_1\, e_2$$

$$= e_1 + R_2/R_1\, (e_1 - e_2)$$

$$e_2' = (1 + R_2/R_1)\, e_2 - R_2/R_1\, e_1$$

$$= e_2 + R_2/R_1\, (e_2 - e_1)$$

Both e_1' and e_2' must always be in the ± 10V range. Since e_1 and e_2 are both nominally 1V and $e_1 - e_2$ is a maximum of 22.5mV,

$$1 + R_2/R_1 \times 22.5\text{mV} \leq 10\text{V}$$

$$R_2/R_1 \leq 400$$

$$G_1 = 1 + 2R_2/R_1 \leq 801$$

2.3.3.3 Bandwidth requirements. As is shown in section 2.4.6, the inter-sample time is 3 or 4 television line periods of 64μsec each. The shortest inter-sample time is therefore 3 x 64μsec = 192μsec. For a force plate using more than the 16 beams used here, the inter-sample time will be reduced accordingly.

As shown in section 2.2.2, the maximum offset between the reference circuit and any force transducer is 19.3mV. Similarly, the maximum offset between any two force transducers is also 19.3mV. If the smallest force to be resolved is 0.5N and the force transducer output is 8.1 μV per newton, it is necessary to measure the force transducer output with a precision of 4 μV.

Consider the situation as the input multiplexer switches from one transducer to another and encounters the maximum offset of 19.3mV. In order to resolve the required 4 μV, the amplifier must settle to an accuracy of 4 μV/19.3mV = 2×10^{-4} or 0.02%. The first stage of the differential amplifier behaves as a first order low pass filter so that the output of this first stage in response to a step input will be of the form $1 - e^{-\omega t}$ where ω is the break point frequency of the low pass filter. If the first stage of the amplifier is to settle in, say, 50 μsec then

$$\exp(-\omega \times 5 \times 10^{-5}) = 2 \times 10^{-4}$$

$$\omega = 1.7 \times 10^{5} \text{ rads/sec}$$

$$\text{or } f = 27 \text{ kHz}$$

In practise, however, due to the switching transients introduced by the complementary metal-oxide-semiconductor (CMOS) multiplexer, it is necessary to increase the bandwidth to 90 kHz to obtain the required settling time.

The two operational amplifiers used in the first stage of the differential amplifier are OP-07's, selected for their low noise and low drift characteristics, which have a gain bandwidth product of 1.0 MHz. By choosing $R_2 = 10R_1$, each amplifier has a gain of 11 thus producing the required 90 kHz bandwidth and a total first stage gain of 21.

The OP-07 operational amplifiers have an equivalent noise input voltage of 10 nanovolts per root hertz. The equivalent noise input voltage from each operational amplifier is therefore

$$10 \times 10^{-9} \times (90 \times 10^{3})^{\frac{1}{2}} = 3\,\mu\text{V}$$

The total equivalent input noise voltage due to both operational amplifiers is therefore $\sqrt{2} \times 3\ \mu V = 4.2\ \mu V$. This noise source is, by far, the dominant one in the complete strain gauge amplifier so that all others may be ignored.

The second stage gain G_2 is set at 10 by letting $n = 10$. The total gain of the differential amplifier is therefore $21 \times 10 = 210$ which limits its output to the range $\pm 22.5\text{mV} \times 210 = \pm 4.7\text{V}$.

The complete circuit diagram of the differential amplifier as well as that of input multiplexer is given in Appendix I.

2.3.4 The automatic bridge balancing circuitry

Referring to the strain gauge amplifier block diagram, figure 2.3.a, the automatic bridge balancing circuitry comprises the offset memory, the differential to single ended converter, the D - A converter, the subtractor, the comparator and the channel balancing circuit.

When a force transducer is selected by the channel selector, that transducer's output is fed to the differential amplifier input by the input multiplexer. Both the offset and the signal due to the load on the force transducer are amplified. The channel selector output is also used to address the offset memory and so recall a 16-bit word corresponding to the offset of that channel. The D - A converter reconstructs that digitally stored voltage which is then subtracted from the differential amplifier output. The resulting signal is then due to the load on the force transducer only.

2.3.5 The digital to analogue converter

As shown in section 2.2.2, the input offset voltage may be as large as ± 19.3mV and the force transducer output only 8.1μV/N. After being amplified by the differential amplifier which has a gain of 210, the offset range is ± 4.1V and the output due to the force transducer is 1.7mV/N.

In order to remove the offset so as to measure the force transducer output to a precision of better than half a newton it is necessary to generate a voltage in the range of ± 4.1V with a precision of 0.85mV. This represents a required resolution of 1 part in 10^4. Using a conventional D - A converter, this would require a 14 bit device ($2^{14} = 16384$) with its attendant high cost.

In this application there is no need for monotonicity in the D - A converter output nor is it necessary that any output voltage be related to one and only one digital code. All that is required is that the D - A converter output be capable of taking on any output voltage over its range with a precision of better than 1 part in 10^4.

The D - A converter used is based on the principle of the conventional R - 2R ladder network as shown in figure 2.3.d. The resistance at any node is 2R looking to the left, the right or towards the switch. The current supplied by any switch is halved at each node as it flows towards the operational amplifier input. In this way the requisite binary weighting of currents is achieved.

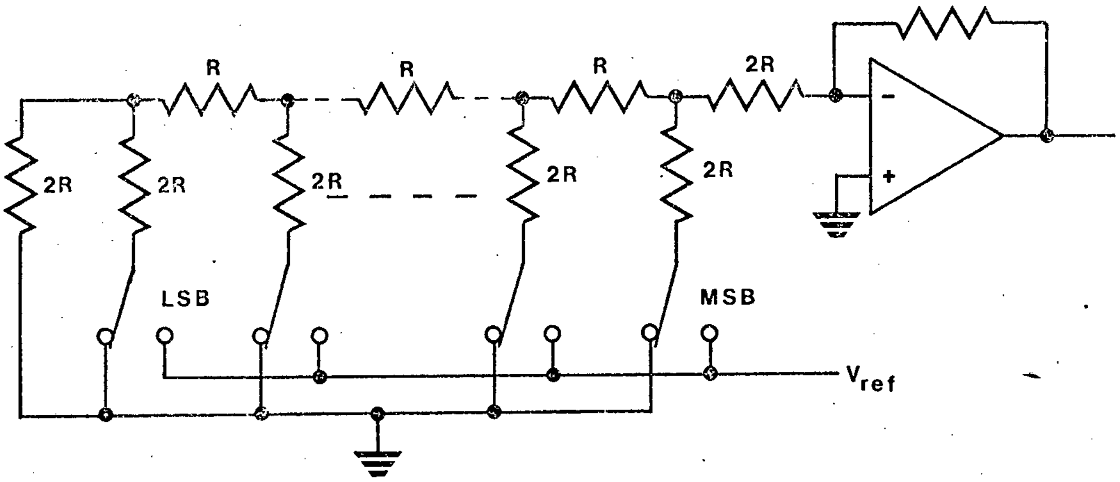


Figure 2.3.d D - A converter using R - 2R ladder network.

Consider a 14-bit D - A converter using this technique where the least significant bit produces an output of 1mV at the operational amplifier output. The outputs corresponding to each of the bits are tabulated below.

bit	0	-	1mV	bit	7	-	128mV
bit	1	-	2mV	bit	8	-	256mV
bit	2	-	4mV	bit	9	-	512mV
bit	3	-	8mV	bit	10	-	1.024V
bit	4	-	16mV	bit	11	-	2.048V
bit	5	-	32mV	bit	12	-	4.096V
bit	6	-	64mV	bit	13	-	8.192V

This D - A converter can produce any voltage in the range OV to 16.383V in 1mV steps. Consider the effect on the output if bit 12, say, has a small error and instead of producing an output of 4.096V produces an output of 4.094V.

MSB Digital input LSB	Analogue output
0 0 0 0 0 0 0 0 0 0 0 0 0 0	0.000V
0 0 0 0 0 0 0 0 0 0 0 0 0 1	0.001V
0 0 1 1 1 1 1 1 1 1 1 1 1 0	4.094V
0 0 1 1 1 1 1 1 1 1 1 1 1 1	4.095V
0 1 0 0 0 0 0 0 0 0 0 0 0 0	4.094V
0 1 0 0 0 0 0 0 0 0 0 0 0 1	4.095V
0 1 0 0 0 0 0 0 0 0 0 0 0 0	4.096V
0 1 1 1 1 1 1 1 1 1 1 1 1 0	8.188V
0 1 1 1 1 1 1 1 1 1 1 1 1 1	8.189V
1 0 0 0 0 0 0 0 0 0 0 0 0 0	8.192V
1 0 0 0 0 0 0 0 0 0 0 0 0 1	8.193V
1 1 1 1 1 1 1 1 1 1 1 1 1 1	16.381V

Note that the output is no longer monotonic and that two distinct digital codes can give rise to the same analogue output. Also, the output voltage skips from 8.189V to 8.192V, missing two steps.

This example not only illustrates the great accuracy necessary to produce a conventional 14 bit D - A converter but also points the way to the technique used here.

If one deliberately uses a weighting factor between bits of less than two, then there may be many digital codes which produce the same output voltage but every output voltage step will be produced. Also any errors, provided they are small enough, will not produce missing steps due to the overlap caused by the reduced weighting factor.

The D - A converter used has a weighting factor of 1.8 between bits. The outputs corresponding to each of the bits are tabulated below, assuming that bit 0 produces an output of 1mV

bit 0 - 1.0mV
bit 1 - 1.8mV
bit 2 - 3.2mV
bit 3 - 5.8mV
bit 4 - 10.5mV
bit 5 - 18.9mV

bit 7 - 61.2mV
bit 8 - 110mV
bit 9 - 198mV
bit 10 - 357mV
bit 11 - 643mV
bit 12 - 1.157V

This D - A converter can produce any voltage, in steps of 1mV or smaller, in the range OV to 4.68 volts. In order to produce a conventional binary D - A converter with a resolution of better than 1 part in 10^4, 14 bits are sufficient. However in the above case where the weighting factor between bits is only 1.8 it is necessary to use two extra bits

bit 14 - 3.749V

bit 15 - 6.749V

This now gives the D - A converter a range of OV to 15.18V.

Consider the possible effects of an error in, say, bit 14. With no error, the output from the D - A converter is as tabulated below.

MSB Digital input LSB	Analogue output
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0.000V
0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0	8.432V
0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	8.433V
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	6.749V
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1	6.750V
1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0	6.751V
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	15.18V

In order to produce a missing step when the digital input changes from 0111111111111111 to 1000000000000000, bit 14 would have to be low by 1.68 volts or bit 15 high by the same amount. This would represent an error of more than 40% in bit 14 or more than 20% in bit 15!

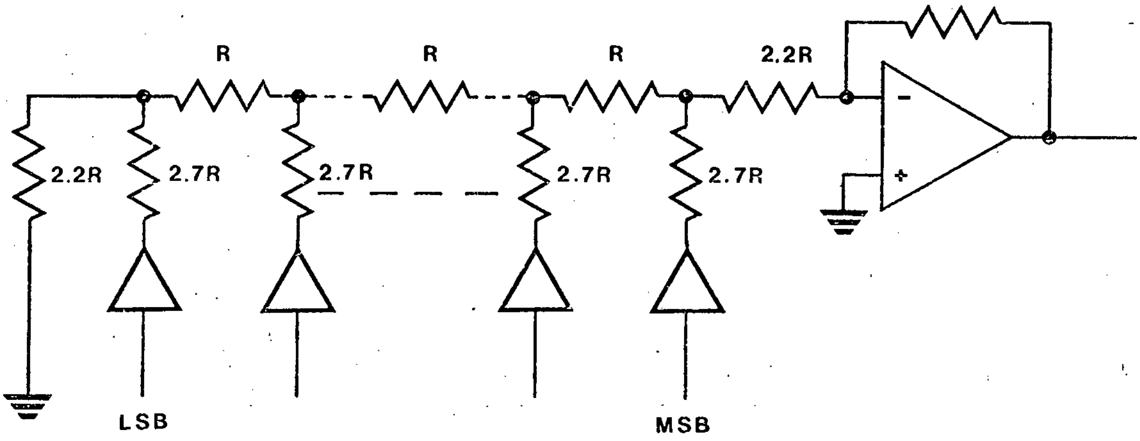


Figure 2.3.e Non-monotonic D - A converter.

The D - A converter uses a R - 2.7R ladder network driven by CMOS buffers as shown in figure 2.3.e. The network is terminated by 2.2R resistors at each end so that at any node the resistance looking left or right is 2.2R and the resistance looking towards the buffer is 2.7R. The current from each buffer is divided by two at the first node it meets and by 1.8 at each subsequent node as it flows towards the operational amplifier input. The output of the buffers is either zero volts or equal to their supply voltage so that by varying this voltage one can scale the output of the D - A converter. The D - A converter may therefore be considered as a multiplying converter with the buffer supply rail as the reference input. The reduced weighting factor between bits overcomes the errors that would normally be introduced by the buffer's non-zero output impedance and the mismatch between the 2% tolerance resistors which comprise the ladder network. A complete circuit diagram of the D - A converter is given in Appendix H.

2.3.6 Summary

The force plate and strain gauge amplifier together may, from a systems point of view, be considered as a force measuring system with four control inputs and one output. The four control inputs are:

(1) RST which resets the input multiplexer to channel 0

(2) INC which increments the input multiplexer by one channel

(3) DEC which decrements the input multiplexer by one channel

(4) ZERO which activates the automatic bridge balancing circuitry

thus removing the offset from the selected channel.

The output is directly proportional to the force exerted on the selected transducer and has a sensitivity of 25 mV ± 1% per newton. The output settles to within about 12 mV of its final value in 50 µsec and the output noise is about 12 mV rms over a 90 kHz bandwidth. Complete circuit diagrams for the strain gauge amplifier may be found in Appendices D to L.

2.4 THE CENTRAL CONTROLLER/VIDEO PROCESSOR

2.4.1 Basic requirements

In order that the complete system may operate as intended, the central controller/video processor is required to perform a number of different functions, namely

(1) synchronise the two television cameras

(2) synchronise the input multiplexer of the strain gauge amplifier

(3) accept the video outputs of the television cameras

(4) accept the output of the strain gauge amplifier and compute the total vertical force and position of the centre of pressure for each force plate beam

(5) generate the composite video picture

(6) balance all the channels of the strain gauge amplifier and put the video tape recorder into the record mode at the start of a measurement cycle

(7) stop the video tape recorder at the end of a measurement cycle

2.4.2 Basic video system

The basic video system is based upon the conventional 625 line system having 2 interlaced fields per picture and 25 pictures per second. The line frequency is therefore 625 x 25 = 15625 Hz and the field frequency 2 x 25 = 50 Hz.

Since the optical resolution requirements for this application are low and since the video tape recorder displays a field and not a picture (2 fields) during stop motion playback anyway, it was decided that the synchronisation circuitry could be greatly simplified by using a non-interlaced video system without adversely affecting picture quality. The video system used is therefore a 624 line system (312 lines per field) having the same 15625 Hz line frequency but a slightly different field frequency of 15625 ÷ 312 = 50.08 Hz

2.4.3 Block diagram

The operation of the central controller/video processor may best be understood by considering each block in figure 2.4.a in turn.

The POWER SUPPLY UNIT produces the necessary supply voltages for all the circuitry of the central controller/video processor.

The 2 MHz CLOCK is a crystal controlled oscillator which is the master timing reference for the entire system.

The ROW COUNTER is a 7-bit binary counter which divides the 2 MHz clock frequency by 128 to give the required 15625 Hz line frequency. The 7-bit output uniquely defines any ½ μsec period in a line.

The LINE COUNTER is a 9-bit binary counter arranged as a divide-by-312 stage. The 9-bit output uniquely defines any line in a video field.

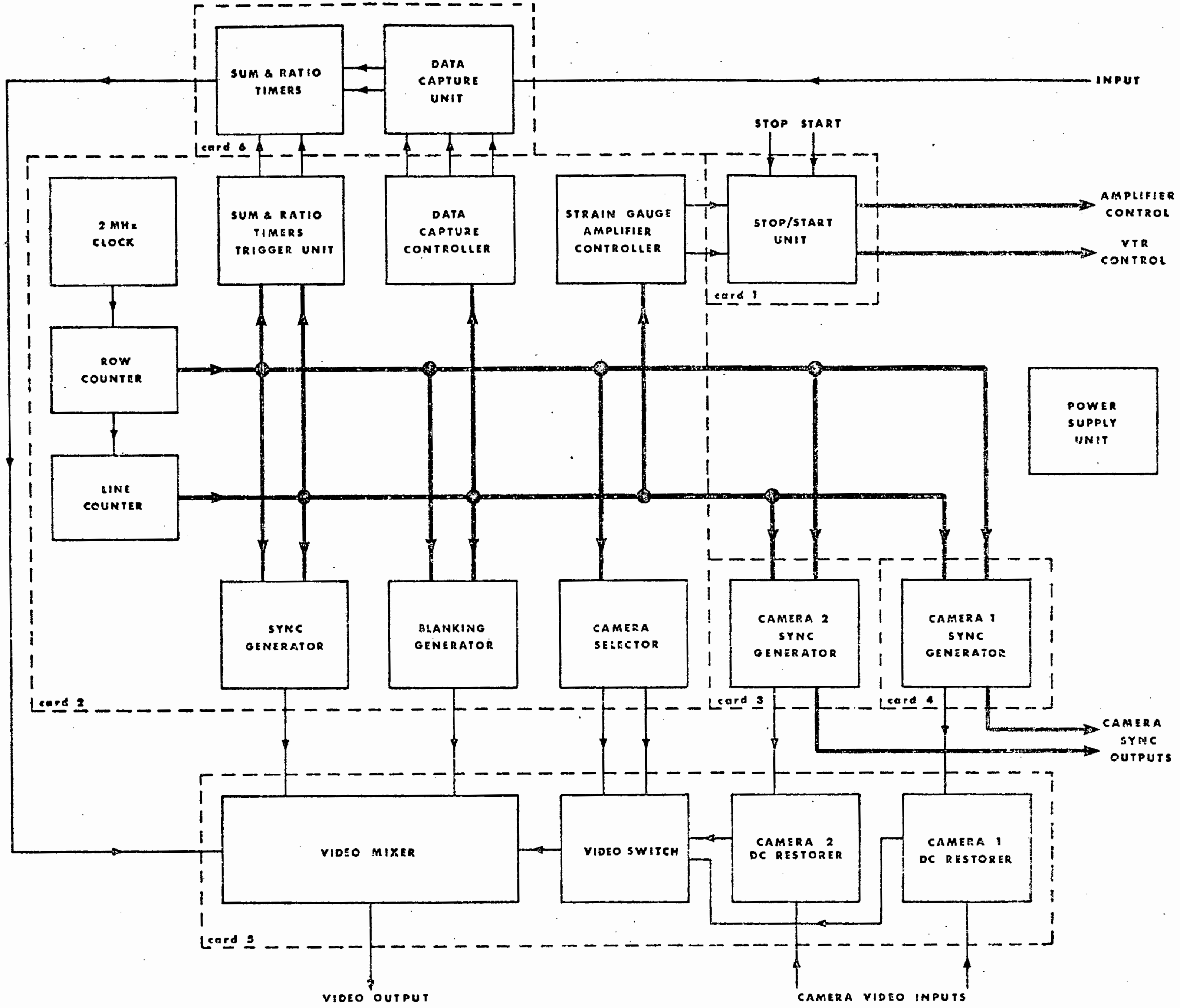


Figure 2.4.a Block diagram of central controller/video processor.

The STOP/START UNIT sequentially selects each of the strain gauge amplifier channels and balances it at the start of a measurement cycle as well as putting the video tape recorder into the record mode. At the end of the measurement cycle it stops the video tape recorder. The start and stop commands may come from front panel switches or from the external control input.

The STRAIN GAUGE AMPLIFIER CONTROLLER controls the input multiplexer of the strain gauge amplifier and thus determines which force transducer is to be sampled.

The DATA CAPTURE UNIT stores the values of the forces as measured sequentially by the multiplexed strain gauge amplifier and outputs these stored values in pairs to the sum and ratio timers. The two values output correspond to the forces at each end of a given force plate beam.

The DATA CAPTURE CONTROLLER controls the storing of samples from the strain gauge amplifier as well as the outputting of these stored samples to the sum and ratio timers.

The SUM AND RATIO TIMERS use the forces, measured by the strain gauge amplifier and stored in the data capture unit, to generate the bar chart and centre of pressure lines respectively.

The SUM AND RATIO TIMERS TRIGGER UNIT triggers these timers at the correct instants.

The CAMERA SYNC GENERATORS produce the necessary line and field sync pulses to synchronise their respective cameras with the row and line counters. Each sync generator also produces a short pulse at some time during the black level output of its associated camera for DC restoration purposes.

The DC RESTORERS adjust the DC level of the video signals from the cameras so that black level corresponds to OV output.

The CAMERA SELECTOR determines which, if any, of the two camera outputs is to be selected for display on the monitor at any instant.

The VIDEO SWITCH, under the control of the camera selector, feeds the video signal from camera 1 or camera 2, or no video signal at all, to the video mixer.

The SYNC GENERATOR produces a digital sync waveform.

The BLANKING GENERATOR produces a digital blanking waveform.

The VIDEO MIXER combines the outputs from the sync generator, blanking generator, video switch and sum and ratio timers to produce the required composite video output.

2.4.4 Video display layout

As mentioned in section 2.4.1, the video system has 312 lines per field, each line lasting 64 μsec. Of this, in accordance with CCIR standards, only 287 lines are visible, the remaining 25 being blanked. Similarly in any given line, only 52 μsec is visible, the remaining 12 μsec being blanked. These blanked lines and parts of lines are necessary for field and line flyback. The visible area therefore consists of 287 lines, each of which lasts 52 μsec. This area fills the screen of the television monitor which has an aspect ratio (height to width ratio) of 3:4.

As explained in section 2.1, the television monitor is operated on its side so that the electron beam scans its lines from bottom to top and its fields from left to right. The relationship between the row and line counter outputs, and the visible and blanked parts of the television scan is shown in figure 2.4.b. Lines 0 - 22 and 310 and 311 are blanked while each line is blanked for rows 0 - 20 and 125 - 127, each row corresponding to a ½ μsec period. The field sync pulse comprises lines 0 - 2 and the line sync pulse, rows 0 - 8.

The visible picture consists of three sections, each occupying an approximately equal area of the screen. The bar chart occupies rows 21 to 54 (17 μsec), the view of the plantar surface of the foot through the force plate, rows 57 to 89 (16.5 μsec), and the lateral view of the subject, rows 92 to 124 (16.5 μsec). Between these three sections are 1 μsec blank areas occupying rows 55, 56 and 90, 91.

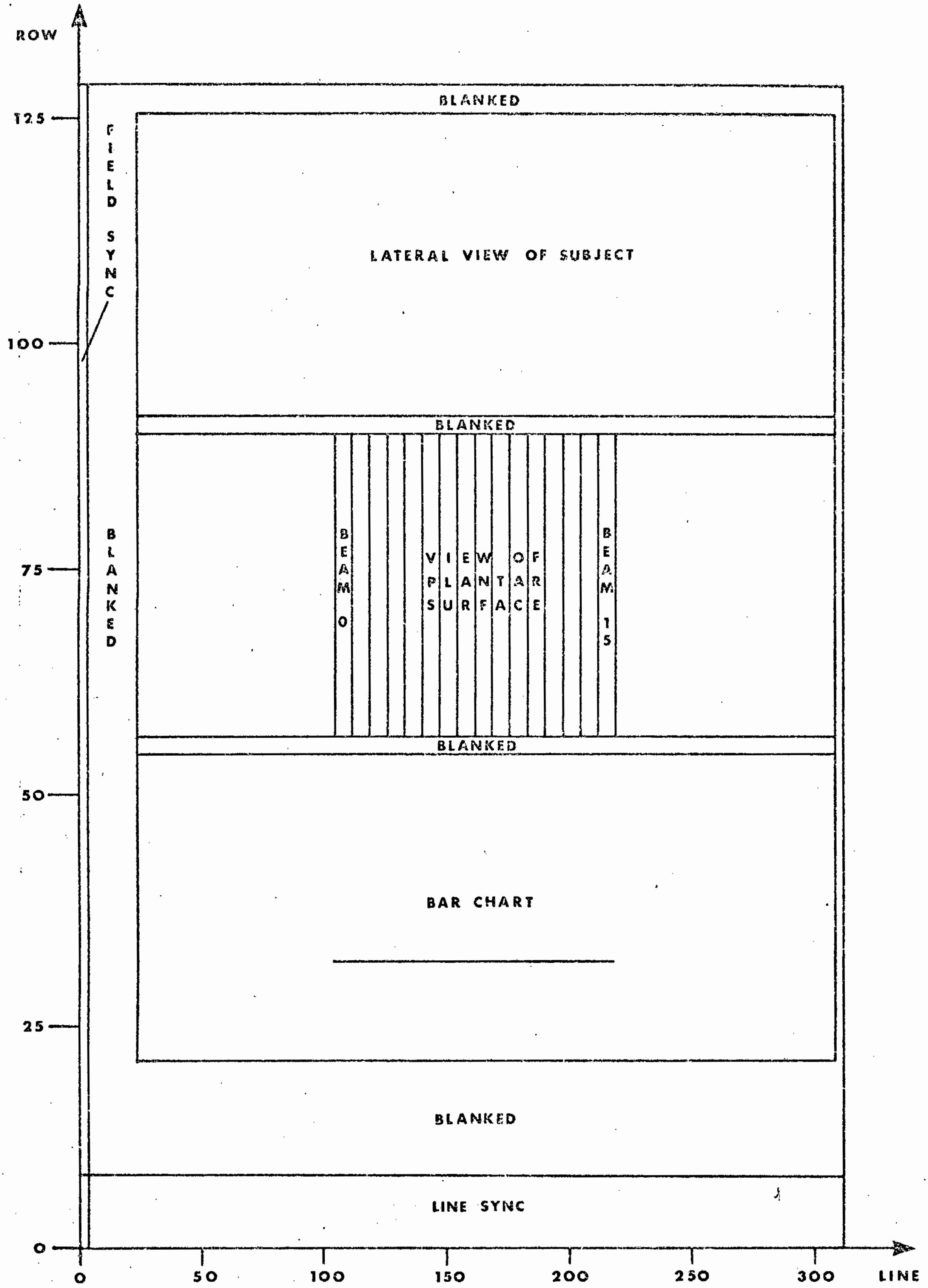


Figure 2. 4. b . Video Display Layout.

The image of the force plate lies in the middle of the screen on lines 110 to 221, each beam occupying 7 lines. The beams are numbered 0 to 15 so that for any given beam J, where J is an integer between 0 and 15, its image occupies lines 110 + 7J to 116 + 7J. Similarly the bar chart also occupies lines 110 to 221, each bar being displayed directly below the beam whose load it indicates.

2.4.5 Synchronisation circuitry

The synchronisation circuitry comprises the sync generator, blanking generator, strain gauge amplifier controller, data capture controller, camera 1 sync generator, camera 2 sync generator, camera selector, sum and ratio timers trigger unit and the stop/start unit.

The 2 MHz clock frequency is divided by 128 by the row counter and further by 312 by the line counter as shown in figure 2.4.c. The row counter outputs R_0 - R_6 together with the line counter outputs L_0 - L_8 uniquely define any ½ μsec interval in a video field.

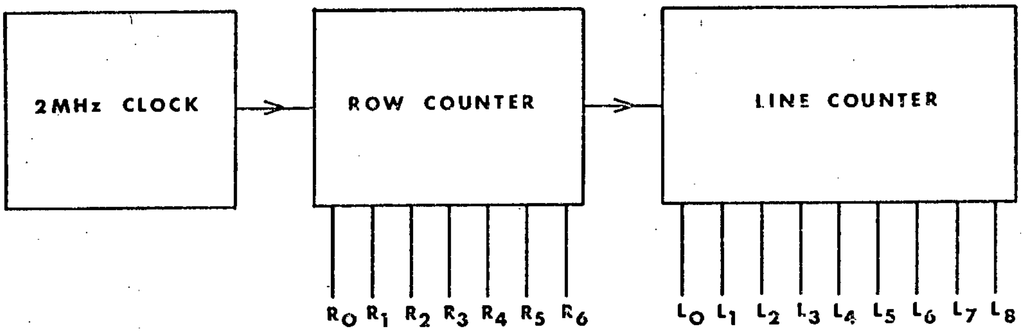


Figure 2.4.c Row and line counters.

Almost all of synchronisation circuitry mentioned above use read-only-memories (ROMs) to produce their complex pulse trains. This is done by using the row or line counter outputs as the address inputs for the ROM as shown in figure 2.4.d.

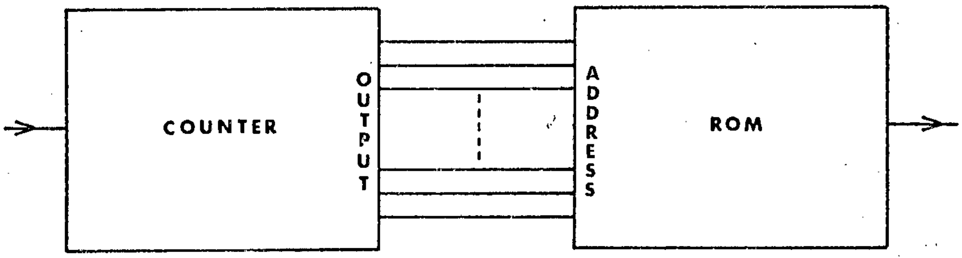


Figure 2.4.d Pulse train generator using a ROM.

As the counter advances, successive memory locations in the ROM are accessed. A logical one or zero may be programmed at any memory location. In this way it is possible to generate any digital waveform in $\frac{1}{2}$ µsec steps with a repetition frequency equal to the line frequency if the row counter outputs are used as the address inputs, or in 64 µsec steps with a repetition frequency equal to the field rate if the line counter outputs are used as the address inputs.

This method of waveform generation is not only efficient in terms of the number of IC packages used but also provides flexibility in the design in that the operation of the system may be altered by reprogramming the ROMs. The ROMs used are National Semiconductor devices 74S287 and 74S571. These fusible link ROMs are relatively easy to programme and, using bipolar Schottky circuitry, are fast enough to generate any of the required video signals. Full circuit diagrams of the synchronisation circuitry may be found in the appendices.

2.4.6 Data capture unit

Since the strain gauge amplifier is a multiplexed amplifier, the output of only one force transducer may be measured at any time. However, in order to calculate the magnitude and position of the centre of pressure of the force applied to any beam, it is necessary to know the force at both ends of that beam. It is therefore necessary to measure and store the value of the force at one end and then measure the force at the other end.

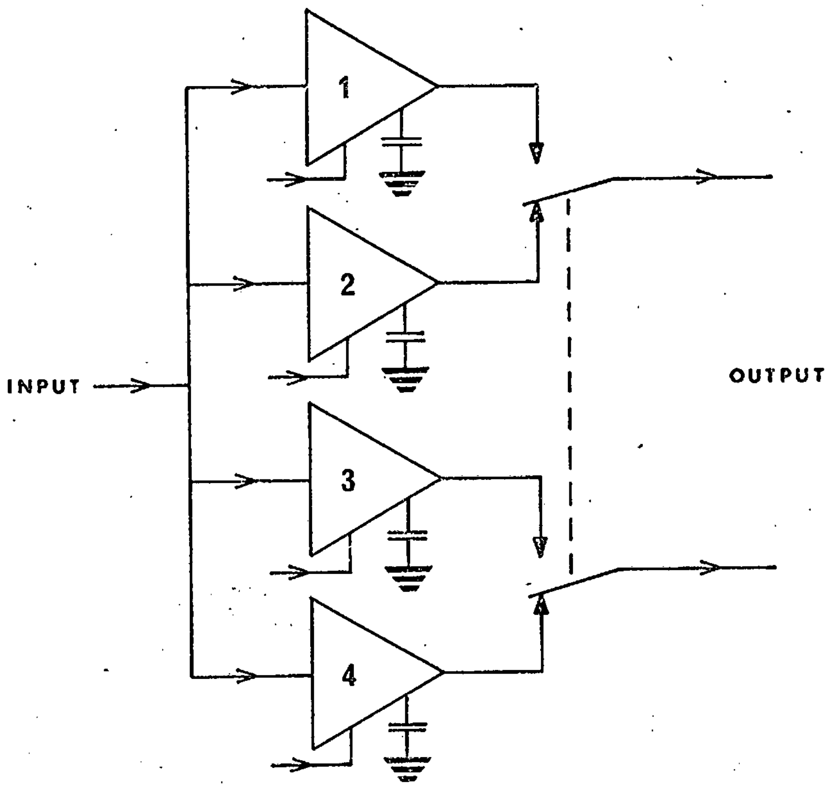


Figure 2.4.e Data capture unit.

This is done by using four sample and hold amplifiers and a double pole cross over (DPCO) analogue switch as shown in figure 2.4.e. The force plate consists of 16 beams numbered 0 to 15, and 32 force transducers numbered 0 to 31. Any beam N is supported by force transducers 2N and 2N+1 where N is any integer between 0 and 15.

The complete selecting and sampling sequence for all 32 channels is listed below. It will be noted that even numbered channels are selected for 3 video lines and odd numbered channels for 4 lines.

BEAM	CHANNEL	SELECTED		SAMPLED		S & H AMPLIFIER
		from line	to line	from line	to line	
	0	215	105	104	105	1
0	1	106	109	108	109	3
	2	110	112	111	112	2
1	3	113	116	115	116	4
	4	117	119	118	119	1
2	5	120	123	122	123	3
	6	124	126	125	126	2
3	7	127	130	129	130	4
	8	131	133	132	133	1
4	9	134	137	136	137	3
	10	138	140	139	140	2
5	11	141	144	143	144	4
	12	145	147	146	147	1
6	13	148	151	150	151	3
	14	152	154	153	154	2
7	15	155	158	157	158	4
	16	159	161	160	161	1
8	17	162	165	164	165	3
	18	166	168	167	168	2
9	19	169	172	171	172	4
	20	173	175	174	175	1
10	21	176	179	178	179	3
	22	180	182	181	182	2
11	23	183	186	185	186	4
	24	187	189	188	189	1
12	25	190	193	192	193	3
	26	194	196	195	196	2
13	27	197	200	199	200	4
	28	201	203	202	203	1
14	29	204	207	206	207	3
	30	208	210	209	210	2
15	31	211	214	213	214	4

The amplifier output is allowed to settle for 1 or 2 video lines depending on whether the channel is odd or even numbered before its output is sampled for 2 video lines. This is a relatively long sampling period (124 μsec) as the sample and hold amplifier, as well as performing a storage function, also low pass filters the amplifier output to remove noise.

This is done by placing a resistor-diode network in series with the storage capacitor as shown in figure 2.4.f. When the sampling switch closes, for a large voltage difference between the input signal and the capacitor voltage, the current needed to charge or discharge the capacitor flows through one of the diodes. When the capacitor voltage is within 0.6V of the input voltage, the diodes are non-conducting and the circuit then behaves as a low pass RC filter. The time constant of this RC network is approximately 50 μsec, effectively reducing the bandwidth to 3.2 kHz from the 90 kHz necessary for the strain gauge amplifier input stage. Since the output noise voltage is proportional to the square root of the bandwidth this gives a 5 fold reduction in noise.

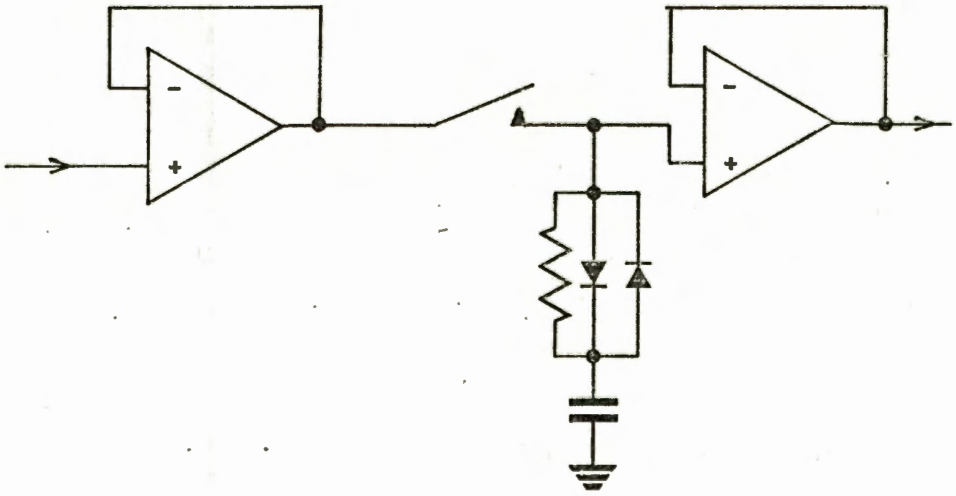


Figure 2.4.f Noise reducing sample and hold amplifier.

2.4.7 Generation of the bar chart and centre of pressure lines

In section 2.4.4 it is explained that each beam of the force plate is displayed for 7 video lines. Each bar of the bar chart is therefore made up of 7 white lines of equal length and each centre of pressure line made up of 7 white dots next to each other.

As mentioned in section 2.1, each line of each bar of the bar chart is produced by generating a white level video signal from some fixed time after the start of the video line scan for a period proportional to the total vertical load on the force plate beam being displayed. This is relatively simple to achieve by using a voltage to period converter which is triggered shortly after the start of a line scan and by using the sum of the measured forces at each end of the beam being displayed as the voltage input to the converter. The converter output produces the white level video signal. In the block diagram, this converter is referred to as the sum timer as it produces an output period proportional to the sum of the two measured forces at the ends of a beam. The sum timer is triggered at the start of row 33 for lines 110 to 221 so that the bar chart lies in the bottom third of the screen, each bar directly below the image of the beam whose load it indicates. The strain gauge amplifier controller and data capture controller ensure that the correct two measured forces are presented to the sum timer at any given time.

Each white dot of the centre of pressure lines is produced by generating a white level video signal of very short duration (200 nsec) at an instant in the video line scan determined by the relative magnitudes of the forces at each end of the beam being displayed. In Appendix B it is shown that the position of the centre of pressure C is given by the relation

$$C \doteq \tfrac{1}{2}L\ (R_1 - R_2)/(R_1 + R_2)$$

where L is the length of the beam and R_1 and R_2 are the vertical reaction forces at each end of the beam. The above relation gives the position of the centre of pressure relative to the centre of the beam. The position relative to the R_1 end of the beam is given by C_1 where

$$\begin{aligned} C_1 &= C + \tfrac{1}{2}L \\ &= LR_1/(R_1 + R_2) \end{aligned}$$

In order to position the centre of pressure line correctly on the screen it is necessary to use a voltage ratio to period converter. The circuit which performs this conversion is shown in figure 2.4.g.

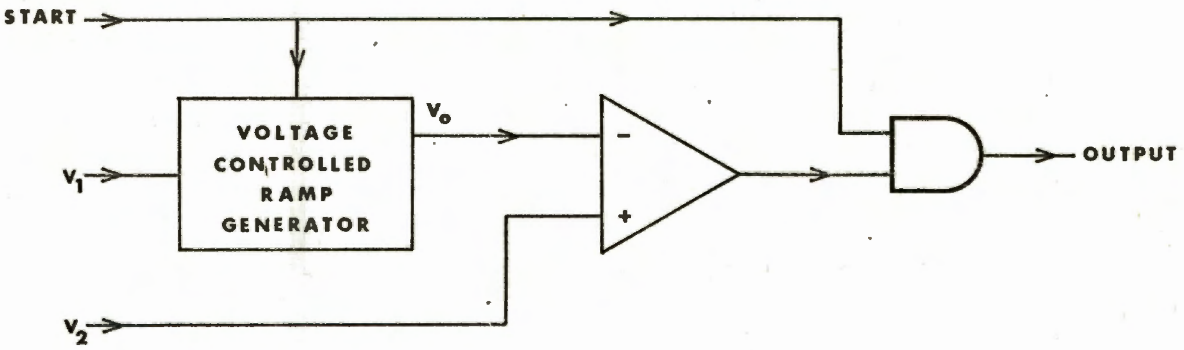


Figure 2.4.g Voltage ratio to period converter.

When the START input goes high at $t = 0$, the ramp generator output begins to rise at a rate proportional to the input voltage V_1 so that $V_o = kV_1t$ where k is a constant. When the ramp generator output exceeds the input voltage V_2, the comparator output goes low. Since the comparator output is gated with the START signal, the converter output is high from $t = 0$ until T when V_o equals V_2

$$kV_1T = V_2$$

$$T = \frac{V_2}{kV_1}$$

By making V_2 proportional to the force R_1, and V_1 proportional to the sum of the forces $R_1 + R_2$, then T is proportional to the distance of the centre of pressure from the end of the beam.

$$T = \frac{b \ldots R_1}{R_1 + R_2} \qquad \text{b is a constant}$$

This converter is referred to as the ratio timer, as it has a period determined by the ratio of the one reaction force to the sum of the reaction forces. The ratio timer produces a 200 nsec white level video signal at the end of its timing period.

The ratio timer is triggered at the start of row 57 which coincides with the start of the middle section of the display. This, as explained in section 2.4.4, occupies 16.5 μsec of each line scan. The timer constant b is chosen to be 16.5 μsec so that as the ratio $R_1/(R_1 + R_2)$ varies from 0 to 1 as the load shifts from one end of the beam to the other, so the centre of pressure line shifts from the lower edge of the middle section of the display to the upper edge.

If the image of the force plate is adjusted by altering the orientation of camera 1 such that the image of the ends of the beams coincide with the edges of the middle section of the display then the centre of pressure lines will be correctly superimposed on the image of the beams and hence on the plantar surface of the foot.

The ratio timer is triggered for lines 110 to 221 so that the centre of pressure lines are superimposed on the images of the beams. The two measured forces required to calculate the position of the centre of pressure are the same as those used by the sum timer to generate the bar chart.

Note that the centre of pressure lines are generated in lines 110 to 221 and in rows 57 to 89 independently of camera 1. It is therefore necessary to optically align camera 1 so that the visual image of the force plate coincides with the electronically generated centre of pressure lines and is in line with the bar chart below.

When a beam is only lightly loaded, the electrical outputs of its associated force transducer are correspondingly low. The effects of noise, drift, offsets, etc. are then significant, making it impossible to accurately calculate the position of the centre of pressure. For this reason, the centre of pressure lines are suppressed for those beams whose loading corresponds to less than 10% of the maximum value that may be indicated by any bar of the bar chart. Thus the display of the plantar surface only indicates those section of the foot which are significantly loaded. Small loads are still displayed on the bar chart.

2.5 SYSTEM COMPONENT INTERCONNECTIONS

The interconnections between the various components of the system are shown in figure 2.5.a below.

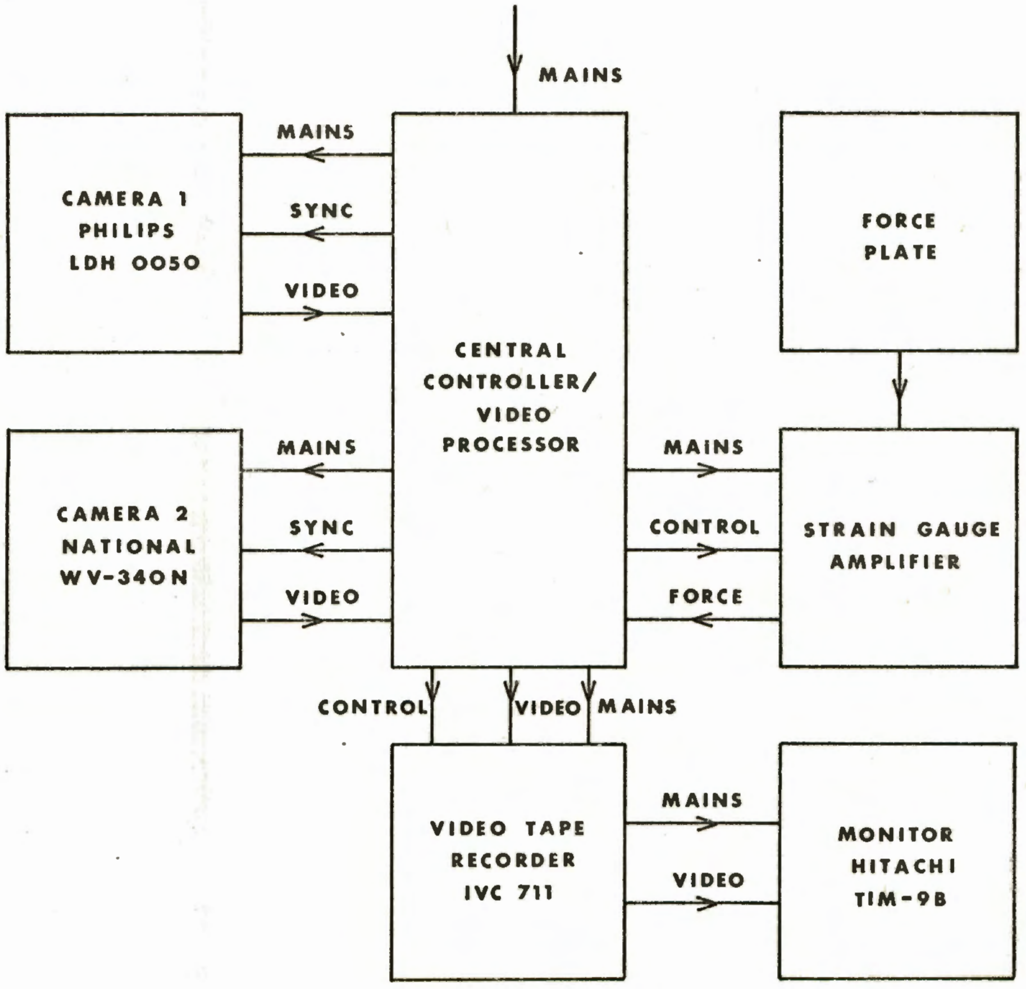


Figure 2.5.a Electrical interconnections between system components.

The mains input to the system is to the central controller/video processor from where it is distributed via its switched power outlets to the two cameras, strain gauge amplifier, video tape recorder and monitor.

In addition to the power cable, there are two cables running to the each of the cameras. One cable carries the synchronisation pulses to the camera and the other the video output from that camera.

The strain gauge amplifier also has two signal cables, one to carry the control signals for the input multiplexer and bridge balancing circuitry, and the other to carry the amplifier output back to the central controller/ video processor.

There are two outputs from the central controller/video processor to the video tape recorder, one being to stop and start the VTR, and the other to carry the video signal to the VTR.

The force plate is connected to the strain gauge amplifier by a single multiway connector which plugs into circuit card 6, which contains the input multiplexer and differential amplifier.

2.6 OPTICAL ALIGNMENTS

The force plate is mounted in a walkway so that the beams are transverse to the direction of walking. The top surface of the plate is adjusted so as to be flush with the rest of the walkway.

Camera 2 is positioned so as to view the subject laterally as he walks on the plate. Camera 2 is fitted with a 12.5 mm wide-angle lens so that a considerable length of the walkway can be photographed. This allows a complete gait cycle to be recorded (i.e. from swing phase through stance phase to swing phase).

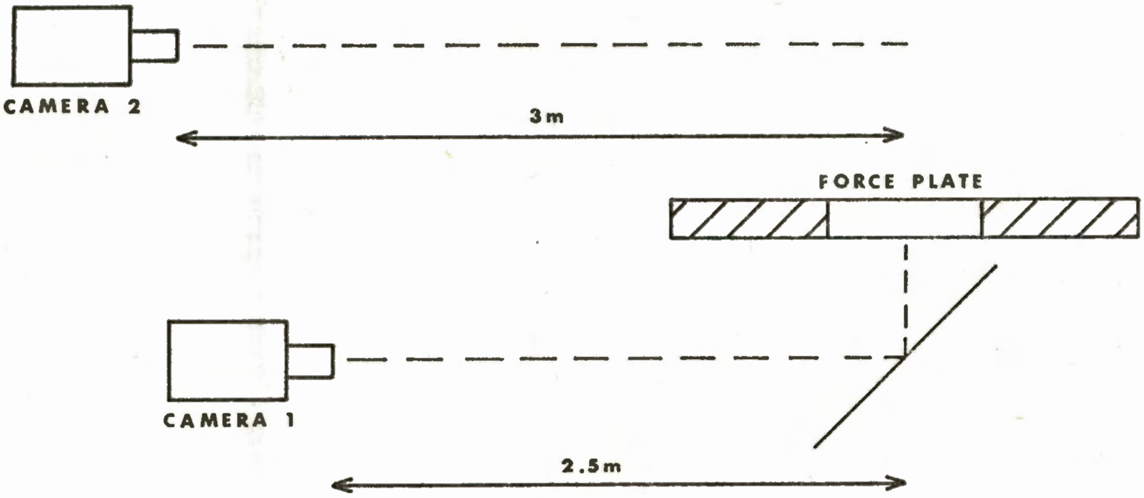


Figure 2.6.a Camera positions.

Camera 1 views the plate via a mirror mounted at 45° to the horizontal and situated below the walkway. The camera is fitted with a zoom lens with a range of 18 to 108 mm. When used in the configuration shown in figure 2.6.a the lens is set nominally to a 50 mm focal length. A telephoto lens allows the force plate to be photographed from a relatively long distance thus ensuring that the vertical edges between the force plate beams do not obscure the foot at the edges of the camera's field of view. (See figure 2.6.b)

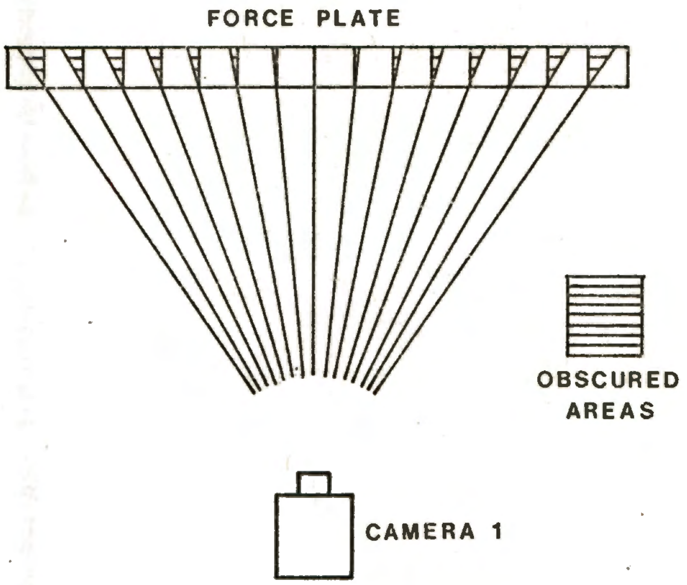


Figure 2.6.b Obscuring of regions of the force plate surface by the beam edges when camera 1 is close to the force plate.

The mirror produces lateral inversion of the image of the force plate so that a right foot appears as a left foot and vice versa. This could be rectified by introducing a second mirror into the optical path or by reversing the connections to the line deflection coils of the camera so that the camera scans its lines in the opposite direction. This lateral inversion of the image of the foot was not troublesome and no attempt at correction was made.

2.6.1 Alignment of camera 1

As mentioned in section 2.4.7, the centre of pressure lines on the display are situated in video lines 110 to 221 and between rows 57 and 89 independantly of camera 1. It is necessary to optically align this camera with the plate so that the visual image of the force plate coincides with the electronically generated centre of pressure lines.

During alignment the input to the central controller/video processor from the strain gauge amplifier is disconnected and a nominal +1V DC voltage applied to the central controller/video processor input. The central controller/video processor sees this as a 40 N load on every force transducer. The bar chart therefore displays each of its bars at a length corresponding to 80 N. More importantly, as there is an apparently equal load at each end of the beams the centre of pressure lines are all in the middle of the screen.

Camera 1 may then be aligned by a combination of zoom lens and camera position adjustment so that

(i) the image of the force plate is the same length as the combined centre of pressure lines (112 video lines).

(ii) the centre of pressure lines are superimposed across the centres of the beams.

Once aligned, the misregistration between the point of application of a point load and the indicated centre of pressure was found to be less than 5 mm for any beam.

2.7 LIGHTING

A number of problems were experienced in providing suitable lighting for the television cameras, namely:

(i) with a high intensity illumination below the force plate, light shining through the force plate cast disturbing shadows onto the legs of the subject walking over it.

(ii) light reflected off the subjects clothing produced bright patches of light around the image of the plantar surface of the foot as viewed by camera 1.

(iii) shadows cast by the subject onto the background reduced the clarity of the lateral view of the subject's legs.

All of these problems were finally eliminated by

(i) having high intensity illumination above the walkway

(ii) having low intensity illumination below the force plate

(iii) letting the subjects wear black tights cut off at the thighs and stretching up to chest height

(iv) using a black background

The illumination above the walkway is supplied by a 2kW quartz halogen studio light while the illumination below the force plate is supplied by two 150W photographic floodlights. In this way shadows cast by the low intensity illumination below the force plate are swamped by the high intensity illumination above the walkway. Operating at a low light level below the force plate has the added advantage of reducing the thermal drift in the strain gauge force transducers by reducing the amount of heat produced.

There were no disturbing patches of light reflected off the tights even though there was a high level of illumination above the walkway and the camera observing the plantar surface of the foot was operating under low light conditions.

The use of a black background prevents one seeing any shadows cast there. The subject's legs now appear light against a dark background instead of vice versa. The resultant improvement in clarity may be judged from the results shown in section 3. 2 as one series of photographs was taken before the black background was introduced.

CHAPTER 3

RESULTS

3.1 OPERATING PROCEDURE

The subject starts walking from a fixed point on the walkway and is instructed to walk along it without looking down at the plate. This prevents him invalidating the measurement by altering his gait so as to deliberately strike the force plate. If his foot does not strike the plate his starting point is adjusted until the foot to be examined lands on the plate. As the subject starts his walk, the START button on the central controller/video processor is pressed so that by the time his foot strikes the plate, all the channels of the strain gauge amplifier have been balanced and the video tape recorder is running at its correct speed. When the subject steps off the force plate the STOP button is pressed which stops the VTR.

As the operation of the system is so quick and simple, and running costs are low, there is no stress from the operator upon the subject if he does not strike the plate. The procedure can be repeated and re-repeated until a satisfactory recording is obtained. This results in a very relaxed atmosphere in the gait laboratory.

The recordings may be examined frame by frame using the stop motion facility of the VTR. A permanent record of any individual frame can be made by photographing the monitor screen although certain precautions need to be taken when doing so.

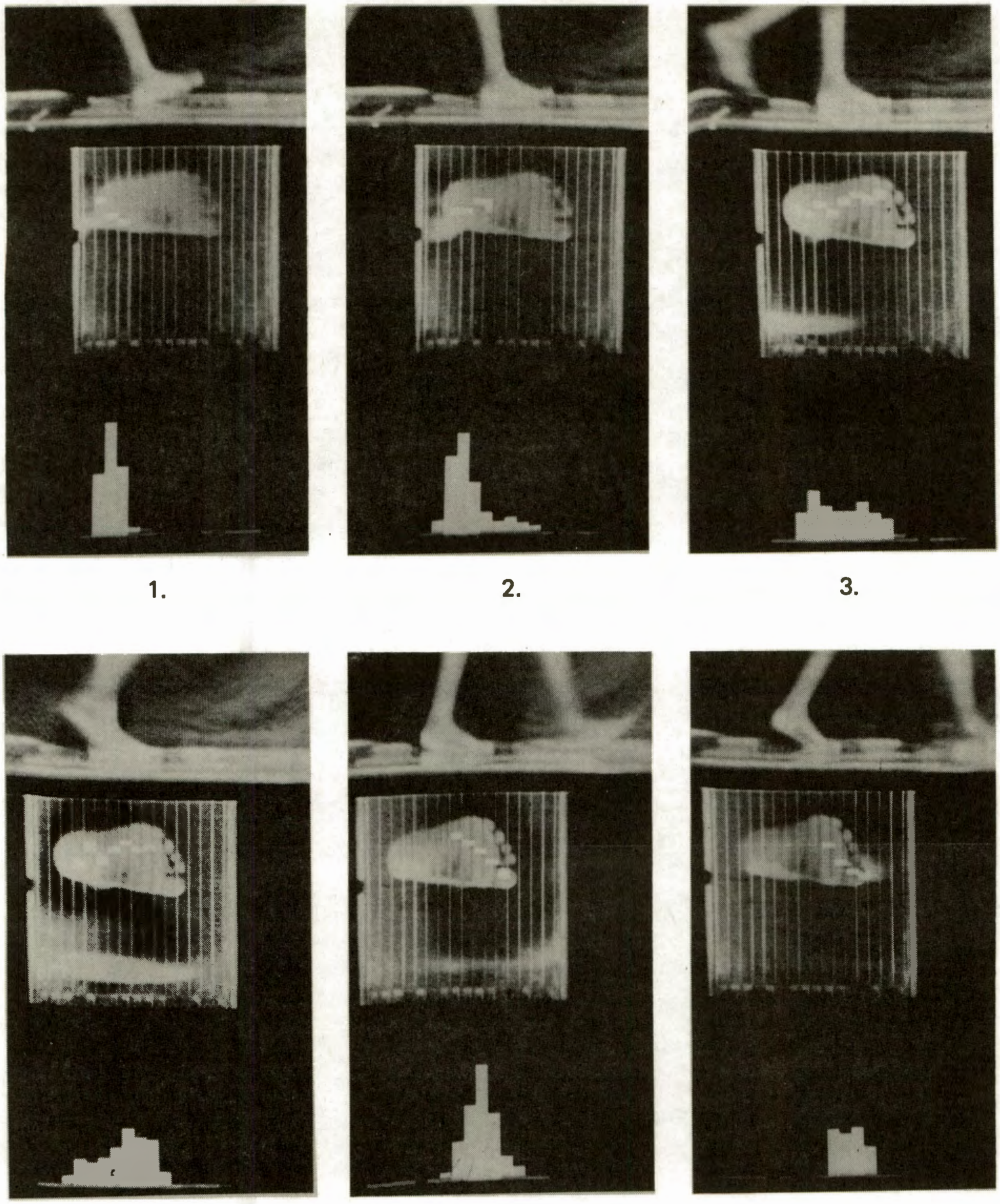
The picture on a television monitor is not static but repeatedly drawn out by the electron beam scanning the monitor screen. Although the human eye may perceive this as a continuous picture, the camera does not. Therefore, to produce a perfect photograph it is necessary to synchronise the camera shutter to the field scanning of the monitor so that the shutter opens during the field blanking time and closes again during a subsequent field blanking time thus photographing an integral number of field scans. This prevents certain areas of the screen being scanned one more time than other areas during the period that the shutter is open and so appearing brighter in the photograph. More simply, a long exposure time, which is not synchronised with the field scanning of the monitor may be used as one extra partial field scan in a large number of complete field scans will not produce a discernable difference in brightness. An unsynchronised exposure time of half a second was used to photograph the pictures which are reproduced in section 3. 2.

3.2 RESULTS

Three subjects have been selected to illustrate the output from the system. The first is a normal subject while the other two each have some functional abnormality. Six photographs have been taken at selected instants during the stance phase of gait for each of the three subjects. The instants depicted are heel strike, the approach to foot flat, foot flat, mid stance, heel rise and the approach to toe off. The upper third of each photograph shows a lateral view of the legs and feet, the middle third shows the plantar surface of the planted foot with centre of pressure lines superimposed, and the bar chart in the lower third displays the load carried by each segment of the foot.

3.2.1 Normal subject

The series of photographs in figure 3.2.a clearly shows that as predicted by traditional gait studies, the heel is subjected to an impact force of considerable magnitude at heel strike. The lateral view shows that at this instant the ankle joint is in a slightly plantar flexed position, and the position of the centre of pressure lines shows that the calcaneus is slightly everted. As the forefoot descends towards the plate and the planted lower leg moves towards the vertical, the heel still carries the majority of the applied load, but the increasing loading of the mid and forefoot is carried somewhat laterally to the longitudinal midline. The longitudinal arch remains the major weight bearing area from foot flat to mid stance, but although the loading is reasonably evenly distributed along the arch at foot flat, by mid stance increasing load is building up on the forefoot. When heel rise occurs, the foot is fully stable and the



1. 2. 3.

4. 5. 6.

Figure 3.2.a The foot distribution on the foot of a normal 36 kg subject during the stance phase of gait

1) Heel strike
2) Approaching foot flat
3) Foot flat
4) Mid stance
5) Heel rise
6) Approaching toe off

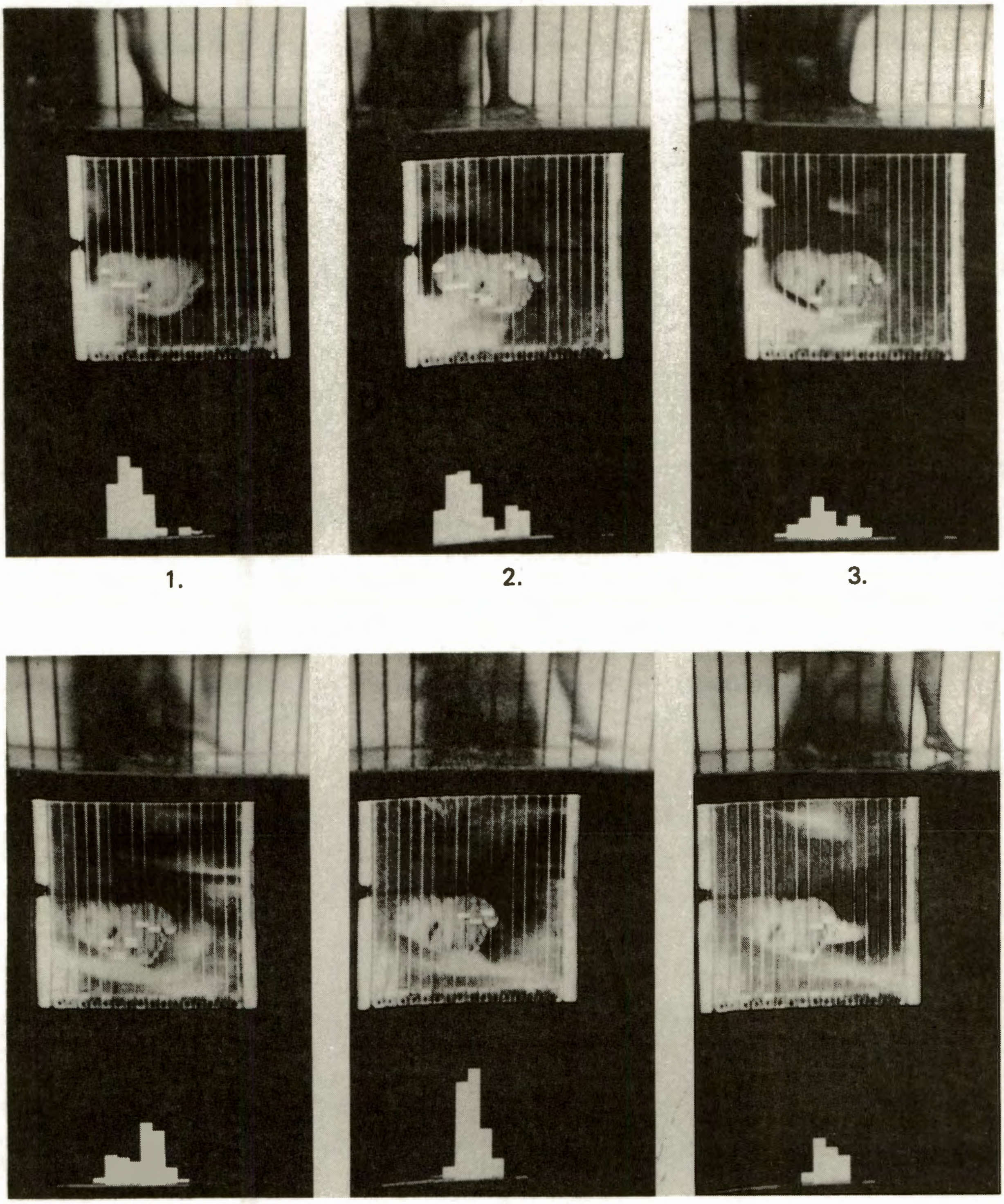
Full scale deflection on the bar chart represents 160 newtons.

loading moves medially across the metatarsal heads, along the line of the metatarsal break, towards the big toe. The centre of the forefoot is now carrying the large impulsive load generated by the lower limb which drives the body forward. The approach to toe off shows further medial movement of the weight bearing area with rapid decrease in applied loading, until the final contact occurs between the plate and the big toe.

3.2.2 Abnormal subject 1

The series of photographs shown in figure 3.2.b were taken during the stance phase of a patient with meningomyelocele and sensory and motor deficit to her feet.

The dark mark visible in the centre of the photographs of the plantar surface is a pressure sore. The first photograph in the sequence shows that "heel" strike occurs in a semi-foot flat position with the loading applied to the lateral edge of the hind foot and to the site of the pressure sore. At foot flat the hind foot is still inverted with loading applied to the lateral border, and the forefoot is now carrying weight on or near the first metatarsal head. By mid stance the majority of body weight is carried by the extreme lateral border of the foot and the area of the pressure sore is still subjected to a high magnitude of load, which is maintained even after heel off has occurred. At this stage forefoot loading has shifted to the area of the second metatarsal where it is maintained while the big toe also comes into contact. The impulsive load on the forefoot builds up to a maximum to propel the body forward, and then dies away to toe off.



1.

2.

3.

4.

5.

6.

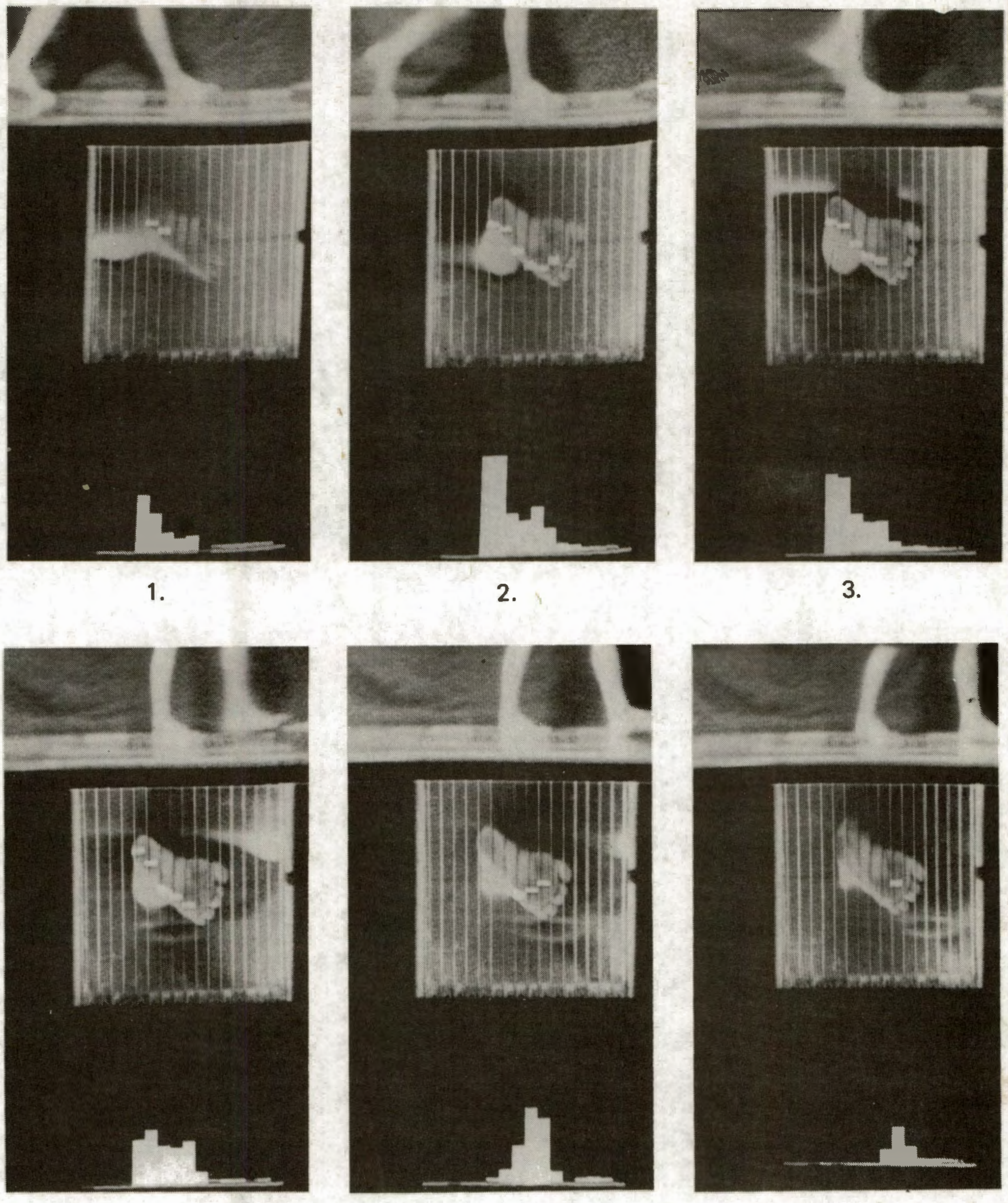
Figure 3.2.b The force distribution on the foot of a 33 kg meningomyelocele patient during the stance phase of gait. The dark mark at the centre of the plantar surface is a pressure sore.

1) Heel strike
2) Approaching foot flat
3) Foot flat
4) Mid stance
5) Heel rise
6) Approaching toe off

Full scale deflection on the bar chart represents 100 newtons.

3.2.3 Abnormal subject 2

The series of photographs shown in figure 3.2.c records the stance phase of a 7 year old, post poliomyelitis patient who originally presented with peroneal weakness and cavus deformity of the foot. This record was taken some three months after tibialis anterior lateral transfer and z-lengthening of the tendo-achilles had been performed. The series of photographs shows that at heel strike the patient's forefoot is abducted about 30°, and the cavus deformity brings the forefoot into contact with the plate before toe off occurs on the swinging foot. Body weight is carried by the full length of the extreme lateral border of the planted foot until well after mid-stance. At heel rise there is a rapid transfer of load onto the third, fourth and fifth metatarsal heads before toe off occurs from the centre of the metatarsal break.



1. 2. 3.

4. 5. 6.

Figure 3.2.c The force distribution on the foot of a 26 kg post-poliomyelitis patient after correction of peroneal weakness and cavus deformity.

1)	Heel strike	2)	Approaching foot flat
3)	Foot flat	4)	Mid stance
5)	Heel rise	6)	Approaching toe off

Full scale deflection on the bar chart represents 125 newtons.

CHAPTER 4

DISCUSSION

4.1 CURRENT PROBLEMS

The system described in this thesis performed as originally intended once the initial problems had all been sorted out. The only persistent difficulty experienced was in producing still frames from the video tape recorder (VTR) without picture roll and line tearing. It was initially thought that this was due to a fault in the VTR but using other VTRs produced no improvement. It was eventually ascertained that the reason for this difficulty is that VTRs, in general, are designed to give optimal performance for a conventional 2:1 interlaced picture, whereas the output of the central controller/video processor was deliberately designed to be non-interlaced for reasons explained in section 2.4.1. In order to explain the difference between producing still frames from interlaced and non-interlaced video pictures, it is necessary to understand the basic operating principles of helical scan VTRs.

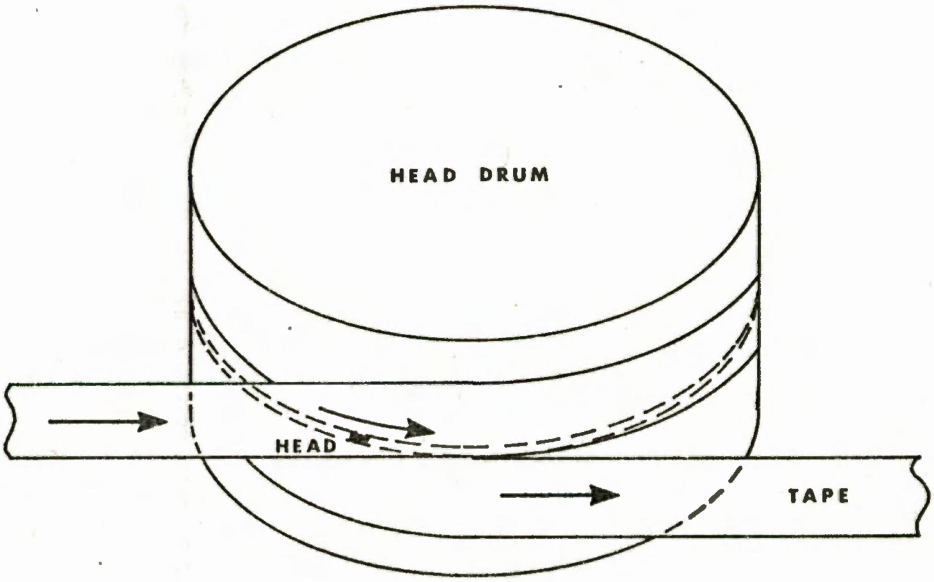


Figure 4.1.a Arrangement of tape and head drum

To record and reproduce video pictures of reasonable quality the tape recorder used must have a large bandwidth of about 3MHz necessitating a high relative velocity between the tape and the recording head. In the helical scan VTR this is achieved by spinning the video head at high speed while the tape advances relatively slowly around the head drum (shown in figure 4. 1. a). The relative motion between the head and tape causes the recorded tracks to run diagonally across the tape as shown in figure 4. 1. b. The rotational speed of the video head is chosen so that one track corresponds to a complete tv field. For a video system having 50 fields per second, the period of rotation of the head is 1/50 of a second, necessitating a head rotational speed of 3000 RPM. The linear tape speed is set so that there is a relatively narrow guard band, on which no signal is recorded, between the recorded tracks.

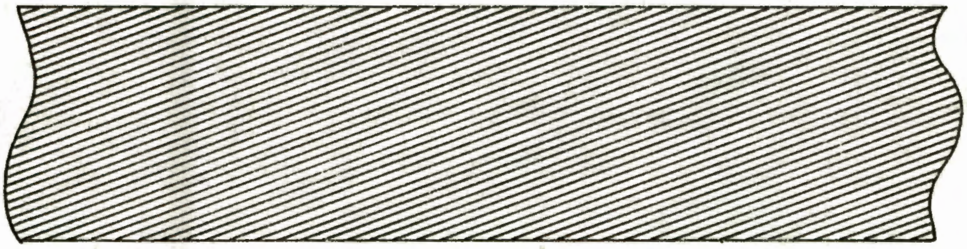


Figure 4. 1. b Layout of recorded tracks.

During playback there is no difference between interlaced and non-interlaced pictures as the video head scans the tracks exactly as they were recorded. The problem arises when one wishes to view a still picture of a particular video field. This is done by stopping the linear motion of the tape so that apparently the spinning head continually scans the same track. However the motion of the spinning head relative to the tape when the tape is moving is not the same as when the tape is stationary. Thus in stop mode if the head starts its scan in the middle of a track at one side of the tape it will then end in the middle of the adjacent track at the opposite side of the tape. This change of track means that the head must scan across the unrecorded guard band, and a few lines of noise known as the noise bar is produced on the display. Since the recording system uses a frequency modulation technique, the loss of signal amplitude as the head moves progressively off the centre of the track is of no consequence. By manually advancing the tape, it is possible to position the noise bar off the screen of the monitor thus producing an apparently perfect still frame.

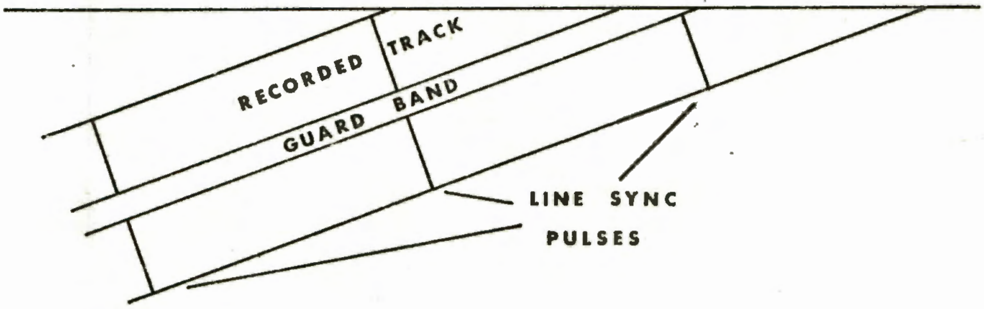


Figure 4.1.c Position of line sync pulses for 2:1 interlaced video signal.

By suitable choice of tape width, drum circumference, linear tape speed, guard band width and track width, it is possible for the VTR manufacturer to arrange the recorded tracks of a 2:1 interlaced video signal so that line synchronising pulses of adjacent tracks are next to each other as shown in figure 4.1.c. Thus as the video head scans from one track to an adjacent track, as it does for still frames, the horizontal synchronising pulses will still appear at regular intervals thus avoiding the necessity for the line oscillator in the monitor to adjust its phase to the incoming video signal.

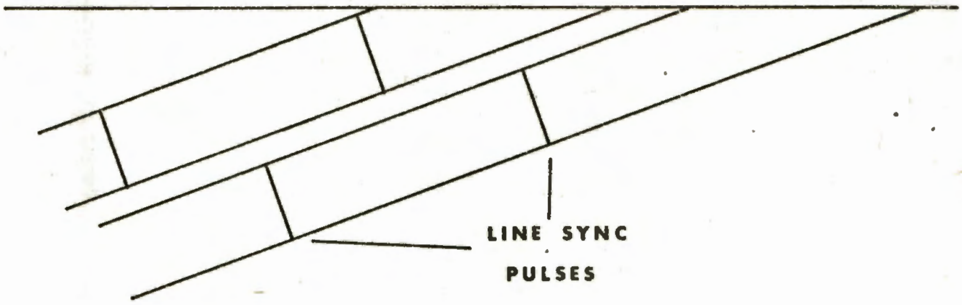


Figure 4.1.d Position of line sync pulses for non-interlaced video signal.

For a non-interlaced system having 312 lines per field as opposed to 312½ lines per field for a 2:1 interlaced system, the recorded tracks are arranged as shown in figure 4.1.d. Note that the line synchronising pulses of adjacent tracks are now displaced by half a line relative to each other so that as the video head scans from one track to an adjacent track, the line oscillator in the monitor finds itself 180° out of phase with respect to the incoming video signal resulting in considerable line tearing of the picture before the line oscillator synchronises itself with the incoming horizontal synchronising pulses.

This problem may be reduced by using a monitor whose line oscillator can rapidly alter its phase so as to achieve synchronisation in as short a time as possible, reducing the extent of the line tearing. In order to produce the stills which were photographed and included in this thesis, the tape guides of the VTR were adjusted for playback to alter the path of the tape around the head drum. Thus the head scanned exactly the same path in stop motion as when recording and there is no crossing of tracks. Because of the narrowness of the tracks, this adjustment is critical and is therefore not recommended as a long term solution to the problem.

In retrospect, the central controller/video processor should have been designed as a 2:1 interlaced system completely eliminating this line tearing problem. This would, however, have further complicated all the synchronisation circuitry involved but is a necessary requirement for long term use.

4.2 POSSIBLE IMPROVEMENTS TO THE SYSTEM

4.2.1 Inclusion of electromyographic information in the display

The system described in this thesis allows the force distribution over the plantar surface of the foot to be displayed and assimilated. In the abnormal foot, deviations from the normal loading pattern may be due to a mechanical abnormality or incorrect muscular balance and control. It would therefore facilitate the understanding of the force plate data if information on muscle activity could be recorded simultaneously. This information may be obtained by monitoring the electrical activity of muscles using either surface electrodes or transcutaneous wires and needles. The electromyogram (EMG) signals thus obtained consist of a "noisy" electrical signal when the muscle is activated and no signal at all when the muscle is relaxed. However it is not possible to relate the magnitude of the EMG signal to the power of muscular contraction.

Most modern gait laboratories use four EMG channels to monitor the muscular activity of each lower limb during gait. In this video system, the outputs of these channels could be displayed as four squares on the monitor screen, each of which is white when the respective muscle is activated and black when relaxed. These squares should preferably be positioned next to the plantar view of the foot and below the lateral view of the subject's legs to facilitate the interpretation of the EMG information together with the loading pattern and position of the lower limbs at that instant.

The EMG information should be sent via a short range telemetry link to avoid trailing long wires to the subject.

A spare circuit card connector is available in the central controller/ video processor for containing the necessary circuitry to display the EMG information.

4.2.2 Inclusion of a field counter in the display

For reference purposes it would be useful to number the video fields to facilitate the rapid selection of a particular video field during the analysis of a subject's gait. Since the fields are recorded at a 50Hz rate, the field numbers would allow the calculation of the elapsed time between any two selected fields.

The frame counter could consist of an on-screen three digit display situated in the lower left or right hand corner of the screen next to the bar chart. The counter could be started when the start button of the central controller/video processor is pressed or preferably when the first load appears on the force plate so that heel strike corresponds to frame number zero.

4.2.3 Automation of the operating routine

By using a number of light beam-photocell units arranged as shown in figure 4.2.a, it is possible to automate the operating routine.

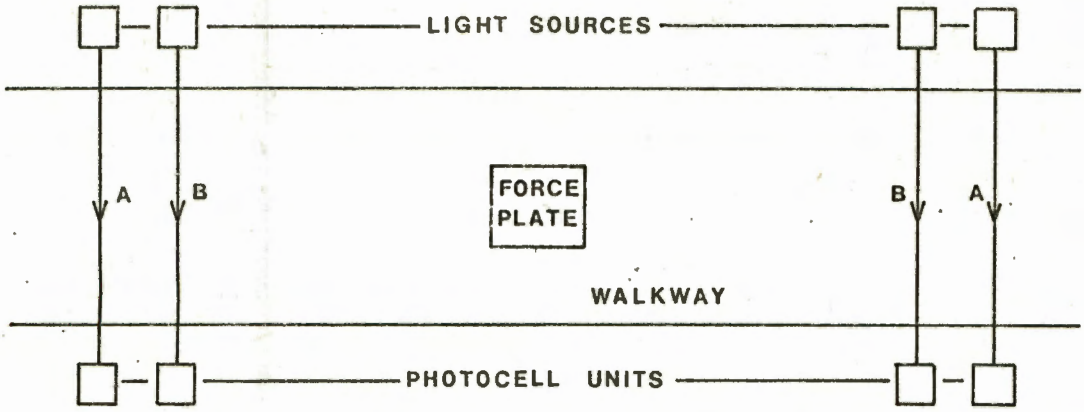


Figure 4.2.a Arrangement of light beam-photocell units.

When the subject walks towards the force plate from either direction he interrupts an A beam before its associated B beam. This sequence of events may be used to activate the external start input to the central controller/video processor. Similarly when the subject walks away from the force plate he interrupts a B beam before an A beam and so activates the stop input. In this way the subject may walk back and forth along the walkway and the system will start and stop itself automatically.

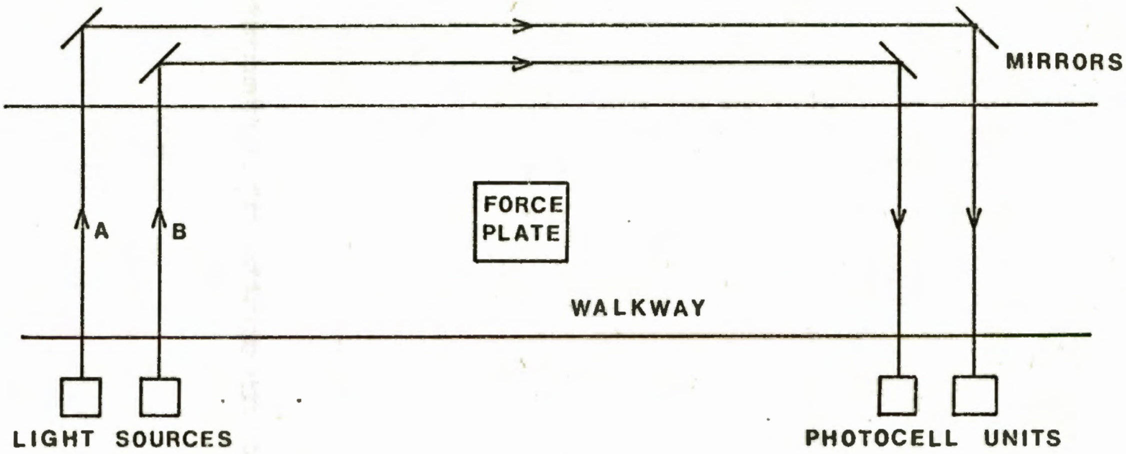


Figure 4.2.b Alternative layout of light beam-photocell units.

The number of photocell units may be reduced to two by using the arrangement shown in figure 4.2.b.

Alternatively the system may be started and stopped by using a pair of pressure sensitive mats at each end of the walkway.

4.2.4 The provision of calibration and camera alignment facilities

The output of the strain gauge amplifier is calibrated at 25 mV/N but the central controller/video processor has a continuously variable sensitivity control. In order to facilitate calibration on the bar chart display, a switch should be provided on the front panel of the central controller/ video processor which, when operated, will disconnect the input to the unit from the strain gauge amplifier and substitute a 1V DC signal. This signal corresponds to a 40 newton load on each end of each beam of the force plate so that each bar of the bar chart will have a length corresponding to an 80 N load for that particular input sensitivity setting. A few seconds of this calibration signal should be recorded on the video tape recorder before or after the patient's foot loading recordings.

The calibration routine could be simplified by automatically applying the 1V DC calibration signal to the input of the central controller/ video processor for approximately one second after the START button had been pressed, during the period before the subject steps onto the plate and while the channels of the strain gauge amplifier are being balanced. This would ensure that there is calibration bar at the start of each recording.

The use of a DC input voltage to align camera 1 is explained in section 2.6.1.

CHAPTER 5

CONCLUSIONS

The instrumentation system described in this thesis measures the dynamic vertical force distribution over the plantar surface of the foot. The data obtained from these measurements is combined with the visual image of the plantar surface of the foot and a lateral view of the subject's legs and feet to produce a pictorial and graphical output which is simple to interpret. As can be seen from the three series of photographs presented, this technique of imaging and assessing the foot clearly shows the differences between normal and abnormal foot function.

In view of the simplicity of operation and ease of interpretation of the display, the system is able to provide an assessment of the patient upon which the clinical corrective programme can be based. The system also provides data which allows the recovery of a patient to be assessed and controlled during rehabilitation.

It is also planned that this system be used for research leading towards a better understanding of both normal and abnormal foot function. This in turn will lead to the development of improved foot and lower limb prostheses for patients with a lower limb abnormality and may also help in the optimisation of performance in the sports medicine field.

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APPENDICES

A	Biomechanics of the Foot
B	Derivation of the Position of the Centre of Moment
C	Electrical Characteristics of Strain Gauge Circuits
D	Card 1 - Channel Selector
E	Card 2 - Gain Factor Memory
F	Card 3 - Successive Approximation Circuitry and Offset Memory
G	Card 4 - Digitally Programmable Gain Amplifier and Comparator
H	Card 5 - Digital to Analogue Converter and Offset Removing Amplifier
I	Card 6 - 64 Channel Multiplexer and Differential Amplifier
J	6-Bit Binary to Binary Coded Decimal Converter and Two Digit Display
K	Power Supply Unit - Strain Gauge Amplifier
L	Main Frame and Front Panel Wiring - Strain Gauge Amplifier
M	Card 1 - Stop/Start Unit
N	Card 2 - Master Clock and Synchronisation Unit
O	Card 3 - Camera 2 Sync Generator
P	Card 4 - Camera 1 Sync Generator
Q	Card 5 - Video Mixer
R	Card 6 - Data Capture Unit and Sum and Ratio Timers
S	Power Supply Unit - Central Controller/Video Processor
T	Main Frame and Front Panel Wiring - Central Controller/ Video Processor

APPENDIX A

Biomechanics of the foot

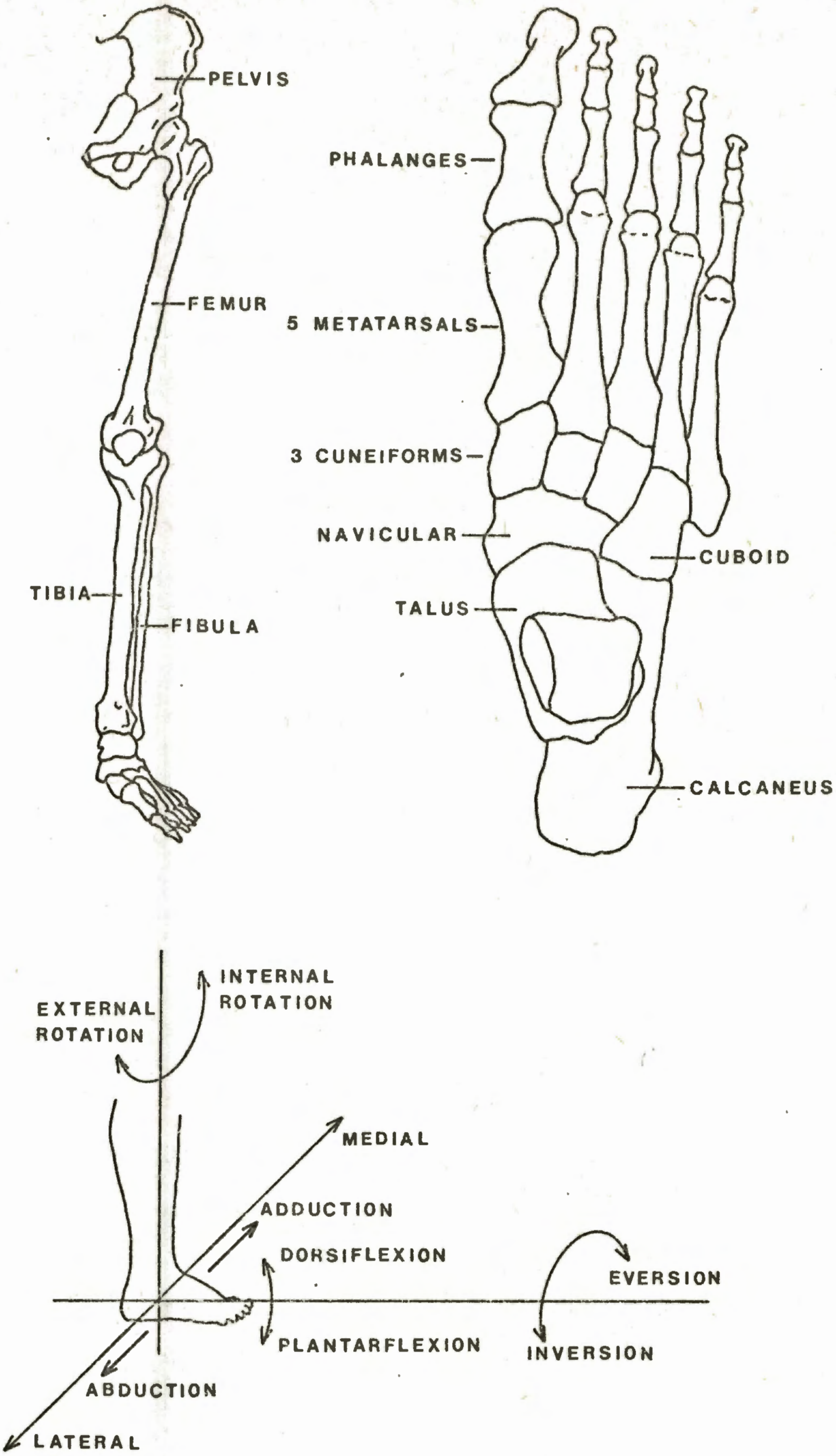
The arrangement of the bones of the lower limb is shown overleaf.

The major axis of free foot motion is the ankle joint, formed by the articulation of the talus between the mortice of the tibia and fibula. Since the ankle axis is not horizontal, plantar flexion causes slight adduction of the forefoot while dorsiflexion causes slight abduction of the forefoot.

The second degree of freedom occurs at the subtalar joint between the talus and calcaneus. The obliquity of this rotational axis is such that it combines abduction with dorsiflexion and adduction with plantarflexion. In addition the calcaneus can rotate on the talus to produce inversion or eversion of the foot.

The third significant rotational axis in the hind foot is the transverse tarsal joint formed by the articulation of the talus on the navicular and the calcaneus on the cuboid. While the axes of these two articulations are parallel to each other, free motion is available at the transverse tarsal joint.

An important "joint" of the forefoot is the metatarsal break. This rotational axis is the oblique axis along the metatarsophalangeal joints and allows extension and flexion of the toes.



Mechanical structure of the lower limb

During normal locomotion the inward and outward rotation of the pelvis causes the femur, fibula and tibia to rotate about the long axis of the limb. In general terms, the intact limb rotates internally during the swing phase and early stance phase, and then externally until the stance phase is complete and toe-off has occurred.

At the beginning of the stance phase (heel strike) the tibia is slightly internally rotated from its neutral toe out position and the ankle joint is in an approximately neutral position. Immediately after heel strike the foot plantar flexes towards the floor, the dorsiflexors controlling this motion to prevent the foot slapping down. From heel strike to just before foot flat the inward rotation of tibia and fibula is transmitted through the ankle joint to the talus and tends to shift the forefoot medially from its neutral toe out position.

As the foot moves into the foot flat position the direction of rotation of the lower limb reverses and the leg begins to rotate externally. Since the foot is planted firmly on the floor, the entire external rotation of the ankle joint is passed to the talus which then tends to invert the foot.

As the leg passes over the weight bearing foot, the ankle begins to dorsiflex but this is opposed by the contraction of the plantarflexors which lift the heel. The phalanges remain flat on the floor and the forefoot articulates at the metatarsal break.

Just before toe-off the talus has reached its maximum degree of external rotation and the foot is inverted, adducted and plantar flexed.

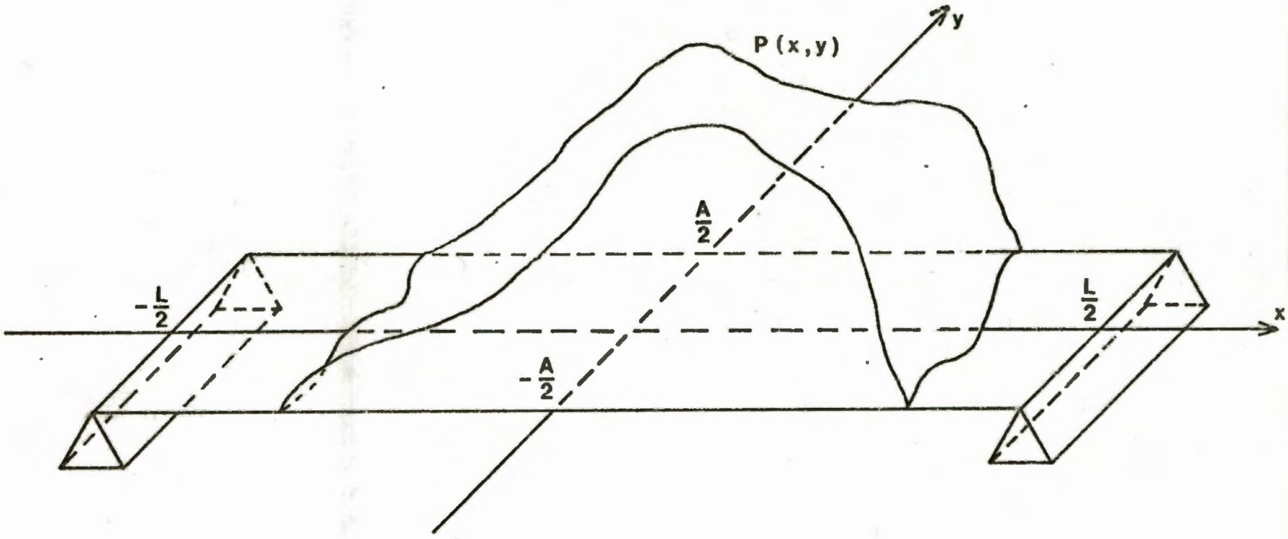
Inversion of the calcaneus shifts the axis of the articulation of the calcaneus on the cuboid thus locking the transverse tarsal joint. This in turn locks the forefoot providing a solid support for push off.

As toe off is completed, the leg begins to rotate internally, the transverse tarsal joint is unlocked and the forefoot becomes flexible. The plantar-flexors relax and the dorsiflexors contract slightly, lifting the forefoot so as to clear the floor during the swing phase.

APPENDIX B

Derivation of the position of the centre of moment

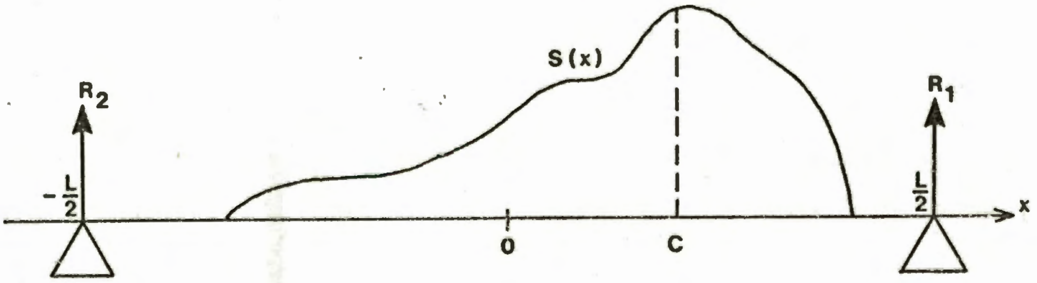
Consider a beam of width A, length L, supported at each end by a knife edge. The vertical force distribution over the beam is specified by a function P (x, y).



The force per unit length along the beam then given by S (x), where

$$S(x) = \int_{-\frac{A}{2}}^{\frac{A}{2}} P(x, y)\,dy$$

The beam may now be considered as a one dimensional element.



Since the beam is in equilibrium, the total force vertically must be zero.

$$R_1 + R_2 - \int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\,dx = 0$$

$$\int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\,dx = R_1 + R_2 \qquad (1)$$

Also, the total moment about any point must be zero. Taking moments about the origin

$$-\tfrac{1}{2}LR_2 + \tfrac{1}{2}LR_1 - \int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\ x\ dx = 0$$

$$\int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\ x\ dx = \tfrac{1}{2}LR_1 - \tfrac{1}{2}LR_2 \qquad (2)$$

The centre of moment of the applied pressure distribution P (x, y) is at C. The moment about C due to P (x, y) and hence S (x) is zero.

$$\int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\,(x-C)\,dx = 0$$

$$\int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\,x\,dx - C\int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\,dx = 0$$

$$\int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\,x\,dx = C\int_{-\frac{L}{2}}^{\frac{L}{2}} S(x)\,dx$$

Substituting from equations 1 and 2

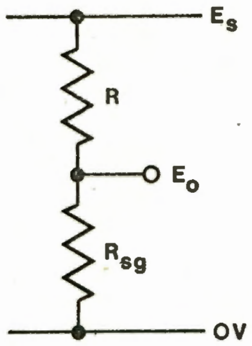
$$\tfrac{1}{2}LR_1 - \tfrac{1}{2}LR_2 = C(R_1 + R_2)$$

$$C = \tfrac{1}{2}L(R_1 - R_2)/(R_1 + R_2)$$

APPENDIX C

Electrical characteristics of strain gauge circuits

Consider a simple strain gauge circuit consisting of a strain gauge of resistance R_{sg}, fixed resistance R energised by a supply voltage E_s.



The output voltage E_o is given by the relation

$$E_o = E_s R_{sg}/(R + R_{sg})$$

$$= E_s (1 + R/R_{sg})^{-1}$$

The variation of E_o with for small changes in R and R_{sg} is given by the differential of E_o

$$\Delta E_o = -E_s (1 + R/R_{sg})^{-2} R_{sg}^{-1} \Delta R + E_s (1 + R/R_{sg})^{-2} R/R_{sg}^2 \Delta R_{sg}$$

$$= E_s (1 + R/R_{sg})^{-2} R/R_{sg} (\Delta R_{sg}/R_{sg} - \Delta R/R)$$

$$= E_o (1 + R/R_{sg})^{-1} R/R_{sg} (\Delta R_{sg}/R_{sg} - \Delta R/R)$$

$$= E_o (1 - (1 + R/R_{sg})^{-1}) (\Delta R_{sg}/R_{sg} - \Delta R/R)$$

$$= E_o (1 - E_o/E_s) (\Delta R_{sg}/R_{sg} - \Delta R/R)$$

In a conventional strain gauge bridge consisting of two strain gauges of equal resistance,

$$E_o = E_s/2$$

and

$$\Delta E_o = E_o(1 - \tfrac{1}{2})(\Delta R_{sg1}/R_{sg1} - \Delta R_{sg2}/R_{sg2})$$

In such a bridge arrangement, one strain gauge is in compression and the other in tension so that $\Delta R_{sg1}/R_{sg1} = -\Delta R_{sg2}/R_{sg2}$ so that

$$\Delta E_o = E_o \Delta R_{sg1}/R_{sg1}$$

APPENDIX D

Card 1 - Channel selector

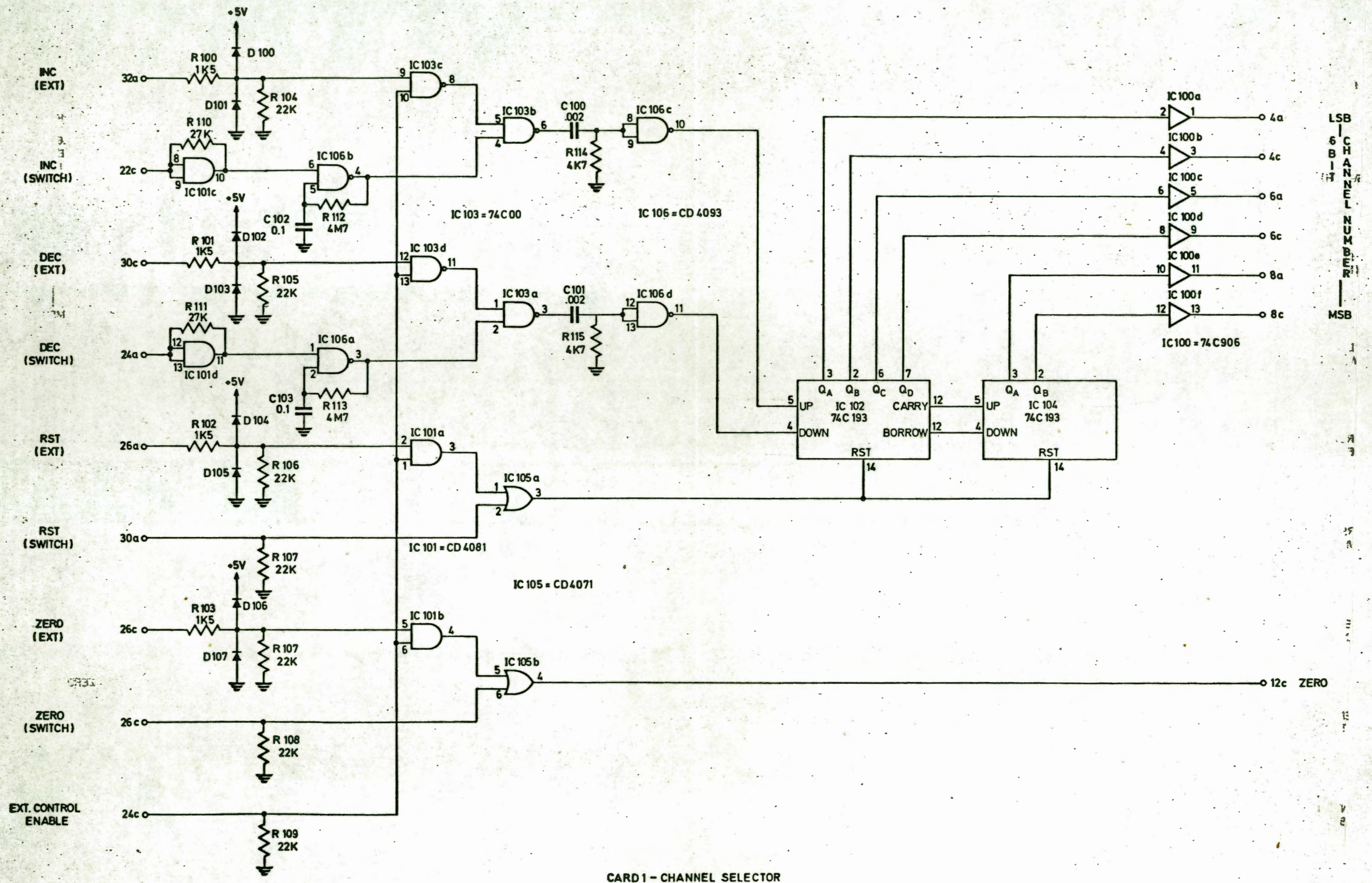
The channel selector generates a 6-bit binary word corresponding to the number of the channel that is to be selected. It comprises essentially a 6-bit binary up/down counter which may be incremented, decremented or reset to zero. These instructions may come from the front panel push buttons for manual operation, or via the external control inputs. The zero inputs, for the balancing circuit, from the front panel switch and external input are routed via this card. When the strain gauge amplifier is used manually, all the external control inputs may be disabled by a front panel switch.

ICs 102 and 104, each a 4-bit up/down counter, are cascaded to form the required 6-bit up/down counter.

ICs 101c and 101d debounce the outputs of the front panel increment and decrement switches respectively while ICs 106b and 106a each form a gated oscillator. If a switch is held down, the respective oscillator is turned on, stepping the counter at a nominal 2Hz rate in the required direction. This facilitates rapid manual access to any desired channel.

All four of the external control inputs are protected against excessive positive or negative input voltages by resistor-diode networks. These inputs are gated by ICs 103c, 103d, 101a and 101b and are disabled when the external control enable line is taken low by the front panel switch.

The 6-bit counter output drives a 15V bus via the open drain buffers of IC 100. If only 32 of the possible 64 channels are to be used, A5 is wired permanently low so that the channel address may only take on values between 0 and 31.



CARD 1 – CHANNEL SELECTOR

APPENDIX E

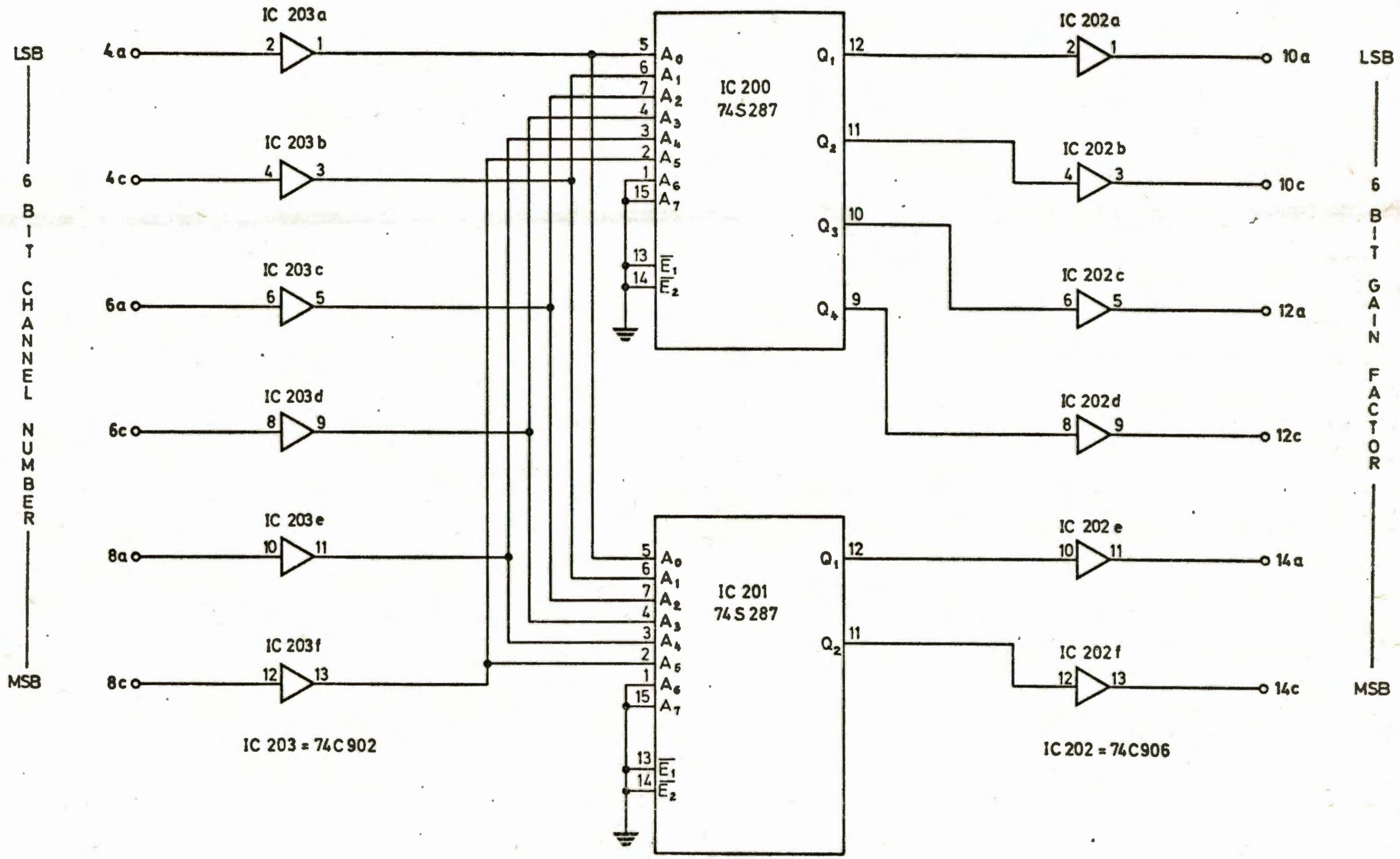
Card 2 - Gain factor memory

The channel gain factors are stored in two fusible link programmable read only memories (PROMs). Each PROM is arranged as 256 words of 4 bits each, the two together making a 256 x 8 bit memory. Of this, only 64 x 6 bits is used.

IC 203 converts the 15V logic of the channel address bus to 5V logic so as to be compatible with the PROMs, ICs 200 and 201. The 6-bit memory output drives a 15V bus via the open drain buffers of IC 202.

Channel	Gain factor	Channel	Gain Factor
0	33 (100001)	16	27 (011011)
1	25 (011001)	17	24 (011000)
2	25 (011001)	18	19 (010011)
3	33 (100001)	19	21 (010101)
4	27 (011011)	20	15 (001111)
5	38 (100110)	21	20 (010100)
6	25 (011001)	22	21 (010101)
7	27 (011011)	23	26 (011010)
8	27 (011011)	24	22 (010110)
9	18 (010010)	25	31 (011111)
10	20 (010100)	26	21 (010101)
11	25 (011001)	27	23 (010111)
12	20 (010100)	28	29 (011101)
13	21 (010101)	29	31 (011111)
14	19 (010011)	30	21 (010101)
15	16 (010000)	31	26 (011010)

32 gain factors have been programmed into memory as the force plate used has only 16 beams and hence 32 force transducers.



CARD 2 - GAIN FACTOR MEMORY

APPENDIX F

Card 3 - Successive approximation circuitry and offset memory

Each channel has, associated with it, a 16-bit memory which is used to store the offset required to drive the strain gauge amplifier output to zero with that channel's force transducer selected by the input multiplexer.

Each of the random access memories (RAMs), ICs 303, 304, 305 and 306, is arranged as 256 words of 4 bits each, the four together making a 256 x 16 bit memory. Of this, only 64 words are used, the required 16-bit word being selected by the 6-bit channel address.

The 16-bit successive approximation conversion is performed in two stages, first the 8 most significant bits followed by the 8 least significant bits. IC 308, a 74C905 12 bit CMOS successive approximation register, forms the basis of the conversion circuitry.

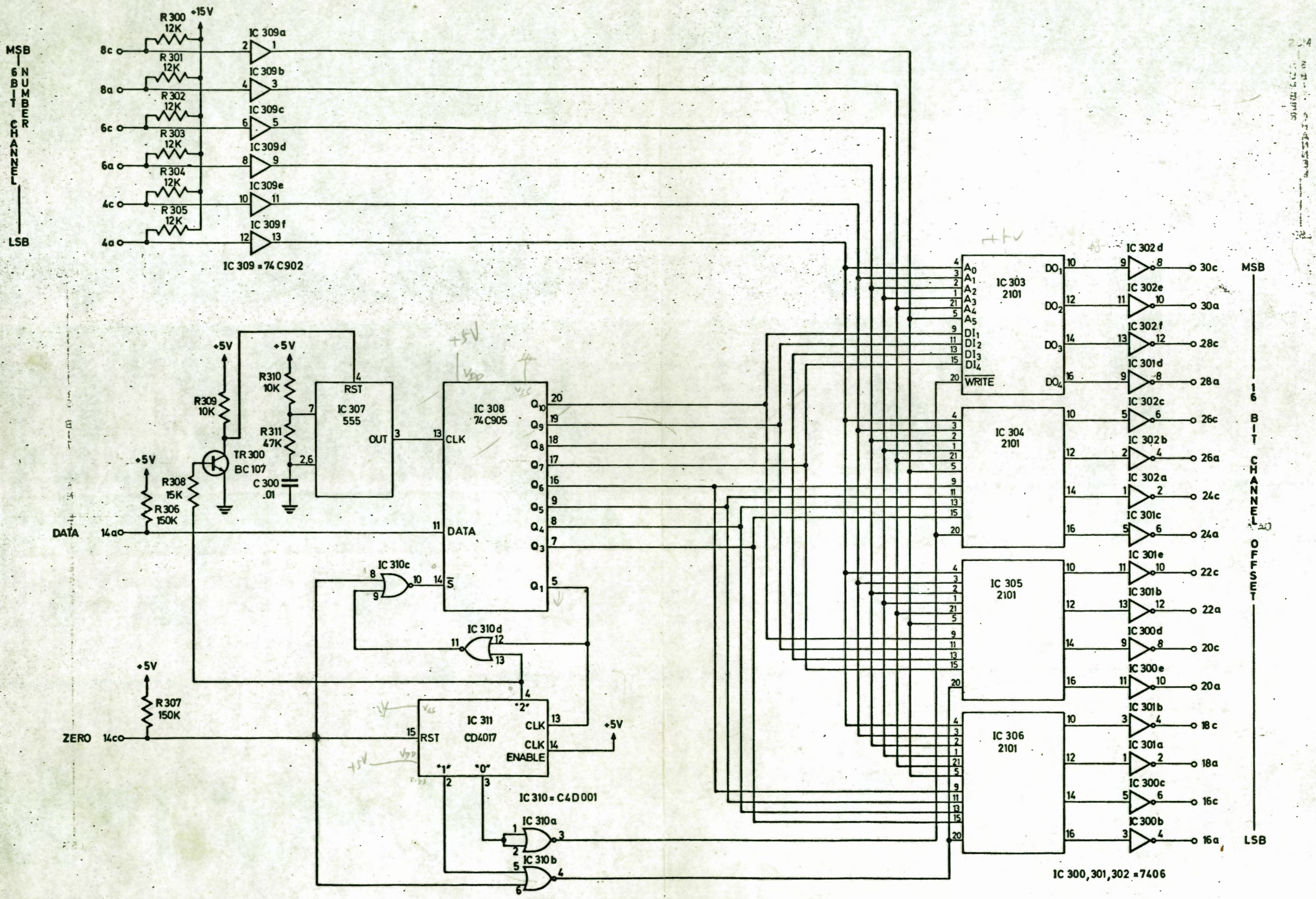
When the ZERO input is taken high, the counter IC 311 and the successive approximation register IC 308 are reset. The outputs, Q_{10} to Q_3, of IC 308 are all low and the $\overline{\text{WRITE}}$ inputs to ICs 303, 304, 305 and 306 are also all low, thus writing zeroes into all 16 bits.

When the ZERO input returns to its low state the $\overline{\text{WRITE}}$ inputs to ICs 303 and 304 remain low keeping these ICs in the write mode while the $\overline{\text{WRITE}}$ inputs to ICs 305 and 306 go $\overset{H}{\text{low}}$, putting them in the read mode. All zeroes were previously written into the memory and these continue to be present at the data outputs of ICs 305 and 306.

IC 308 then performs an 8-bit successive approximation conversion on the eight most significant bits. The outputs Q_{10} to Q_3 are taken high in succession and will remain high or return to their low state depending on the DATA input to IC 308 as determined by the comparator at the strain gauge amplifier output. At the end of this first cycle the 8 most significant bits have been determined.

Q_1 then goes high, advancing the counter IC 311 to a count of "1". This causes ICs 303 and 304 to be put into the read mode thus storing the 8 most significant bits while ICs 305 and 306 are put into the write mode enabling the second cycle of the conversion to be effected. Q_1 also resets the successive approximation register IC 308 thus initiating the second cycle for the 8 least significant bits.

When Q_1 goes high for the second time, the counter is advanced to a count of "2". The $\overline{\text{WRITE}}$ inputs of all four memory ICs are then high and the entire 16-bit conversion is complete. The 1.4 kHz clock used for IC 308 is turned off to reduce interference to other parts of the strain gauge amplifier.



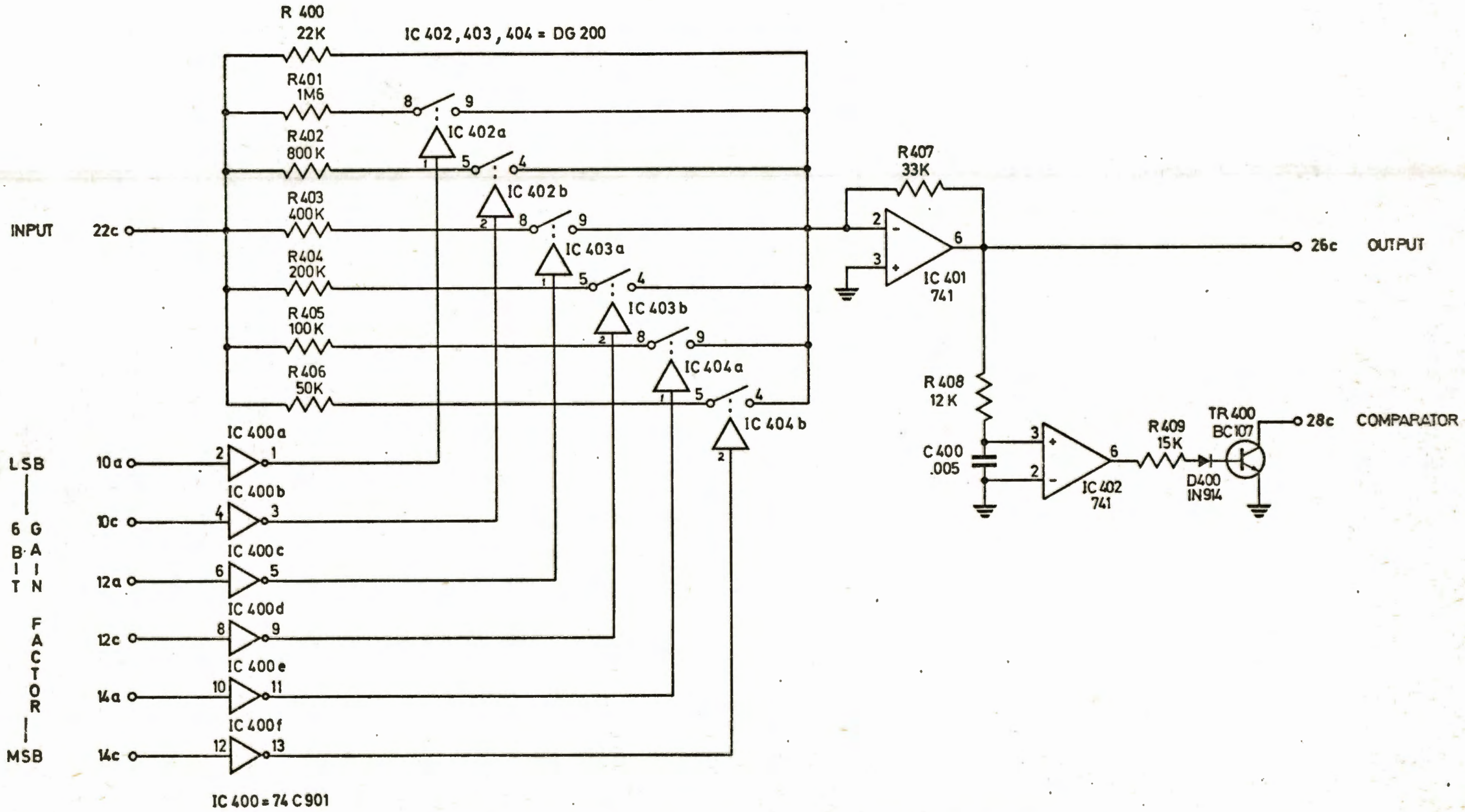
CARD 3 – SUCCESSIVE APPROXIMATION CIRCUITRY AND OFFSET MEMORY

APPENDIX G

Card 4 - Digitally programmable gain amplifier and comparator

The programmable gain amplifier is a conventional inverting amplifier configuration using an operational amplifier in which the gain is specified by the ratio of feedback resistance to input resistance. The effective input resistance is dependent on the states of the 6 analogue switches of ICs 402, 403 and 404 which are controlled by the 6-bit gain factor. The input resistance may vary from 22k, for a gain factor of 0 (000000), to 11.8k for a gain factor of 63 (111111). Since the feedback resistance is 33k, the gain may vary from 1.5 to 2.8. This gives a gain control range of 2.05 ± 36% in 64 discrete steps which is sufficient to calibrate any of the force transducers to an accuracy of better than 1%.

The output is low pass filtered by R409 and C400 before being fed to the comparator used in the bridge balancing circuitry to determine whether the output is greater or less than zero. R410, D400 and TR400 convert the comparator output to logic levels compatible with the bridge balancing circuitry.



CARD 4 – DIGITALLY PROGRAMMABLE GAIN AMPLIFIER AND COMPARATOR

APPENDIX H

Card 5 - Digital to analogue converter and offset removing amplifier

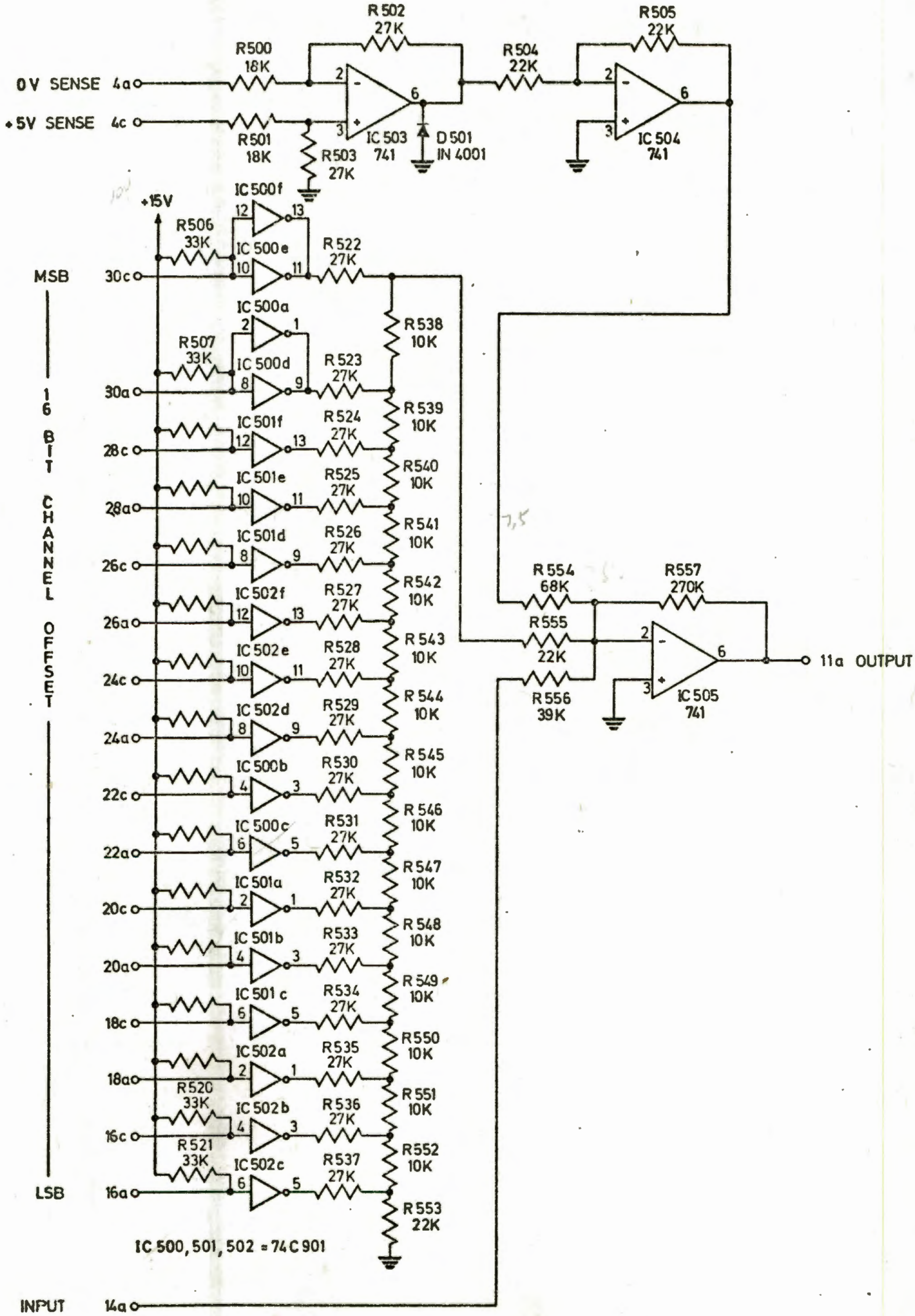
This card comprises a differential to single ended (D-SE) converter, a 16-bit digital to analogue (D-A) converter, an analogue inverter and an adder.

The differential to single ended converter incorporating the operational amplifier IC 503 senses the strain gauge bridge energising voltage at the force plate and converts it to a ground references potential. The converter has a gain of 1.5 so that the bridge energising voltage of 5V results in an output of 7.5V which is used as the voltage reference for the D-A converter.

The D-A converter consists of 18 CMOS buffers driving a 10k-27k resistor ladder network. The D-SE converter output is used as the positive supply rail of the buffers which means that the output of any buffer may be OV or equal to the converter output voltage.

The D-A converter output is added to the input from the strain gauge pre-amplifier at the virtual earth summing point of IC 505. With a D-SE converter output of 7.5V, the ladder network can source from 0 to 220μA. The D-SE converter output is inverted by IC 504 and is used to sink a fixed current of 110μA from the virtual earth point. This gives the D-A converter an effective range of ± 110μA which is sufficient to remove the largest possible offset from any input signal from the strain gauge pre-amplifier.

IC 505, as well as removing the offset, amplifies the input signal by 270k/39k = 6.92.



CARD 5 — DIGITAL TO ANALOGUE CONVERTER AND OFFSET REMOVING AMPLIFIER

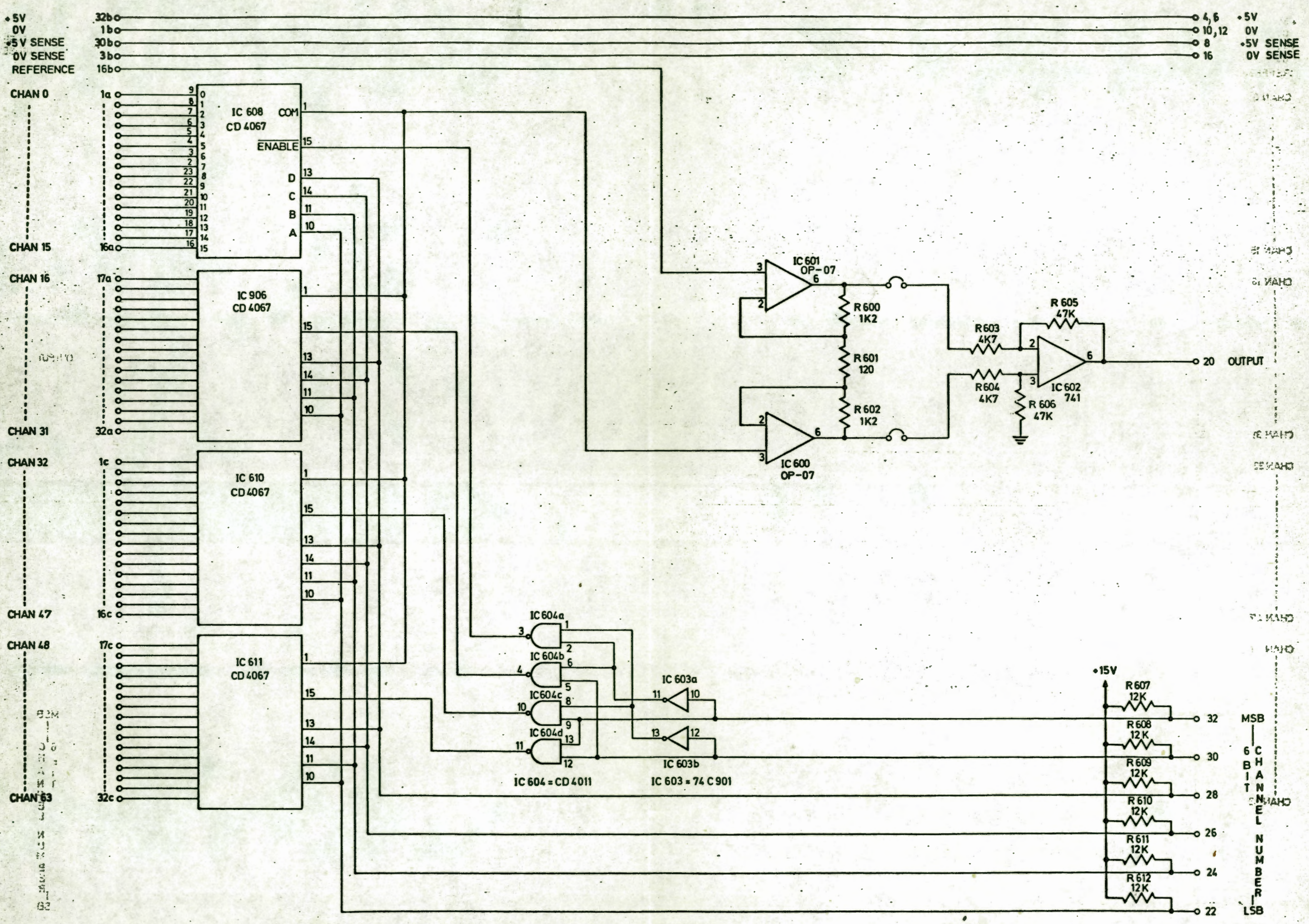
APPENDIX I

Card 6 - 64 channel multiplexer and differential amplifier

The 64 channel multiplexer consists of four CD4067 16 channel CMOS multiplexers. The 4 least significant bits of the channel address are fed directly to the address inputs of each multiplexer. The 2 most significant bits are decoded by ICs 603 and 604 to generate a one out of four output, each of which is used to enable one or the four multiplexers. In this way an individual channel is selected.

The differential voltage between the force transducer selected by the input multiplexer and the reference strain gauge circuit is amplified by the high input impedance differential stage consisting of two OP-07 operational amplifiers ICs 600 and 601. This multiplies the differential voltage by 21 and the common mode voltage by unity.

The second stage uses a 741 operational amplifier in a differential to single ended converter with a gain of ten. In order to achieve a large common mode rejection ratio in this stage it is necessary for the resistors R603, R604, R605 and R606 to be accurately matched. This is done by slightly reducing the resistance of R603 or R604, as required, by placing a large value resistor in parallel with it.



CARD 6 - 64 CHANNEL MULTIPLEXER AND DIFFERENTIAL AMPLIFIER

APPENDIX J

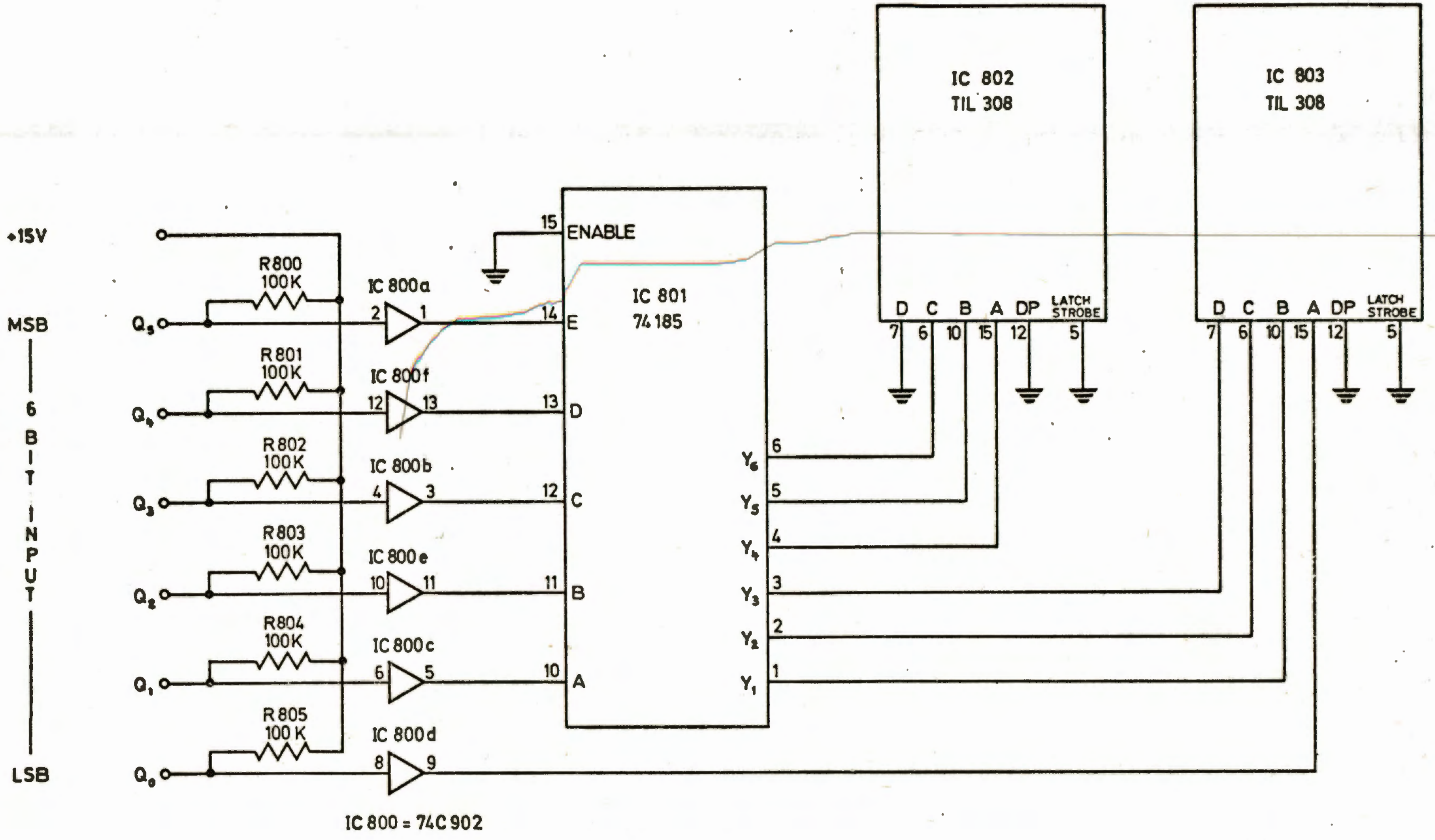
6-bit binary to binary coded decimal converter and 2 digit display

During manual operation of the strain gauge amplifier, it is necessary to know which channel has been selected.

The channel address as generated by card 1, the channel selector, is in binary format. This 6-bit binary word is buffered by IC 800 and converted to BCD by IC 801 which then drives a two digit display. IC 802 and IC 803 are 7-segment numeric displays with incorporated latch, decoder and LED drivers. The latch facility is not used here and the latch strobe is therefore tied low.

When the displays are not needed, they may be switched off by the front panel switch S705 which removes the 5V power to ICs 800, 801, 802 and 803. IC 800 does not have internal protection diodes and the input voltage may therefore exceed the supply voltage without damage.

An identical display module is used to display the 6-bit gain factor of the selected channel.



DISPLAY MODULE

APPENDIX K

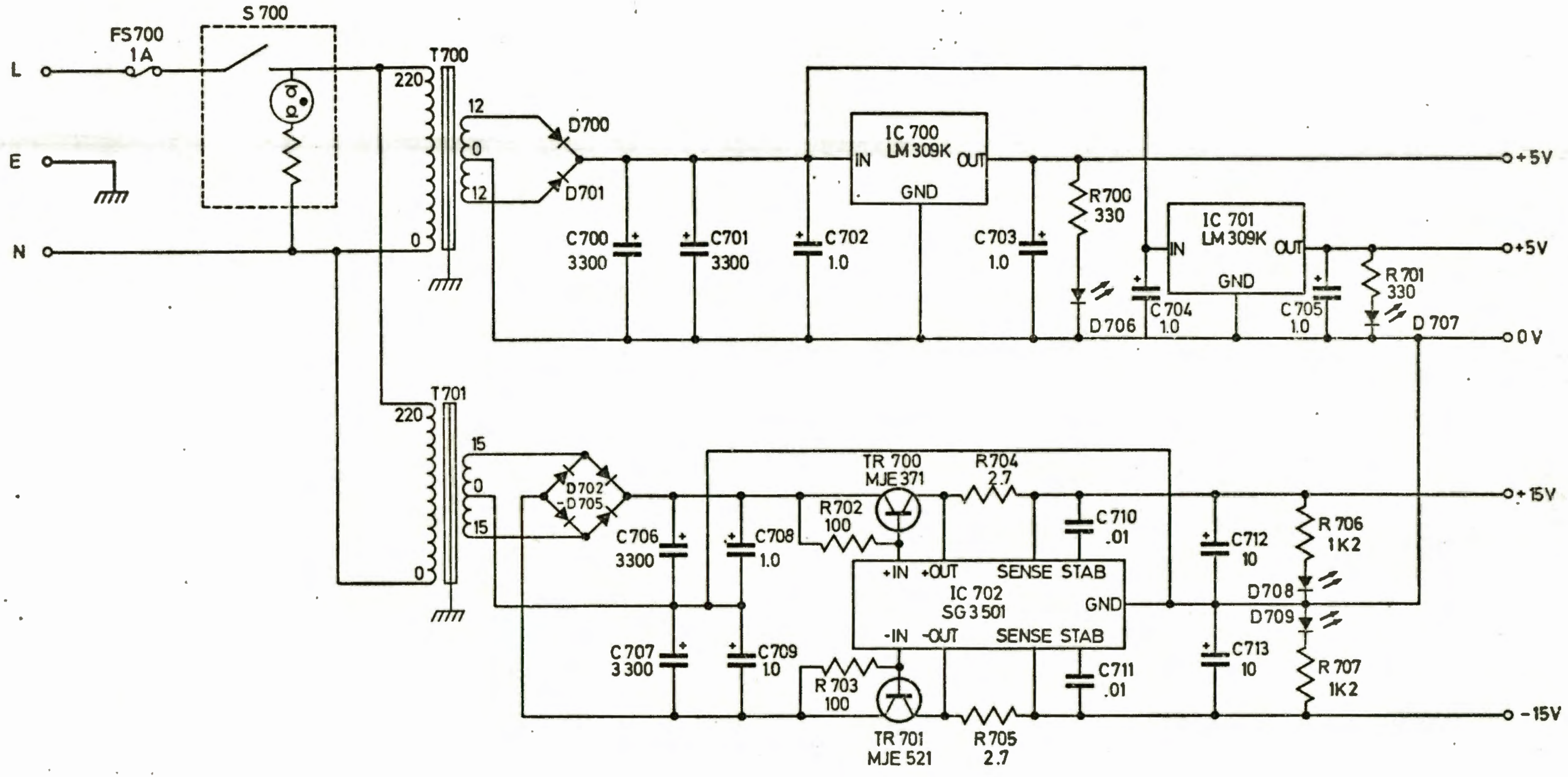
Power supply unit - strain gauge amplifier

The strain gauge amplifier power supply unit produces 5V at 1 amp to energise the strain gauge force transducers. In addition it produces 5V at 1 amp and ± 15V at .25 amps each to power the electronic circuitry.

The mains input to transformers T700 and T701 is via the 1 amp fuse FS700 and illuminated power switch S700. The output of transformer T700 is rectified by diodes D700 and D701, smoothed by capacitors C700 and C701, and regulated by ICs 700 and 701 to produce two separate 5V supplies, each capable of supplying 1 amp. Separate supplies are used for the strain gauge force transducers and the electronic circuitry so that any noise generated by the digital logic does not reach the force transducers via the power rails and so enter the input to the amplifier. Tantalum capacitors C702 to C705 improve the stability and regulation of the two 5V supplies.

The output of transformer T701 is rectified by diodes D702 to D705, smoothed by capacitors C706 and C707, and regulated by IC 702. The external pass transistors TR700 and TR701 carry the output currents for the +15V and -15V supplies respectively. Resistors R704 and R705 set the current limiting of these two supplies at 0.25 amps each. Capacitors C708 to C713 improve the stability and regulation of these supplies.

Light emitting diodes D706 to D709 are mounted on the front panel of the power supply unit and indicate the presence of each of the supply voltages.



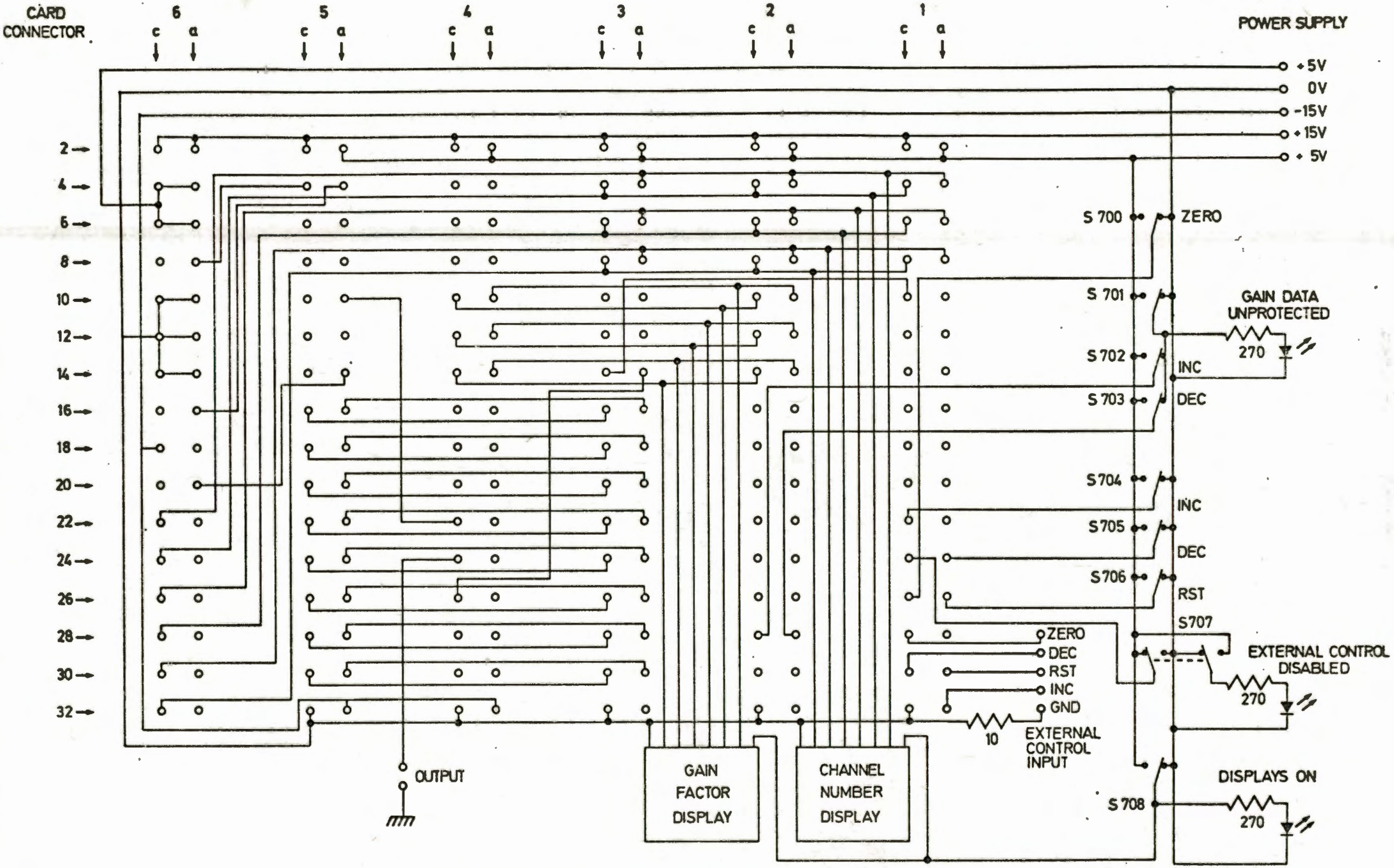
STRAIN GAUGE AMPLIFIER POWER SUPPLY UNIT

APPENDIX L

Main frame and front panel wiring - strain gauge amplifier

The interconnections between the circuit card edge connectors, power supply and front panel components is shown overleaf.

Switches S701, S702 and S703 were originally used to enter and store the channel gain factors into a CMOS memory which used a standby battery to maintain this data when the amplifier was turned off. This circuit card was eventually replaced by card 2 which has these gain factors permanently programmed into a read-only-memory. The switches mentioned above therefore perform no function at all in the final design.



STRAIN GAUGE AMPLIFIER MAIN FRAME AND FRONT PANEL WIRING

APPENDIX M

Card 1 - Stop/start unit

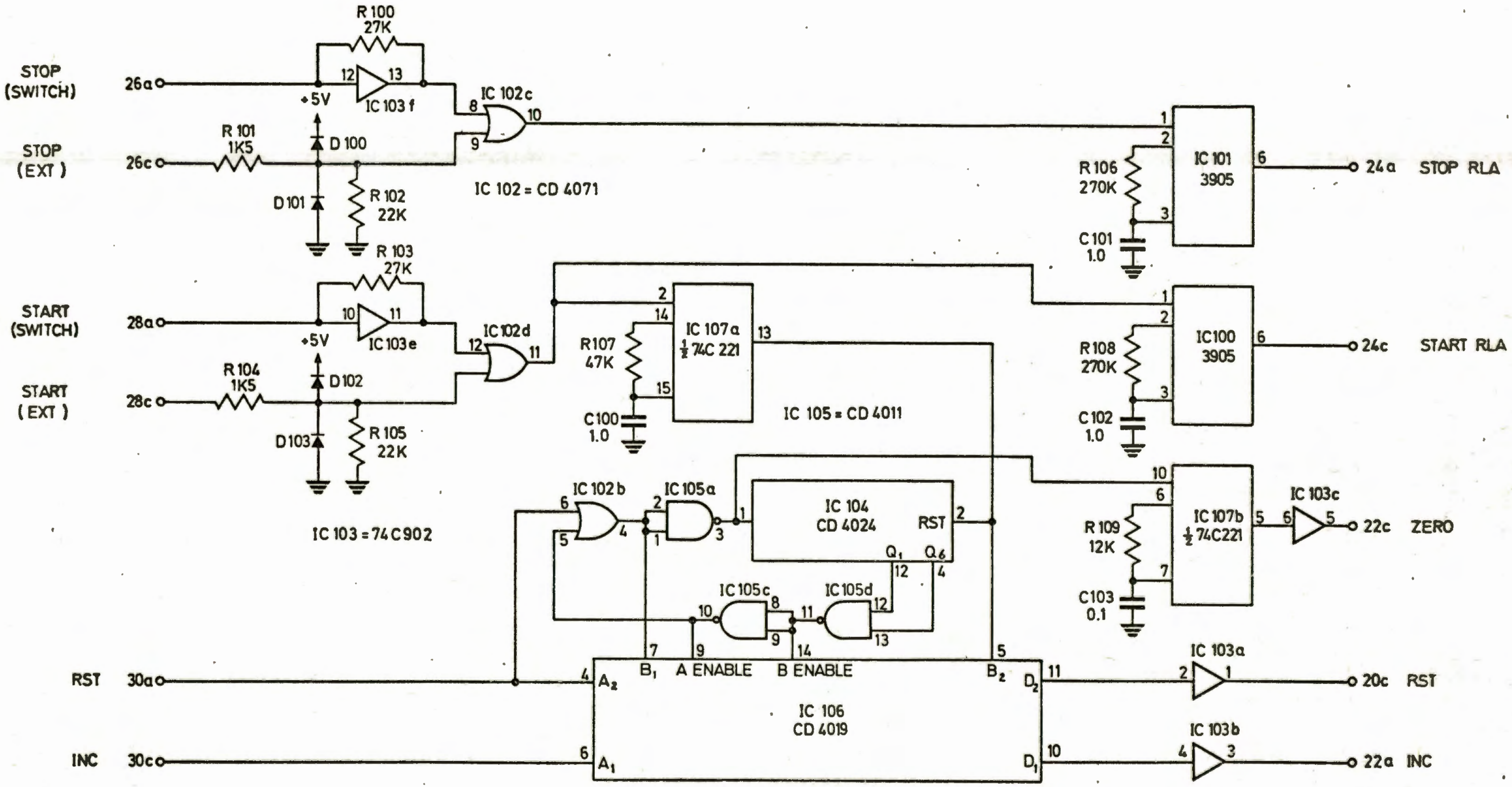
When a START command is given, each channel of the strain gauge amplifier is selected and balanced. Also the video tape recorder (VTR) is started and put into the record mode. When a STOP command is given, the VTR is stopped. These stop and start instructions may come from the front panel switches or via the external control inputs.

ICs 103f and 103c debounce the outputs of the front panel stop and start switches respectively. The external control inputs are protected against excessive positive or negative input voltages by resistor-diode networks. The two stop inputs are gated together by IC 102c while the two start inputs are gated together by IC 102d to give single stop and start outputs.

The RST and INC inputs to the stop/start unit are both generated by the master clock and synchronisation card. The RST input is a rectangular waveform which goes high for lines 0-2 in each video field while the INC input is a more complex pulse train consisting of 32 pulses every video frame. Normally these inputs are fed via the AND-OR select gate, IC 106, and buffers, IC 103a and IC 103b, to the strain gauge amplifier to control its input multiplexer.

When a START command is given, the output of IC 102d goes high triggering monostables IC 100 and IC 107a. IC 100 produces an output pulse with a period of about 300 msec, directly operating an external relay which starts the VTR running in the record mode. IC 107a produces a positive going pulse with a period of about 50 msec, resetting the counter IC 104 which was previously at a count of 33. Since the Q outputs of the counter are now all low, the output of IC 105d is high and the output of IC 105c is low. This disables the A inputs to the selector gate IC 106 and enables its B inputs. The output pulse of monostable IC 107a, which reset the counter, is now fed to the RST output thus resetting the input multiplexer of the strain gauge amplifier to channel 0. With the output of IC 105c high, the RST input to the stop/start unit is fed via IC 102b to the B_1 input of the selector gate and via IC 105a to the clock input of the counter and to the trigger input of monostable IC 107b. When the RST input goes high, the counter is advanced and the INC output goes high, advancing the input multiplexer of the strain gauge amplifier by one channel. When the RST input goes low again, so does the INC output. In addition, the monostable IC 107b is triggered, producing a 1.2 msec positive going pulse which activates the bridge balancing circuitry of the strain gauge amplifier thus zeroing the selected channel. This incrementing and zeroing routine continues for 32 pulses of the RST input thus balancing all 32 channels of the strain gauge amplifier. When the RST input goes high for the 33rd time, the counter is advanced to a count of 33 so that the Q_1 and Q_6 outputs are both high. This causes the output of IC 105d to go low and the output of IC 105c to go high, enabling the A inputs and disabling the B inputs of the selector gate. This also prevents further pulses from reaching the counter via IC 102b so that the counter remains at a count of 33 until reset. All 32 channels of the strain gauge amplifier have now been balanced and the input multiplexer is once again under the control of the master clock and synchronisation card. The entire bridge balancing routine lasts for 32 x 20 msec = 640 msec.

When a STOP command is given, the output of IC 102c goes high triggering monostable IC 101 which produces a 300 msec pulse to operate an external relay to stop the VTR. External relays are used so as to be able to interface to any VTR which has remote control facilities by using a suitable 2 relay control unit. VTRs may therefore be interchanged without having to alter any internal wiring. Also a number of VTRs use relatively high voltages to operate their controls. Using external relays keeps these dangerous potentials out of the central controller/video processor thus eliminating the shock hazard to anyone servicing or repairing the unit who might not be aware of this danger.



CARD 1 – STOP/START UNIT

APPENDIX N

Card 2 - Master clock and synchronisation unit

ICs 202a and 202b form an oscillator whose frequency is held at 10 MHz by a crystal. This oscillator is buffered by IC 202d and divided in frequency by 5, by IC 201, to produce the basic 2 MHz clock frequency.

The 2 MHz clock frequency is divided by 39936 by the synchronous counting chain consisting of ICs 204, 203, 206, 205 and 200. This divider may be considered as a divide by 128 stage and a divide by 312 stage. The output of the divide by 128 counter or row counter uniquely define any ½ μsec period in a video line while the divide by 312 counter or line counter uniquely defines any video line in the video field. Together, these two counters define any ½ μsec period in a video field.

The complex pulse trains required to synchronise the system are stored in read only memories (ROMs). The row counter outputs R_0 - R_6 address the inputs to the ROMs, ICs 207 and 208 and the line counter outputs L_0 - L_8 address ROMs, ICs 209 and 210.

The Q_1 output of IC 207 has logical highs programmed for rows 119 - 8. The Q_1 output of IC 209 has logical highs programmed for lines 0 - 2. These two outputs and the R_6 output of the row counter are gated together by ICs 211d, 212b, 212c, 212d and 213d to produce the digital SYNC output to CCIR timing standards.

The Q_2 output of IC 207 has logical highs programmed for rows 125 - 20 while the Q_2 output of IC 209 has logical highs programmed for lines 310 - 22. IC 211d gates these two outputs together to produce the BLANK output.

The Q_3 output of IC 207 has logical highs programmed for rows 92 - 124 to enable the video output of camera 2 for these rows. Similarly, the Q_4 output of IC 207 has logical highs programmed for rows 57 - 89 to enable the video output from camera 1 for these rows.

The Q_1 output of IC 208 has logical highs programmed for rows 33 - 54 to trigger the sum timer. Similarly, the Q_2 output of IC 208 has logical highs programmed for rows 57 - 89 to trigger the ratio timer. These two outputs are gated with the Q_1 output of IC 210 which has logical highs programmed for lines 110 - 221 so that the sum and ratio timers are triggered for these lines only.

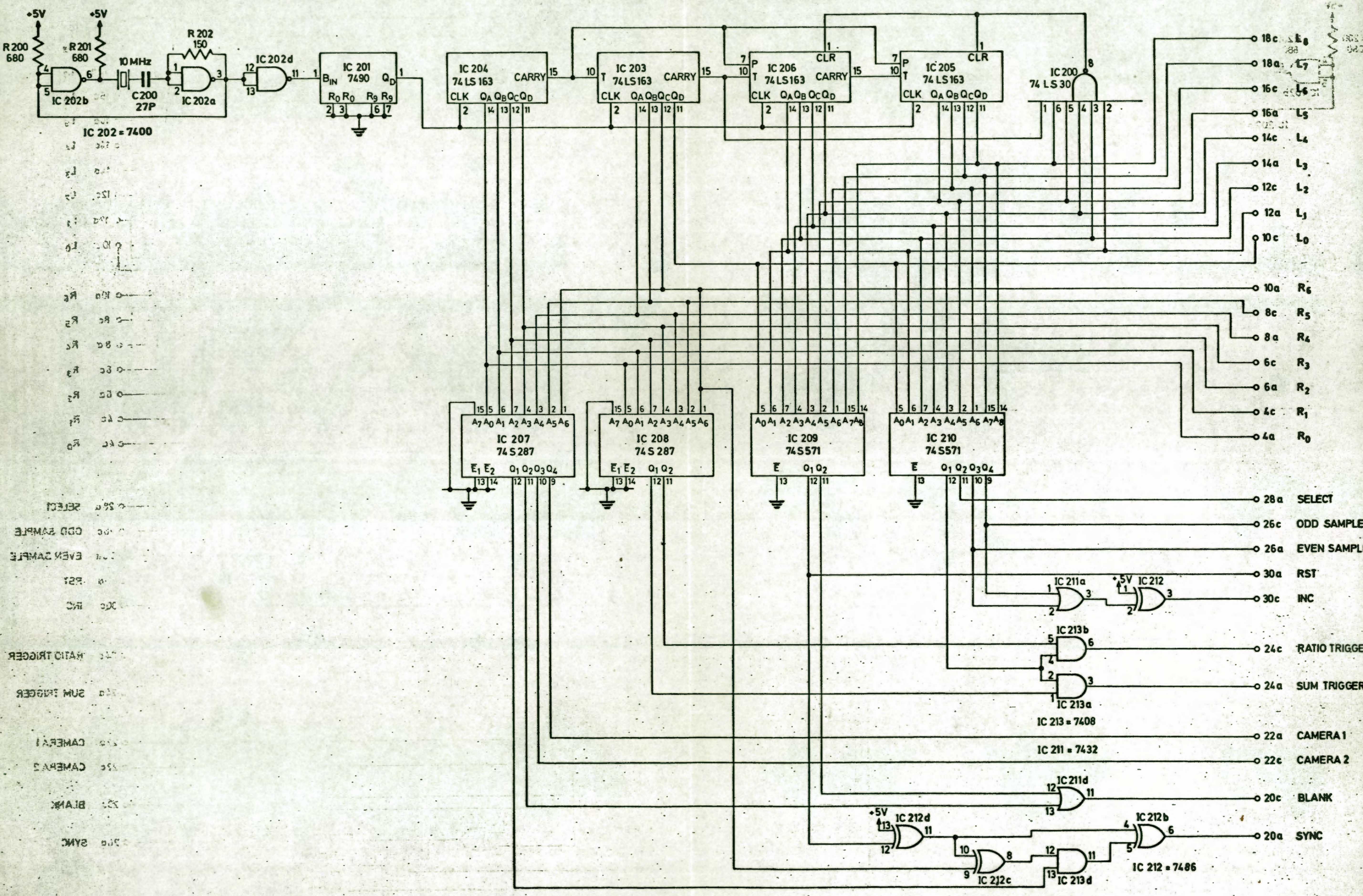
The Q_2 output of IC 210 has logical highs programmed for lines 110 - 116, 124 - 130, 138 - 144, 152 - 158, 166 - 172, 180 - 186, 194 - 200 and 208 - 214.

The Q_3 output of IC 210 has logical highs programmed for lines 104, 105, 111, 112, 118, 119, 125, 126, 132, 133, 139, 140, 146, 147, 153, 154, 160, 161, 167, 168, 174, 175, 181, 182, 188, 189, 195, 196, 202, 203, 209 and 210.

The Q_4 output of IC 210 has logical highs programmed for lines 108, 109, 115, 116, 122, 123, 129, 130, 136, 137, 143, 144, 150, 151, 157, 158, 164, 165, 171, 172, 178, 179, 185, 186, 192, 193, 199, 200, 206, 207, 213 and 214.

These three signals control the storing and outputting of samples in the data capture unit as explained in section 2.4.6.

The Q_1 output of IC 209 is also used to reset the input multiplexer of the strain gauge amplifier to channel 0 at the start of a video field. The Q_3 and Q_4 outputs of IC 210, mentioned above, are also used to increment the input multiplexer. This is done by gating these two outputs together using ICs 211a and 212a so that the INC output goes high at the start of lines 106, 110, 113, 117, 120, 124, 127, 131, 134, 138, 141, 145, 148, 152, 155, 159, 162, 166, 169, 173, 176, 180, 183, 187, 190, 194, 197, 201, 204, 208, 211 and 215.



CARD 2 – MASTER CLOCK AND SYNCHRONISATION UNIT

APPENDIX O

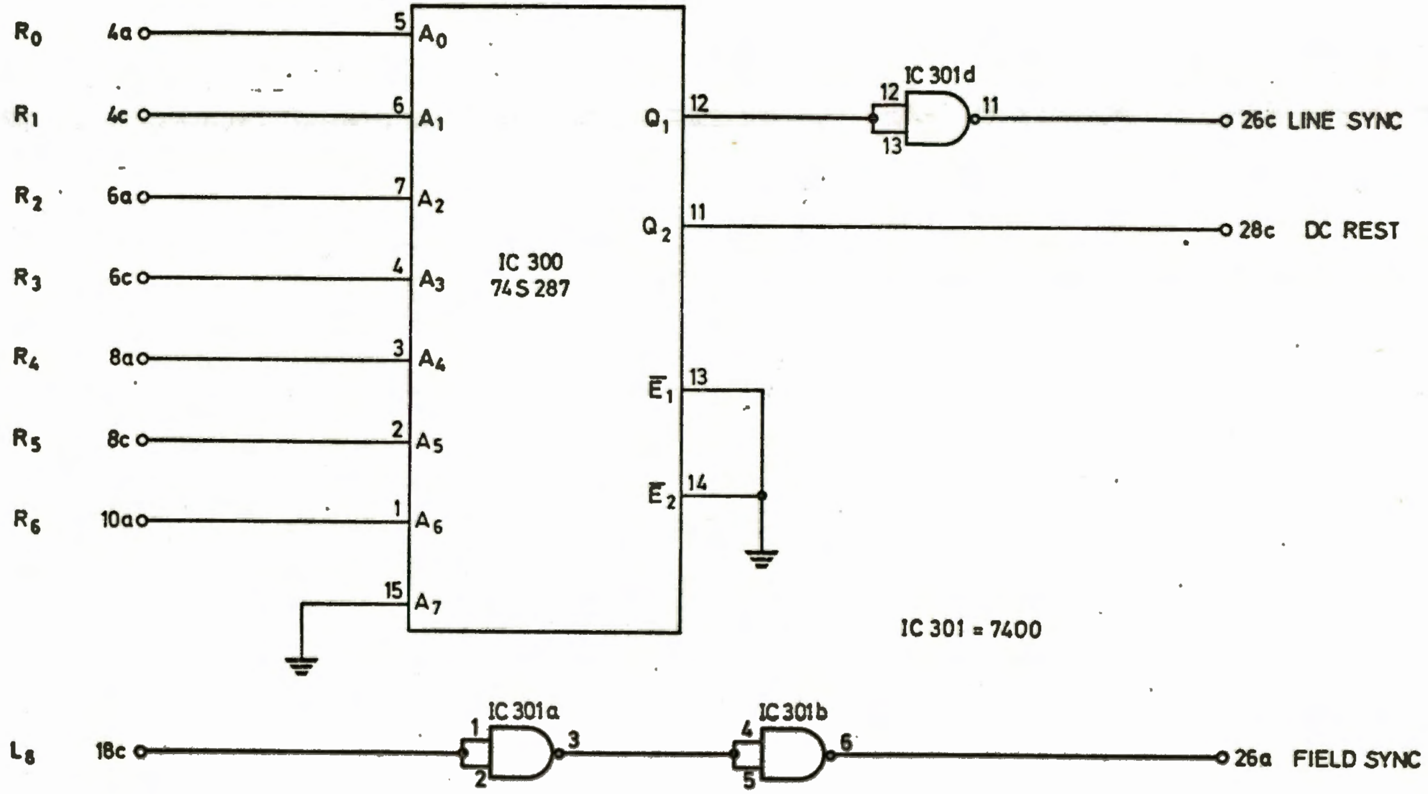
Card 3 - Camera 2 sync generator

Camera 2 is a National closed circuit television camera model WV-340N. This type of camera has facilities for external synchronisation, requiring negative going pulses to initiate its line and field scans.

The row counter outputs R_0 - R_6 are fed to the address inputs of the programmable read-only-memory (ROM) IC 300. This is a 256 x 4 bit memory of which only 128 x 2 bits are used. For the Q_1 output, logical highs have been programmed at locations 124 - 127 and 0 - 5 which produces a 5 µsec positive pulse at the beginning of each line. This pulse is inverted by IC 301d and used as the line sync signal for the camera.

With the line deflection circuitry triggered by this signal, the back porch black level signal in the video output of the camera occurs during rows 9 - 20 of the row counter. The Q_2 output of IC 300 therefore has logical highs programmed at locations 12 - 17 which produces a 3 µsec pulse in the middle of the back porch for DC restoration purposes.

The negative going pulse required to trigger the field deflection circuitry is directly available as the L_8 output of the line counter. This is buffered by ICs 301a and 301b before being fed to the camera.



CARD 3 – CAMERA 2 SYNC GENERATOR

APPENDIX P

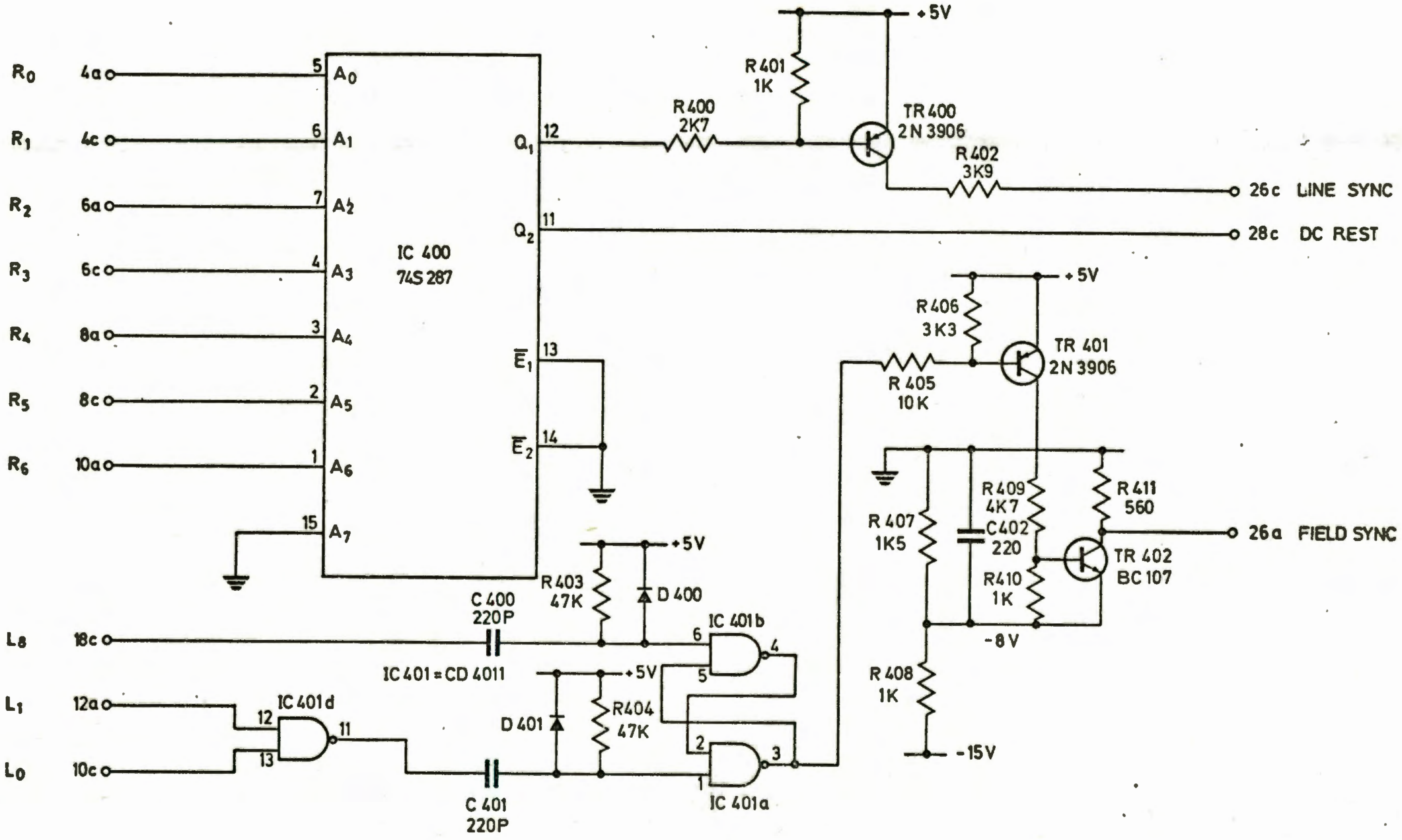
Card 4 - camera 1 sync generator

Camera 1 is a Philips closed circuit television camera model LDH 0050. Although this type of camera is not specifically designed for external synchronisation, there are removable links between the line oscillator and line scanning circuitry and between the field oscillator and field scanning circuitry. By removing these links it is possible to feed external signals into the line and field scanning circuitry and thus achieve external synchronisation.

The row counter outputs R_0 - R_6 are fed to the address inputs of the programmable read-only-memory (ROM) IC 400. This is a 256 x 4 bit memory of which only 128 x 2 bits are used. For the Q_1 output, logical highs have been programmed at memory locations 40 - 101 which produces a square wave output. This is interfaced to the line scanning circuitry by transistor TR400 which sources current only when the Q_1 output of IC 400 is low.

With the line scanning circuitry synchronised to this signal, the back porch black level signal in the video output of the camera occurs during rows 10 - 21 of the row counter. The Q_2 output of IC 400 therefore has logical highs programmed at locations 13 - 18 which produces a 3 μsec pulse in the middle of the back porch period for DC restoration purposes.

The field scanning circuitry requires an approximately 200 μsec pulse going down to -8V to initiate its scan. ICs 401a and 401b together form a set-reset latch. At the beginning of line 0, the L_8 output of the line counter goes low setting the latch so that the output of IC 401a goes low. At the beginning of line 3, the L_0 and L_1 outputs of the line counter are both high which causes the output of IC 401d to go low resetting the latch. The output of IC 401a is therefore low for lines 0 - 2, a period of 3 x 64 μsec = 194 μsec. During this period, transistors TR401 and TR402 are both turned on producing an output voltage of -8V. For the rest of the field, the output is at OV.



CARD 4 – CAMERA 1 SYNC GENERATOR

APPENDIX Q

Card 5 - Video mixer

The video mixer generates the composite video output of the complete system from the two camera video signals, the WHITE output of the sum and ratio timers, and the SYNC signal generated by the master clock and synchronisation unit.

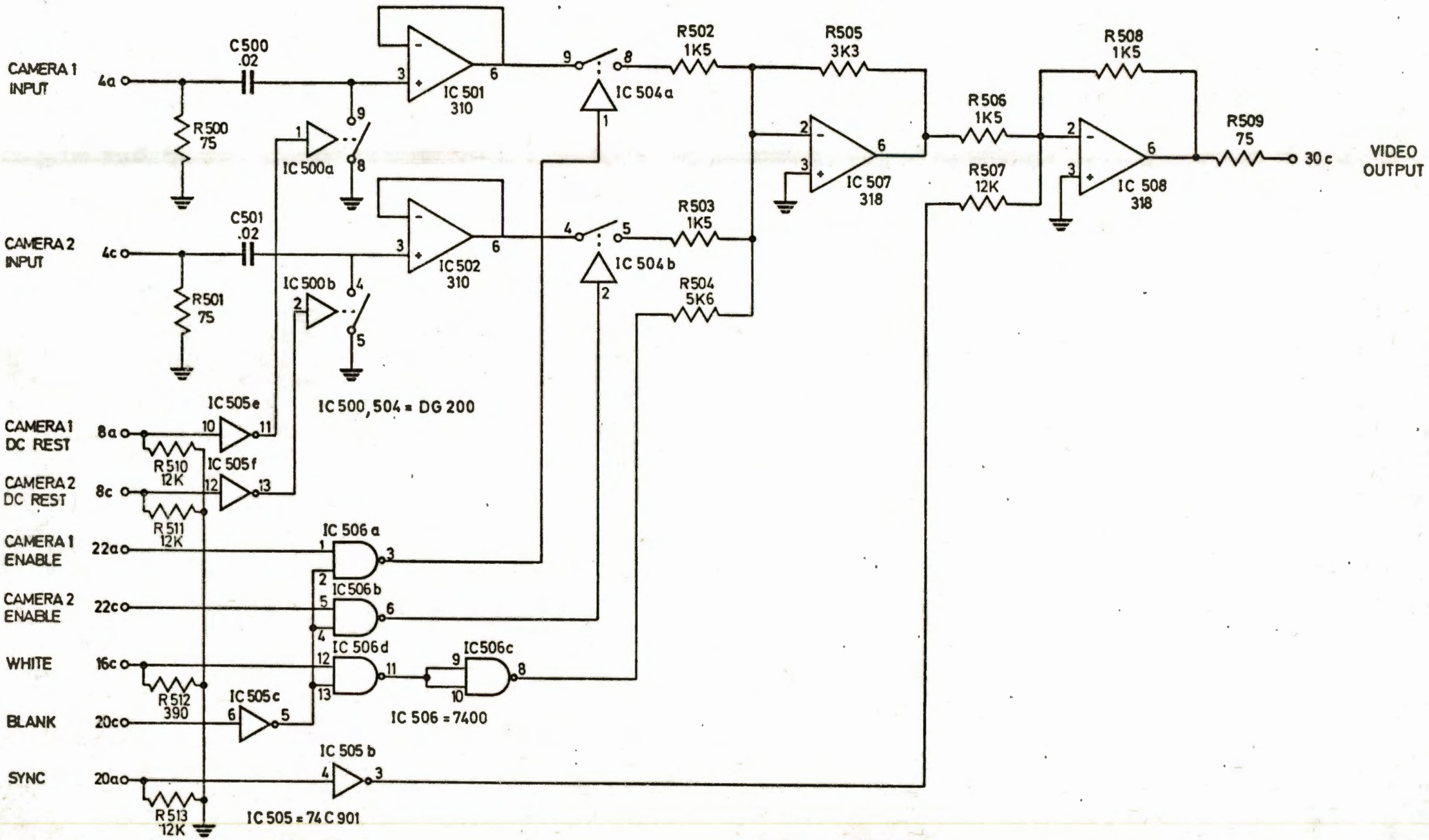
Each of the camera inputs has a standard 75 ohm input impedance. DC restoration of the input video signals is necessary so as to standardise the black and white video levels from each camera. The analogue switch IC 500a, under the control of the camera 1 sync generator, is closed for a 3 μsec period every line during the back porch black level video output of camera 1 so that the capacitor C500 is kept charged up to the DC level corresponding to the black level of that video signal. The output of the voltage follower IC 501 is therefore DC shifted in relation to the CAMERA 1 INPUT by the voltage stored in the capacitor so that a black level input produces a OV output.

DC restoration is similarly performed on the camera 2 video signal by ICs 500b and 502 together with capacitor C501.

Either of the DC restored video signals from the cameras may be fed to the summing point of IC 507 by taking the respective CAMERA ENABLE input high. The white level video signals required to produce the bar chart and centre of pressure display are generated by taking the WHITE input high at the correct instants. When the BLANK input goes high, during line and field flyback, both CAMERA ENABLE inputs and the WHITE input are disabled.

IC 507 inverts and amplifies the selected camera video signal by a factor of two and IC 508, having unity gain, re-inverts the video signal. The VIDEO OUTPUT has an output impedance of 75 ohm which is determined by R509. This, together with a 75 ohm external load, halves the open circuit output voltage so that the cmaera video signal is restored to its original amplitude.

The line and field sync pulses occur during the blanking time. When the $\overline{\text{SYNC}}$ input goes low, the output of IC 505b goes high to +5V which in turn causes the output of IC 508 to go to -0.6V. Since the VIDEO OUTPUT drives a 75 ohm load the sync output level there is halved to -0.3V.



CARD 5 - VIDEO MIXER

APPENDIX R

Card 6 - Data capture unit and sum and ratio timers

IC 605 amplifies the strain gauge amplifier output by 10 before feeding it to the inputs of the four sample and hold amplifiers ICs 601 to 604. The storing of samples in these amplifiers and the outputting of these stored samples onto the ODD and EVEN busses is controlled by the three inputs, EVEN SAMPLE, ODD SAMPLE and SELECT. Each beam N is supported by two force transducers 2N and 2N+1 so that each beam has an odd and an even numbered force transducer associated with it. The ODD and EVEN busses at any given moments are at potentials corresponding to the loads on the odd and even force transducers of the force plate beam being displayed by the monitor at that moment. The way that this is achieved is explained in section 2.4.6.

When the SELECT input is low, the outputs of ICs 602 and 604 drive the EVEN and ODD busses respectively via the analogue switches of IC 606. ICs 600a and 600b are enabled so that the output of IC 605 may be stored in sample and hold amplifier IC 601 or 603 by taking the EVEN SAMPLE or ODD SAMPLE input high. Conversely, when the SELECT input is high, the outputs of ICs 601 and 603 drive the EVEN and ODD busses and samples may be stored in sample and hold amplifiers ICs 602 and 604.

The resistor-diode networks in series with each of the storage capacitors reduce the effects of input noise on the voltage stored in that capacitor. This noise reduction technique is explained in section 2.4.6.

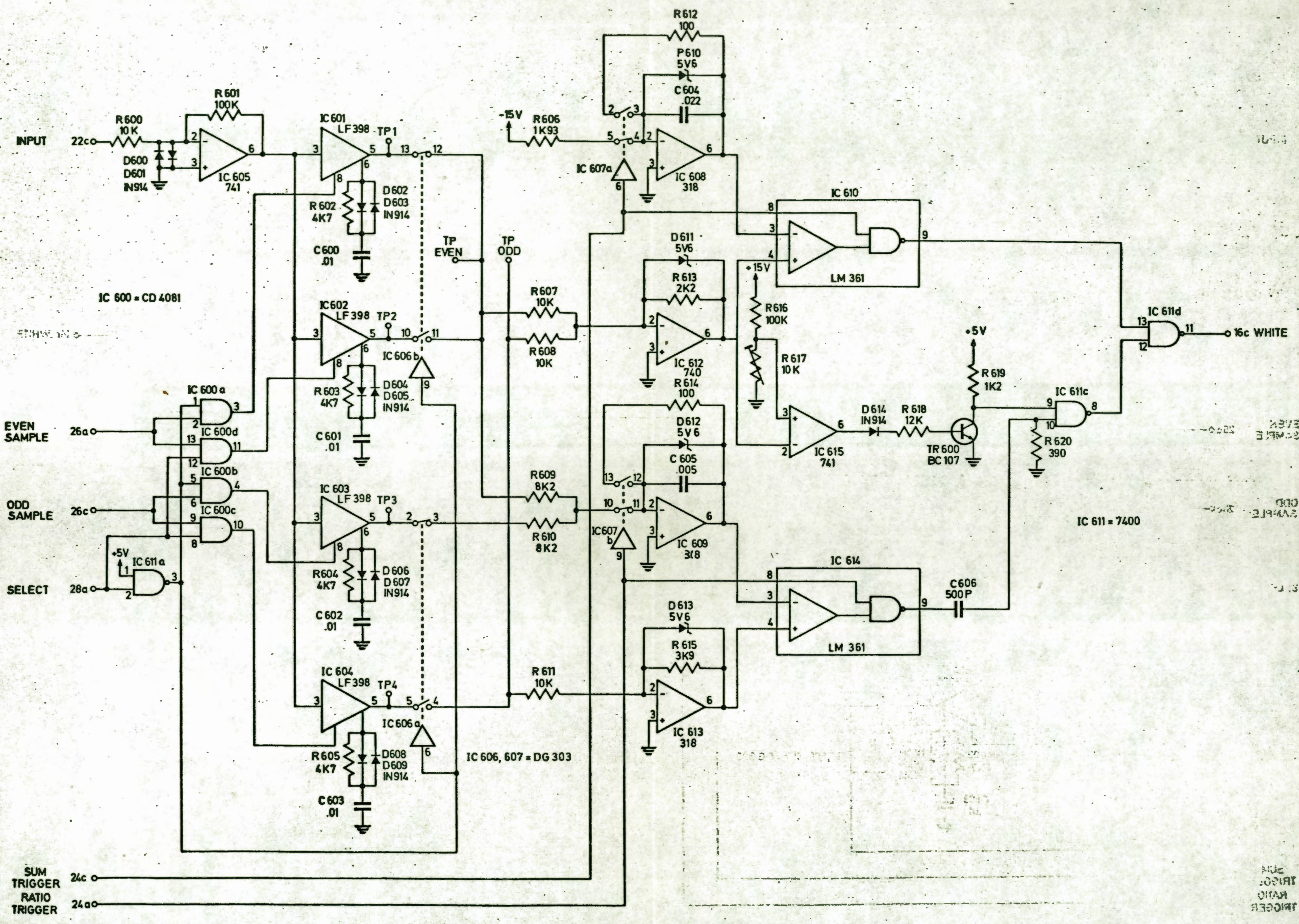
The ratio timer, which determines the position of the centre of pressure lines from the voltages on the EVEN and ODD busses and hence from the forces at each end of the beam being displayed, consists of ICs 607b, 609, 613, 614 and 611c.

When the RATIO TRIGGER input goes high, the output of the integrator IC 609 begins to rise at a rate proportional to the sum of the voltage on the ODD and EVEN busses. When the integrator output exceeds the threshold set by the output of IC 613, which is proportional to the voltage on the ODD buss, the output of the comparator IC 614 goes high. The pin 10 input to IC 611c goes high for a period of 200 nsec determined by R620 and C606. This, in turn, causes the WHITE output to go high for 200nsec producing a white spot on the monitor screen.

The time elapsed between the RATIO TRIGGER input going high and the output of IC 614 going high is proportional to the voltage on the ODD bus, and inversely proportional to the sum of the voltages on the EVEN and ODD busses. With equal voltages on the two busses the elapsed time is 8.2 μsec which will position the centre of pressure line in the middle of the 16.5 μsec period of the line scan allocated to the view of the plantar surface of the foot and hence in the middle of the image of the force plate beam.

The sum timer, which determines the length of each bar of the bar chart from the sum of the voltages on the EVEN and ODD busses and hence from the sum of the force at each end of the force plate beam being displayed, consists of ICs 607a, 608, 612 and 610. The sum timer is almost identical to the ratio timer except that the integrator input is connected to the -15V power rail so that the integrator output always rises at the same rate when triggered. The output of IC 610 is low from the time that the SUM TRIGGER is taken high until the integrator output exceeds the threshold set by the output of IC 612 which is proportional to the sum of the voltages on the EVEN and ODD busses. The WHITE output is high for this period so that the bar chart height is proportional to the sum of the forces on the ends of the force plate beam.

The comparator IC 614 senses the output of IC 612 and if it falls below the threshold set by R616 and R617 then its output goes high. This saturates transistor TR600 thus disabling the output of the ratio timer and so suppressing the display of the centre of pressure line.



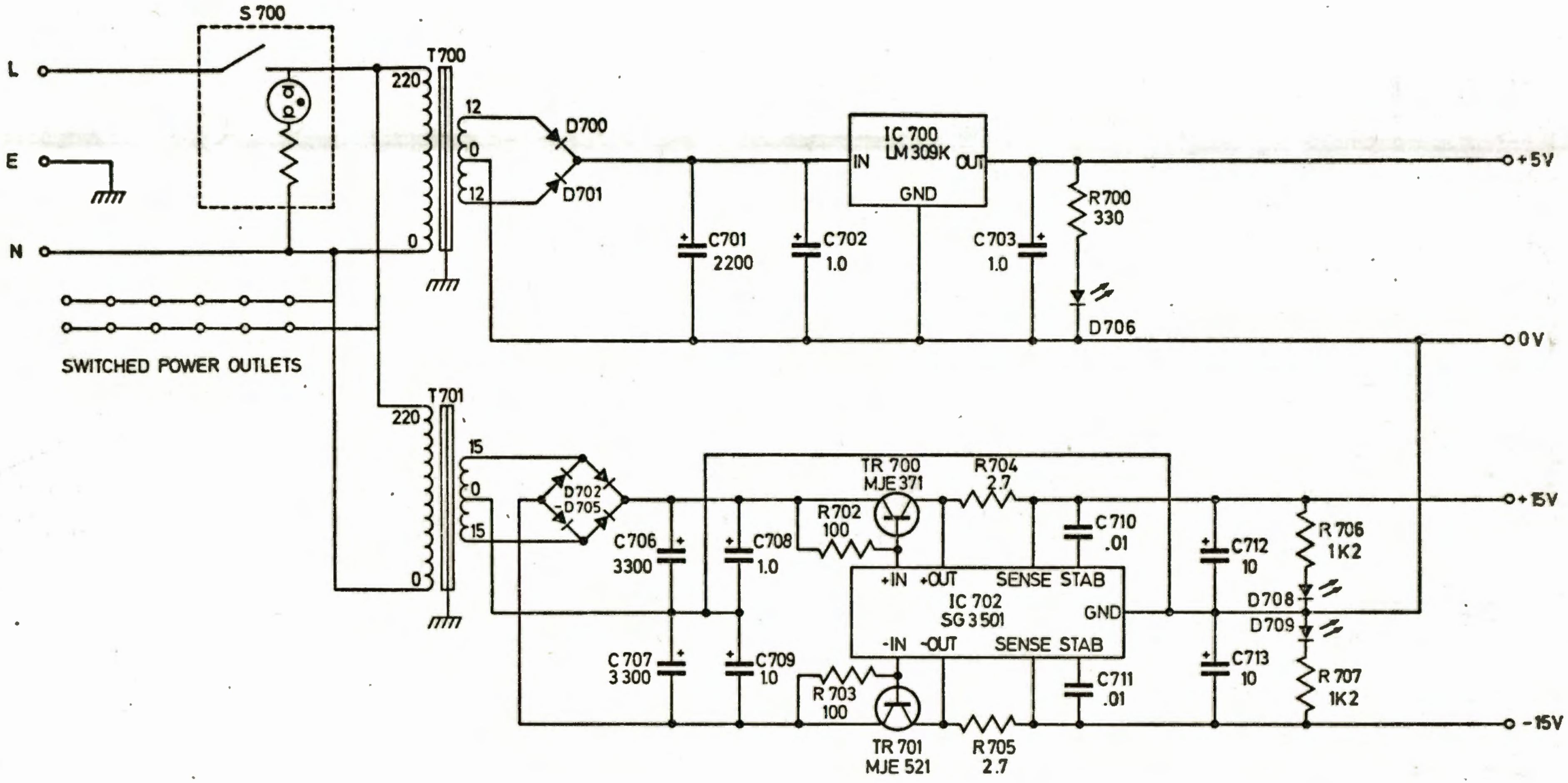
CARD 6 – DATA CAPTURE UNIT AND SUM AND RATIO TIMERS

APPENDIX S

Power supply unit - central controller/video processor

The circuit diagram of the power supply unit of the central controller/ video processor is shown overleaf. It is identical to that of the strain gauge amplifier except that there is only a single +5V supply. Consequently one of the 5V regulators (IC 701) and its associated components have been omitted and the storage capacitance for the 5V supply has been reduced to 2200 μF.

Six switched power outlets have been provided to supply power to the two cameras, the strain gauge amplifier, video tape recorder and television monitor. There is one spare outlet.



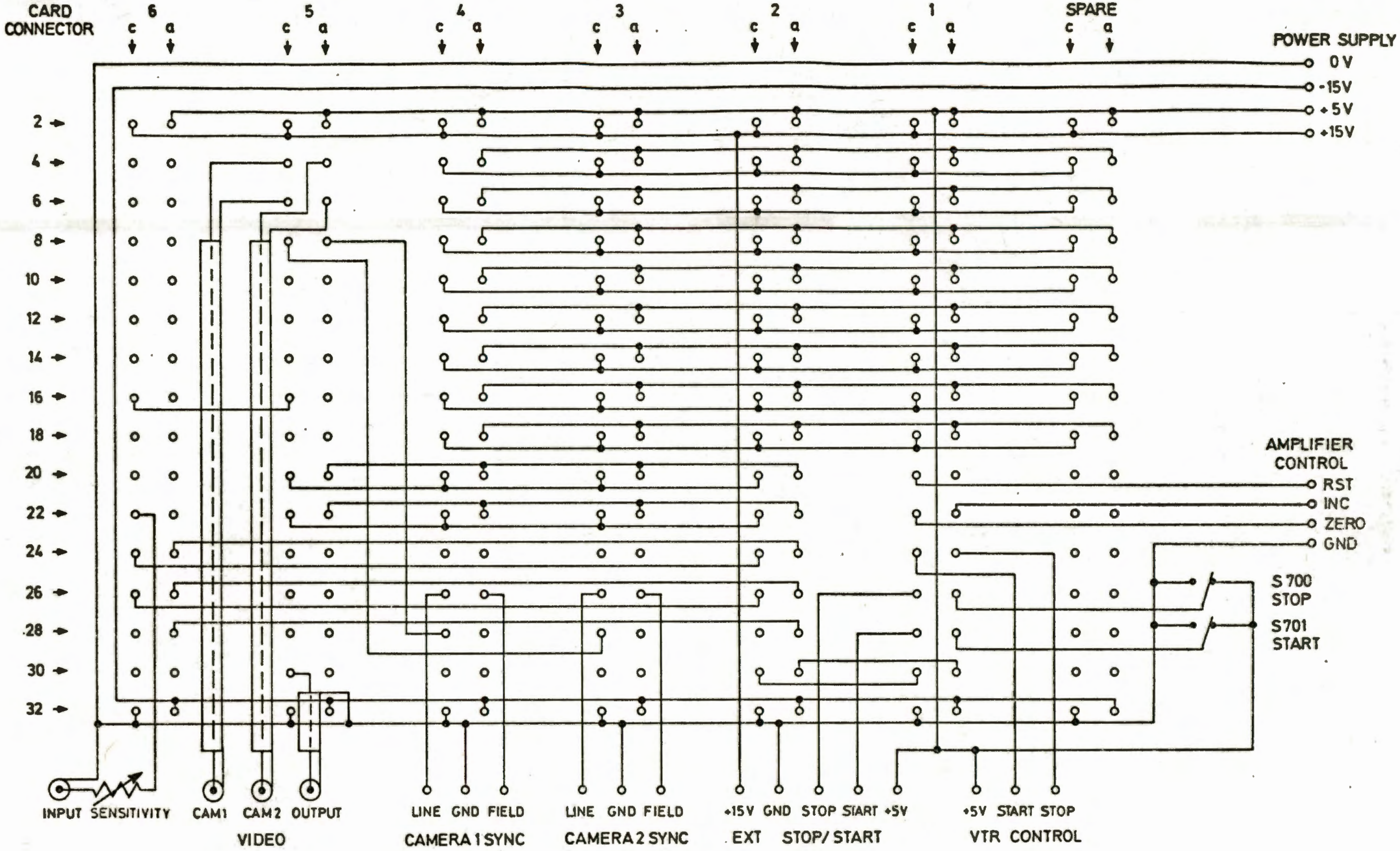
CENTRAL CONTROLLER / VIDEO PROCESSOR POWER SUPPLY UNIT

APPENDIX T

Main frame and front panel wiring - central controller/video processor

The interconnections between the circuit card edge connectors, power supply and front panel components is shown overleaf.

Although there are only six circuit cards in the central controller/video processor, seven edge connectors have been provided. The connector labelled SPARE is intended to hold the circuitry required to provide any additional facility which may be added at a later date.



CENTRAL CONTROLLER VIDEO PROCESSOR MAIN FRAME AND FRONT PANEL WIRING