CHARGE-COUPLED-DEVICES AND COMPUTERS IN TRACKING OF HUMAN LOCOMOTION

CHARGE-COUPLED-DEVICES AND COMPUTERS IN OPTICAL REMOTE ON-LINE TRACKING OF HUMAN LOCOMOTION

by

WERNER BRUEGGER, Dipl. Ing. ETH

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AUTHOR : Werner Bruegger, Dipl. Ing. ETH
(Eidgenössische Technische Hochschule, Zürich)

SUPERVISOR : Professor M. Milner

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ABSTRACT

The recording, measurement and study of kinesiological aspects of human locomotion is of great importance to rehabilitation engineers and clinicians. Clinical needs which stimulated the development of the system designed include the design and evaluation of prosthetic and orthotic devices; follow-up of the dynamic performance of patients undergoing therapeutic or surgical treatment such as major joint replacement; biofeedback relating to human movements and facilitated by on-line displays; general use in studying human movements. A list of important factors for such a system should take cognisance of the following:

- The patient or the subject should be influenced as little as possible by the instrumentation set-up.
- For comprehensive data collection several body points have to be recorded simultaneously.
- Spatial information is required in three dimensions.
- Visual real-time (or virtually so) displays of body movements are produced.
- Data storage and processing with inexpensive mini- or micro-computers should be possible.

This thesis deals with a solution which addresses itself to the aspects outlined above.

The work constitutes a significant advance in, and realization of, a 3-dimensional optoelectronic camera system embodying recently available charge-coupled devices of the area-image-sensor variety. The cameras are interfaced to a minicomputer and appropriate software (programmes) have been developed to permit relevant processing and achieve pertinent displays of the kinesiological data acquired. A major concern was to generate results which are of substantial use to clinicians. This "clinical digestibility" feature has been incorporated wherever possible.

The essential specifications alluded to above have been met and analyses are incorporated. The thesis embraces detailed information to enable developmental work on further prototype camera systems to be undertaken. In its present form, the system appears to meet the essential needs, and future refinements such as implementing larger sensors and expanding the software routines to produce a wider variety of analyses and display possibilities are indicated. Recordings allied with a variety of locomotion disorders have been made. These include hemiplegic gait.

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TO MIRELLA

WITH LOVE

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SYMBOLS AND KEY TO FIGURES

a	Distance lens - image plane
AB	Antiblooming bias
b	Distance lens - object plane
D_1	X-coordinate camera #1, with respect to selected origin
D_2	Z-coordinate camera #2, with respect to selected origin
f	Lens focal length
HIN	Horizontal clock inhibit signal
HOLD	Master clock disable period
$I_{1,2}$	Interrupt signals
Label	Signal indicating the presence of a label in X-direction
$L_{B,E}$	Signal indicating Label Begin, Label End
LSB	Least Significant Bit
MSB	Most Significant Bit
$P_{1,2}$	Points in object plane
$P'_{1,2}$	Points in image plane
$X_{B,E}$	Horizontal (X-) count at the occurrence of the signals L_B and L_E
X,Y,Z	Object coordinates
X',Y',Z'	Image coordinates
$\phi H_{1,2}$	Horizontal clock signal #1, #2
$\phi V_{1,2}$	Vertical clock signal #1, #2
ϕBE	Bias electrode clock signal
ϕP	Photogate clock signal

CHAPTER 1

INTRODUCTION AND REVIEW

CHAPTER 1

1.1. The problem and historical review.

The body movements associated with a walking human are very complex. Analysing the overall walking process requires the examination of a large number of parameters. Despite this, investigations of human movements have fascinated many people going back to the Greeks or maybe even earlier.

One of the first scientifically acceptable works is the publication by E. Weber and W. Weber (1836). In this they state that the multiple fast movements of the body during walking and running, require special instrumentation and experimental arrangements for performing suitable studies.

It is evident, that even early researchers realised that the multiplicity of movements in human locomotion requires an exact definition of whatever study is to be carried out. The lack of proper instrumentation limited investigations in the earlier times, up to about the beginning of this century.

The development of photography led to the recording of more than just simple line and distance measurements related to locomotion. E. J. Marey (1894) not only was the first person who used photography for human movements studies, but he used his "photographic gun" which allowed him to shoot successive pictures within short time intervals (12 pictures/sec.). Realizing the important aspect of time-sampling he was able to register successive phases of movements. By dressing his subjects in black clothes together with reflective stripes, he went into an abstract form of trajectory description, known as "stick-diagrams". In this, limb segments are represented by straight line segments. To this day, the technique is useful and employed by many researchers.

Cinematography tremendously expanded the recording possibilities together with stereo and other 3-dimensional techniques. As an example, the work done by Bullock and Harley (1972) is based on a cinematography-photogrammetric system.

It can be realized from these and many other recent investigations (for references refer to section 2.1.) that a dominant interest exists in the recording of trajectories of a body or a body segment.

The recording and display of raw spatial trajectory data is predominantly achieved by well tried photographic techniques. Related data such as time-derivatives (velocities, accelerations) or angular information can be derived from the original spatio-temporal data by classical methods of calculation. It is evident, that for a large number of points of interest (data points) being recorded at a high sample-rate, the resulting accumulation of data can become extremely large. If, e.g., for each data point (coordinate pair) 2 words are required for computerized storage, the storage requirements (number of words) are simply twice the product of the number of labels (data points), sampling rate and acquisition time. For example, 10 labels, 100 Hz sampling rate and 10 s acquisition time results in the need for 20000 words.

With electronic data processing available nowadays, the processing and computations can be done by automatic computation.

Workers in the field evidently soon realized the potential available to them and appreciated the problems of entering data for machine processing. Many different systems have been described in recent times. Some of the more important ones will be evaluated in Chapter 2.

1.2. Definition of the problem.

The limited interest in human movements analysis in the medical field was probably due to a lack of appropriate instrumentation to facilitate studies. Also, for medical studies, many more problems exist than just for "normal" studies.

In general, it is not always possible to determine a priori all the parameters required for a particular study. Therefore, redundancy of data will always be present.

In the practical case of a person walking and being in motion, the question arises: What has to be measured?

Apart from the obvious need to examine the displacements of the body and body segments, there are also the related data such as angular movements, torsions, velocities, accelerations, and forces. In most cases, the additional information can be obtained from the basic spatial information.

Returning to the hospital environment, where patients have to be examined, the human aspect cannot be neglected. Therefore, the instrumentation should allow as comfortable as possible performances of the study. Aspects for consideration include the attachment of essential parts of the instrumentation to the body, the required time for this setup, and the laboratory environmental conditions, such as lighting. All these factors might influence the gait pattern, and, therefore, the acquired results.

Since patients usually have to be called in, time constraints are of importance. The turnaround time from data acquisition until diagnosable results are obtained should be, ideally, in the order of a few minutes to virtually no time lapse. The duration of the study is also of importance for physically disabled patients.

The aforementioned factors are perhaps the most important, since results for evaluating patients during a study should give the potential for making comparisons with the direct observations. In the case of unsuitable results, the experiment could be repeated immediately. This means that the patient would not have to be called in again. Also, prosthesis adjustments could be done immediately, followed by a repetition of the walk. Virtually instantaneous displays might well lead to a suitable biofeedback to the patient, to enable him to more rapidly learn to control his prosthesis.

Hospital data filing requires appropriate recording with suitable playback facilities such as oscilloscope displays and hardcopy features (for patient filing), ideally suited for mini- or micro-computers.

Despite the expected technical complexity of such a system, it should be possible for it to be operated by hospital personnel such as nurses or therapists.

These above points can be summarized in the following:

- The patient or the subject should be influenced as little as possible by the instrumentation setup.
- Setup and calibration procedures will be operated by non-technical personnel (nurses or therapists).
- For comprehensive data collection, many body points (data points) have to be recorded simultaneously; e.g., in the sagittal plane, trunk and leg recording would require 5 points for one side.
- Spatial information is required in all three dimensions.
- Visual real-time (or virtually so) displays of the body or body outlines are preferred.
- Data storage and processing with inexpensive mini- or micro-computers should be possible.
- Computer "on-line" processing and displays with a minimum of "dead" time in between acquisition and results. (real-time).

The factors discussed above were dominant throughout the systems design, but other factors were also kept in mind.

Tracking other motions, e.g., sports manoevres, introduces additional problems: wire connections to the subject are not tolerable; the higher speed of the body and body segments (up to an order of magnitude higher than for normal walking) require higher sampling rates, and the need for a possible larger distance between subject and measuring equipment (e.g., 10 m or more).

System costs are also of importance, especially where applications in many places is considered.

The existing systems described in the literature will meet the above requirements to varying degrees. An engineering evaluation of these systems, together with recent advances in relevant semiconductor technology, will follow in Chapter 2. Also, the technical aspects of the problem of tracking human movements will be presented.

1.3. Contributions and layout of this thesis

From the evaluations in Chapter 2, the dominating advantages of optical systems will be seen. Optical and optoelectronic methods are discussed, as well as nonoptical systems.

Among optical systems, television seems to be the most suited for the application of tracking of motions. Comparing a charge-coupled - device camera with regular TV-tube cameras only, there would seem to be no evident advantages of a CCD-system over existing TV-systems. However, a CCD-camera and its interface to a minicomputer, as a combined system, leads to many new possibilities, as will be shown in this work.

This thesis deals with interfacing charge-coupled-device image sensors with a minicomputer. A first prototype was built employing a 100 x 100* area-sensor. It was the only sensor commercially available at the commencement of construction and development early in 1975. Low resolution, photoresponse nonuniformity, and image-blemishes are some of the device deficiencies which had to be dealt with.

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* FAIRCHILD CCD 201

Nevertheless, the very promising results acquired led to the construction of a camera with the more recently available 244 x 190* sensor. A high data rate (of approximately 4 MHz for the CCD 211 at 100 frames/s.) required preprocessing before being sent to a relatively slow minicomputer (PDP 11/10 instruction time, including addressing, approximately 10 μs). It was also intended to design the interface such that computer-interrupt-control was possible together with a fast machine-language driver under a higher level language such as FORTRAN. Routines for evaluating processing techniques and various display programs to be used with an oscilloscope monitor or a graphics-terminal (TEKTRONIX 4006-1) were written. Experiments in which data in the sagittal plane were acquired for normal subjects and patients were performed. The acquired data are processed using digital filtering and manipulated to obtain the "stick-diagrams" and displayed on-line, virtually in real-time. Further displays include the vertical and horizontal displacement of the individual joints, their velocities and accelerations.

Studies done by C. Hershler (1977) showed the usage of the system for further data analysis. In these, investigation of angle-angle-data (eg. hipangle vs. kneeangle for corresponding instants of time), calculated from the trajectories, were done on the angle-angle-loops by calculating the perimeter, the area, and the ratio perimeter/square-root area. Shape recognition methods such as the latter provide possible tools for physical interpretation such as coordination, control and range from the data.

A complete description of the one camera-system with some pertinent displays is to be found in Bruegger and Milner (1977). For the convenience of the reader, the requisite details are presented here in Chapter 5, sections 5.1. and 5.2., and Chapter 6, sections 6.1. and 6.2.

The one camera system was expanded to a two camera version, permitting the simultaneous recording of body movements in two planes. The same concept of interrupt control was adopted, i.e., the camera is treated as a standard input device to the computer similar to, e.g., a keyboard console. The control module for the cameras was designed such that the cameras can be operated independently, either one, or simultaneously together, with synchronous clocks.

The software developed for the system includes direct on-line display-routines, speed-optimized machine-language handlers to operate the system under FORTRAN-control and a detection and identification algorithm to identify the individual labels within the data-stream together with an extrapolation procedure. The processing of the identified target trajectories includes creation of the displays mentioned above, angle-angle computations and generating perspective views from the back (second camera) and the perspective compensation.

In Chapter 2, an engineering evaluation of the existing systems is done, which led to the decision for building the CCD-system described in this work. Also, some important optical considerations are given.

Chapter 3 highlights the existing optical sensors for possible applications for body tracking and is continued in Chapter 4, where an examination on the charge-coupled-device image sensors is done, as a base for building a camera and a computer interface.

Chapter 5 deals with the camera systems design, i.e., the required logic to drive a CCD image sensor. The interface to the computer is explained, including features which enable the use of almost any slow mini-computer, the interrupt control, and the required design of a high-speed data link to the computer. The interface with the interrupt control contains features which, although simple in principle, take advantage of the possibilities of the charge-coupled-devices to enable a controllable scan of the device without introducing nonlinearities, which would be difficult to achieve with television tubes. In addition, to enhance resolution and reduce storage requirements, a hardware segment to perform an averaging function is incorporated in the interface. It is believed that this original principle makes the system unique, in the sense of storing coordinate information with more than one coordinate pair per sample.

The 2-camera system, as built, is explained, with the necessary control logic, and a design proposal is given, based on the results obtained for implementing, e.g., 2 cameras with common drive and control logic. The design principle of the interface adapts to the standard conventions for regular I/O-devices, which, theoretically, enables the connection and operation of any number of cameras to the computer together with other inputs such as A/D-inputs.

Chapter 6 explains the data collection process under program control, camera and display handlers, and the trajectory identification process. Error analysis and a calibration method are shown, as well as experimental test results. The explanation of the "clinical digestible" displays is illustrated with various typical displays obtained from experimental gait studies performed on "normals" and hemiplegic patients.

The conclusion, in Chapter 7, summarizes the potentiality of this experimental system. Directions for expansion and improvement of hard- and software are given, for possible future applications.

Appendix A contains the detailed circuit diagrams for the circuits that were utilized in the system. It provides more detailed information on the operating principles; the software section, Appendix B, contains the relevant programs and drivers to operate the system.

CHAPTER 2

ENGINEERING EVALUATION OF EXISTING SYSTEMS AND NEW DESIGN CONSIDERATIONS

CHAPTER 2

2.1. Analysis of pertinent existing systems

For a comprehensive recording of body movements, photographic techniques have been used extensively. Techniques other than photography have been described, but are essentially concerned with single or few parameters and are not suited for a more general application. A example of an interesting system is described by Molen and Boon (1972). The walking speed of a subject is recorded by running a magnetic tape containing marker track information through a playback head. The authors arranged for the tape to be connected to the centre of gravity of the body. Spatial information in one dimension could be calculated by integration of the original velocity signal. Although an extension to more points seems to be possible, the information obtained by such a system is very limited. It would also be most cumbersome to apply in a routine clinical situation.

Since we are interested in analysing the movements of a moving body, it is evident that all visible spatial information is contained in a 3D photographic recording. Derived data computed from the original data could become unreliable through the computation process by emphasizing the errors inherent in the original signal. It is well known that processes such as time-derivatives will emphasize the noise inherent in the signal. Obtaining accelerations from spatial data requires the second derivative. If one is interested in accelerations only, it might be more advantageous to obtain them directly with accelerometers.

However, the remoteness of the instrumentation from the subject, together with other advantages, such as flexibility of the setup and no hindrance of the subject, resulted in the fact that many people have built and described optical and photographic systems. The major disadvantages in using photographic methods are the requirement of processing the film and preparing and entering data to a computer for subsequent processing. Kasvand and Milner (1972) have developed a flying-spot-scanner computer system to acquire data directly from movie-film. The controlling computer deflects the beam of an electron-tube which scans the movie-film frame. Although this system works automatically with little operator interaction, it is still an off-line process. Since data storage and handling are so important, a computer is almost unavoidable.

The recent technological advances in the optoelectronic field permit the exploitation of the advantages of "optical remote sensing", including television and other optoelectronic measurement techniques.

Probably a milestone in the television-computer interfacing for body locomotion is the work by Dinn et al (1970). The information from a regular TV-camera is sampled in a 96 X 96 matrix and stored in a computer. The subsequent processing of this data extracts the trajectory information of the appropriately marked subject and background. The limited resolution is overcome by moving the camera parallel to the walkway and filling in the field as much as possible. Winter et al (1972) show that a large marker size, covering more than one coordinate pair, effectively increases the obtainable resolution. Nevertheless, since all the video-information is stored prior to processing, a large amount of storage space is required and no immediate data displays are available.

Cheng's (1974) television system passes the video-information through a threshold detector and stores in a PDP 11/10 computer only the coordinates of the events exceeding the set illumination threshold. Data is then punched on tape and processed by a larger machine. Many programsteps are involved in the real-time data transfer, which makes it impossible to have more than one data point detectable on the same TV-line.

A more sophisticated multiple TV-camera system by Jarrett (1976) uses direct memory access to a PDP 12-computer. Coordinates generated by a threshold detector on any one TV-line are stored in a buffer memory and then transported to the computer during the line blank period. Provisions are made for acquiring other data such as force-plate information. This is the first work reported on a multiple camera system, but it seems to require a relatively fast computer (1,2 microsec/word transfer). The commercially available Optical Data Digitizer (ODD), by EMR Schlumberger (1973) uses special TV-tubes and operates only under computer control. The sensor surface of the electron-tube can be randomly accessed and scanned by the applied control voltages. The resulting video output is quantized into 255 levels and available in digital form. This is basically the ideal TV-flying-spot-scanner, but the operating speed depends on the controlling computer and its controlling program. The complexity of the program and the number of data points to be scanned can slow down the operating speed considerably. No programs for tracking are supplied, and the cost for one unit is very high (approximately $ 15000).

A somewhat different approach, described by Gueth et al (1973), operates with regular photodetectors located on pertinent parts of the body, while a V-shaped light pattern scans the subject. Information from the photodiodes and a reference diode enables the determination of the planar coordinates, using a PDP-8 computer. The light pattern is generated by a rotating mirror system. Difficulties in obtaining steadiness of rotation are reported by the authors.

The Selspot, commercially available from Selcom AB (1975), is a very promising non-television system utilising light-emitting diodes for the marker points and a tetra-lateral silicon photosensor. The output of the photosensor is a function of the light intensity, as well as the position of the lightsource focused by the lens onto the sensor surface. The nonuniform illumination of the P-N junction results in a photopotential along the junction barrier, since the common transverse photopotential varies with the incident light distribution. This lateral photo-effect, first reported by Schottky (1930), is the basis of the Selspot-system. Multiple locations are obtained by sequentially switching the LED-diodes. The control can handle two sensor units, as well as up to 30 LED's per unit. The analog output of the system allows the observation directly on an oscilloscope. The digital output can be used to transfer the data to a computer, but, due to the time-division multiplexing, data for one channel is present at the digital output only for a very short time. Except for high-speed computers, this time is too short, and intermediate storage usually has to be provided. The high resolution, claimed at 1 : 1000, but depending on light intensity, and the simplicity of operation make the Selspot a very promising system.

Disadvantages are, that any background light, not coming from the diodes and in the same spectral range, will affect the output; the cable connections required from the diodes to the control unit; a fixed sampling rate (322 Hz); and the relatively high cost (approximately $ 17000 for 2 cameras). Woltring's (1977) work describes in detail the photosensors and 3D-aspects of motion monitoring, using the Selspot system.

Except for Gueth's work, all the systems described thus far use regular optics to obtain an image focused onto the sensor surface. Using cylindrical lenses and laser diodes as targets, Mitchelson (1975) describes the CODA-system (for Cartesian Optoelectronic Dynamic Anthropometer), which is claimed to have a resolution of 12 -14 bits. Three cameras are required, facing the same direction. The very high resolution is obtained by placing an optical digital encoding mask in front of a photo-diode array with an analog vernier optical mask to enhance the digital resolution. The utilized sampling rate of 1 kHz can also be considered as very high. This is probably the most accurate system in existence at present, but cylindrical lenses and the encoding masks are difficult to manufacture and not readily commercially available.

Common to all these optical systems is the idea of imaging, and in most cases, a regular lens is used. The characteristics of the different systems are mainly given by the image sensors. A summary on optoelectronic sensors will be found in Chapter 3. Some of the optical aspects which are of importance for the data processing are highlighted in the following.

2.2. Optical considerations

2.2.1. Definition of the coordinate system.

Spatial measurements require the use of a coordinate system to define the points with regard to some reference point. In the following, and throughout this thesis, the Cartesian coordinate system will be used and strictly adhered to, with the axes defined as follows:

vertical direction	: Y-axis	positive direction upwards
horizontal direction	: X-axis	positive from left to right
optical axis	: Z-axis	positive towards object plane.

In practice, the X-axis will be lined up with the walking direction, resulting in the X-Y plane for the sagittal plane. It is usually this plane which is looked at for 2-dimensional considerations.

For 3-dimensional monitoring, a second observation plane is required. Basically, this plane can lie anywhere except in the X-Y plane, but Cartesian coordinates are directly obtained if the remaining Z-axis and either X- or Y-axis form this observation plane.

For the selected camera setup as described in Chapter 6, the Y-Z plane is selected as the object plane for the second camera, which results in a change of the above coordinate definition for the second camera, namely the X- and Z-axis are interchanged.

Some optical imaging relations have to be considered. They are shown for one single optical system, but can be applied for a 3D 2-camera system for the individual systems independently.

2.2.2. Imaging relations.

If the object plane (coordinate system) and image plane are parallel and share the common Z-axis, which will be the optical axis, then the basic lens equation holds: (Fig. 2.1.)

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f} , \qquad (2.1.)$$

with f as the focal length of the lens system.
From geometric considerations any 2 points in the object plane P1(X1,Y1) and P2(X2, Y2) and their images in the image plane P1'(X1',Y1') and P2'(X2',Y2'), the ratio

$$\frac{P_1' - P_2'}{P_1 - P_2} = \frac{a}{b} \qquad (2.2.)$$

is constant and determined by the focal length f and object distance b. For object distances b>>f, for a focused image, a becomes

$$a = f , \qquad (2.3.)$$

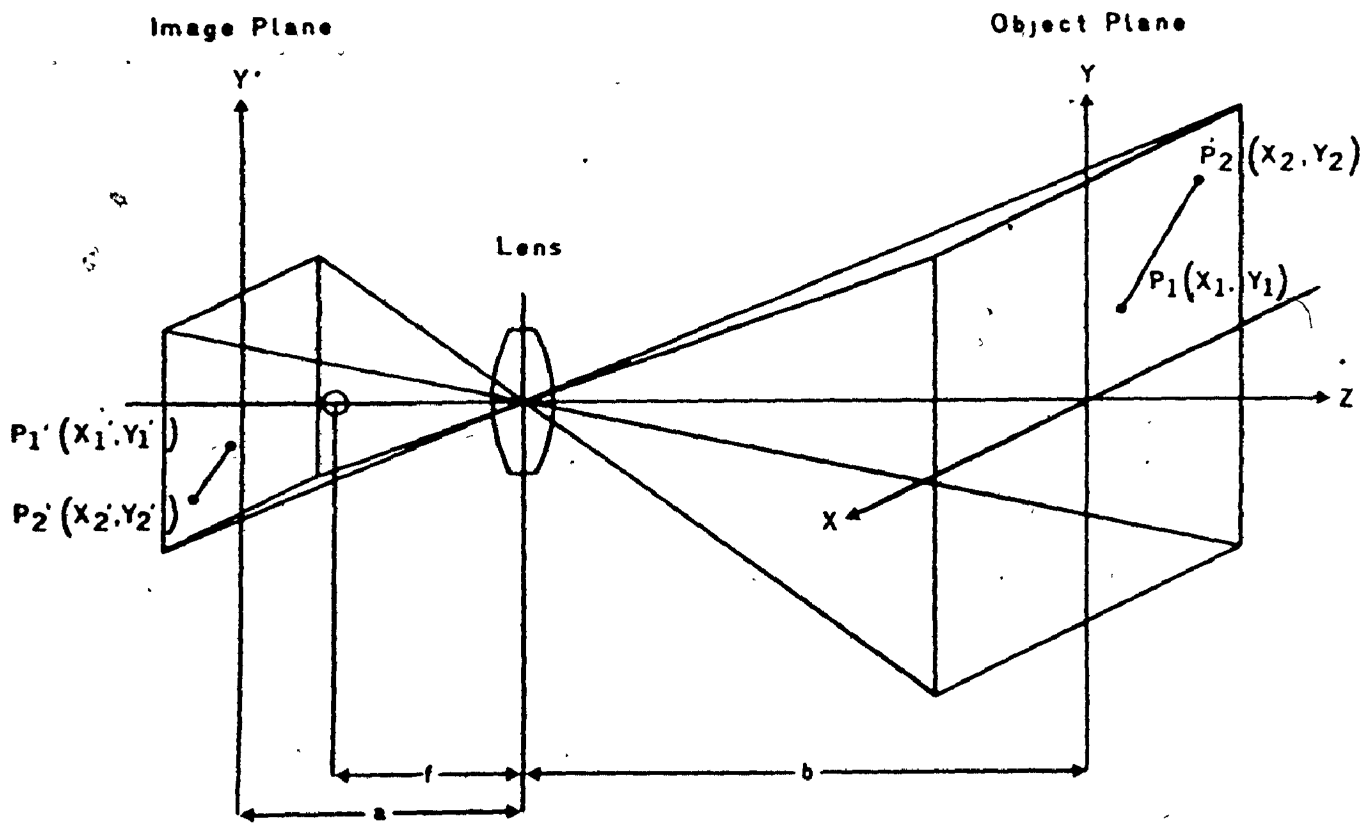

Fig. 2.1. Geometrical imaging relations

and the image size becomes

$$P_1' - P_2' = \frac{f}{b} \cdot (P_1 - P_2) \; . \tag{2.3.}$$

Having the focal length as a constant, the magnification or reduction factor of the image is inversely proportional to the object distance.

This property becomes very important for human locomotion, where, usually, the laboratory dimensions define or restrict the object distances. If a person walks in the X-direction, he will generally stay within that plane with only small deviations in the Z-direction. These deviations ΔZ change the object distance b, resulting in an unwanted change of image size. In the case of a Y-Z plane, where object distance becomes the X-direction, which is the walking direction, the change of image size is proportional to the walking distance and much larger than the Z-movements (horizontal movements perpendicular to the walking direction). The choice of the imaging planes and camera setup will depend on the study performed, but in any case, the change of image size mentioned cannot always be neglected. This problem will be further discussed in Chapter 6, section 6.3.

Compensations required, as mentioned above, which will also be discussed in Chapter 6 and mentioned as "perspective compensation", as well as other calibration procedures, are possible, and will be discussed in Chapter 6, section 6.3.

Pra lens sys ems ave ore ing in

deviations from the ideal, such as:

- barrel- and pincushion-distortion
- spherical and chromatic aberrations,

which will be, in general, very difficult to describe analytically, but their global nature can be simply summarized as lens errors.

Since, for a given lens, these errors are constant, it is possible to describe the error approximately in closed form or to determine a calibration table for a given range in which the lens is being used. If computers are being used, complex operations can be readily performed to obtain a calibrated value. Pertinent aspects will be highlighted in Chapter 6.

2.3. Data processing and display.

The processing and nature of displays is determined by the nature of the study which requires results that can be interpreted for diagnostic purposes. Since, as mentioned in Chapter 1, it is important to display the data at a time they can be compared with visually obtained impressions, as little time as possible should pass between data acquisition and the return of the results in suitable forms of display.

The computer involved has to be used in an "on-line" fashion, which means that direct operator intervention is possible. Real-time results would be highly desirable, but, as long as the computation time is within reason, e.g., not longer than 1 minute, this would be accepted as "almost real-time". With the usually large amount of data, complex operations in a higher level language can become very time consuming, resulting in many minutes being required to process a data set.

Resolution and linearity of the system will limit the accuracy of the results. Standards, to give sufficient accuracy to enable the interpretation of the results toward physical meanings or diagnosis, have not been found in the literature, but results with an error of less than 5% would seem to be desirable. In cases of processing, such as computing the time derivatives, where the noise within the signal gets enhanced, or any other process resulting in a loss of significant figures, the final results can be burdened with much larger errors than the errors originally inherent in the signal. The particular application and experiments have to determine, in each case, the usefulness of a given system. As an example, if one is interested in the trajectory information alone, the required accuracy of a system would be less than in a case, where accelerations are of interest, and this information has to be derived from the spatial data. In this latter case, higher resolution and higher sampling rate are required to allow the computation of the time-derivatives.

Since no low-pass filtering of the data prior to sampling is possible, and the sampling theorem requires a sampling frequency of at least twice the maximum signal frequency component to avoid aliasing effects, the signal frequency spectrum has to be known.

In the work of Winter and Reimer (1972), it was shown that 99.7% of the signal power of the vertical displacement of the toe is contained in the first 7 harmonics. The toe marker was found to be the one with the highest frequency components evident. Others (Mitchelson (1975)) state that 150 Hz is the minimum acceptable sampling rate, with 1 KHz being preferred.

Sampling at the Nyquist-rate can be sufficient for signal processing, but for direct visual displays, a higher rate is required. Storage requirements and equipment cost will set the upper limit. Typical operating TV-systems (Winter (1972), Cheng (1974)) showed satisfactory results with 30 or 60 Hz. For the system described in the following chapters, 100 Hz was chosen as a reasonable compromise between storage requirement and number of points for a display.

It is the purpose of the next chapter to examine the optoelectronic sensors with regard to the above requirements, which are: resolution and sampling rates, and also with regard to their implementation in a computerized system.

CHAPTER 3

OPTICAL SENSORS

CHAPTER 3

3.1. Classification.

The factors discussed in the previous chapters led to the decision to concentrate on optical sensors for the purpose of creating a system for tracking body motions. Optical remote sensing may involve active or passive targets for the points to be tracked. The particular choice of optical sensors will depend on the light source being used and various other characteristics of the sensor, such as linearity and resolution, speed, size, required hardware, availability and cost. The optical position sensor, since the output of the sensor will relate to a spatial (usually planar) position, can be either addressable or non-addressable. A description of a non-addresssable sensor will be given in section 3.3.1.

3.1.1. Addressable sensors.

The output of sensors of this type depends on the selection of an address to the sensor and the light distribution on the sensor itself.

The selected address relates directly to a coordinate pair which, through the optical system, relates to the planar coordinates of the object.

Addressing of the sensor can be in digital or analog fashion. The most ideal case of an addressable sensor is when the addressing can be done on a random access basis, to allow a free selection of the addresses given to the sensor. Such a sensor could be used in a closed-loop tracking form similar to the principle of the flying-spot-scanner, where the spot position is given by the address to the sensor.

For single target tracking, such a system can be very efficient, but multiple targets require more program steps in the controlling computer which will slow down the tracking algorithm.

Television-camera-tubes, in themselves, are randomly accessible, but the most commonly used Vidicon-tube requires a continuous scan over the entire active surface, in order to remove dark-current charge build-up. In addition, standard TV-equipment uses a scanning mechanism which does not allow random access.

As a result, the standard TV-tube can only be used as a sequential access system. Other devices, such as the CCD-image-sensor, will also fall in this category.

3.2. Television tubes.

As previously mentioned, the standard TV-tubes such as the Vidicon or Orthicon, have to employ a continuous scan. Deflection nonlinearities usually are compensated only for a fixed scanning frequency. The standard frame-rates are 30 or 25 Hz. Usually 525 or 625 TV-lines are used in the standard system, yielding respective resolutions of approximately 1:500 or 1:600. Only specialized and expensive tubes, such as, e.g., high quality vidicons, would allow a higher resolution.

A comprehensive description on television tubes can be found in Bibermann and Nudelmann (1971).

A relatively new development, the SEC-tube (Secondary Electron Conduction), as well as the classical image dissector-tube, have the advantage of a long integration period (low dark current), thus allowing the principle of the flying-spot-scanner to be exploited. The ODD-system (EMR Schlumberger, 1974) employs these tubes as the optical sensor.

3.3. Solid state sensors.

Many disadvantages of the imaging tubes such as bulkiness, high power consumption, high voltages, will not be found in solid-state sensors, where problems such as low resolution or noise, non-uniformities and blemishes have to be dealt with.

3.3.1. Non-addressable sensors.

The longitudinal photo effect, first reported by Schottky (1930), can be used in such a way that position information from the total light distribution on the sensor surface is available at the sensor output. All light falling onto the sensor contributes to the output. Position information can be obtained only if the shape of the image of the light source is well defined and no other light is present. Multiple positions can only be obtained by time-multiplexing. A detailed analysis of these detectors is to be found in Woltring (1975). The commercially available SELSPOT is based on these detectors, and Woltring (1977) describes the usage of the SELSPOT for human movement measurement.

3.3.2. Addressable sensors.

The optical photo effect, which led to the construction of photosensitive elements such as photoresistors or photodiodes and advances in integrated circuit technology enabled the manufacture of array sensors. Relatively easy to build are linear (line) sensors and they find their application in systems such as page readers, character-recognition systems and early satellite cameras. Cylindrical optics are required for the imaging.

Area image-sensors were first built utilising intersecting XY-address-strips connected to each picture element which can be either a photo-conductor, photo-diode or even photo-transistor element. In principle, the XY-addressing enables the random access, but most manufacturers' ultimate goal is self-scanning image sensors yielding a video-signal output similar to or compatible with television tubes, because a consumer-oriented closed-circuit TV-system with low cost, low power consumption and small size has a tremendeous potential application.

Although the internal gain in the element itself for the photoconductor and phototransistor appears attractive, disadvantages such as internal lag for the photoconductor, and the random variations in transistor gain for the phototransistor resulting in a great photoresponse nonuniformity detract from the suitability of these devices.

The recent advances in MOS-technology favour the photodiode systems, which do not have the above-mentioned disadvantages to the same extent, and the manufacturing principle, which is also shown in chapter 4, is very simple. XY-addressed photodiode sensors are commercially available, e.g., the RETICON (1973) 50 x 50 area-image sensor.

The development of integrated charge-transfer registers led to the construction of devices with a completely different scanning system; mainly the MOS-bucket brigade and the Charge-Coupled-Device.

The principle of operation of these devices is similar to a digital shift register, but the analog signal introduced into the register is transferred through it as a spatial sequence of modulated charge packets. The signal can be introduced by the photo-sensitive cells themselves, and, depending on the layout of the device, a one-dimensional (linear) or 2-dimensional area sensor-array can be made.

The CCD-area-image sensors, which recently (1973) became commercially available, with very promising characteristics, have opened many new possibilities for image sensing. Early sensors were not much larger in size (where, here, size stands for the total number of elements), than, e.g., the RETICON-sensor, but, at present, sizes of a magnitude larger than the RETICON, in both dimensions, are available (RCA SID 52501, Fairchild CCD 221).

Compared to the XY-addressable diode array, no random access is possible for the CCD', the device is sequential in nature. For computerized data acquisition, this is not a disadvantage, because the device can be operated without computer intervention, and the video signal can be utilized for monitoring purposes.

After investigating the possibilities of using CCD-image-sensors for interfacing with a computer, the following major advantages of the CCD-camera, in contrast with TV-cameras, became clear:

- With the CCD-device, no A/D-conversions are necessary to obtain the spatial coordinates.
- The construction of the CCD-device assures geometric and related mechanical precision. By contrast with TV-systems, no "open-loop" scanning with the concomitant error sources takes place.
- A wide range of frame rates is possible with CCD-devices and achieved very simply. For regular TV-systems, major electronic changes are required.
- The possibility of control over the scanning mechanism allows for additional computer functions whilst the CCD-device is not actively scanned.

Taking cognisance of these factors in particular, it was decided to pursue the development of a CCD-camera and computer-system.

After a first prototype of a CCD-camera and computer-interface was built by the author, it was confirmed that straightforward interfacing is possible by designing the interface in such a way that the camera-device can be treated for input to the computer like other I/O-devices. As will be apparent in subsequent chapters, the aforementioned attributes were borne out in the final version of the system developed.

Although the functional principle of operation of the CCDs is very simple, some basic understanding is necessary, as summarized in Chapter 4.

CHAPTER 4

THE CCD IMAGE SENSOR

CHAPTER 4

4.1. Principles of operation.

A mechanical analogy for charge-transfer-devices, pouring water from one bucket into the next one, created the term "bucket brigade". Water represents electric charge. The charge-coupled-device is similar to the bucket brigade, except that the transport channel is continuous, and does not have the p^+-islands (see Fig. 4.1.).

The formation of the potential wells, which hold the charge, is established by applying clocking voltages to the electrodes (see Fig. 4.2.). The time difference between the 3-phasic clock forms the potential. The shifting of this potential structure transports the charge along the channel. The 3-phase clock electrode system allows a very simple integrated structure design, as well as the possibility of transporting the charge in either the left or the right direction, depending on the phasic relation between the 3 clocks.

For digital circuits, 2 phase-clocks are easier to obtain, and CCD's can be built using a 2-phase clock only. To obtain a directionality in the channel, the potential well has to be formed asymmetrically. Many ways of doing this are possible, such as overlapping electrodes, ion-implantation, etc. An example of stepped electrodes, to introduce asymmetry, is given in Fig. 4.3., showing the potential well structure.

The charge pattern, present or introduced into the cells of the charge-transfer register, can be converted into a time-varying

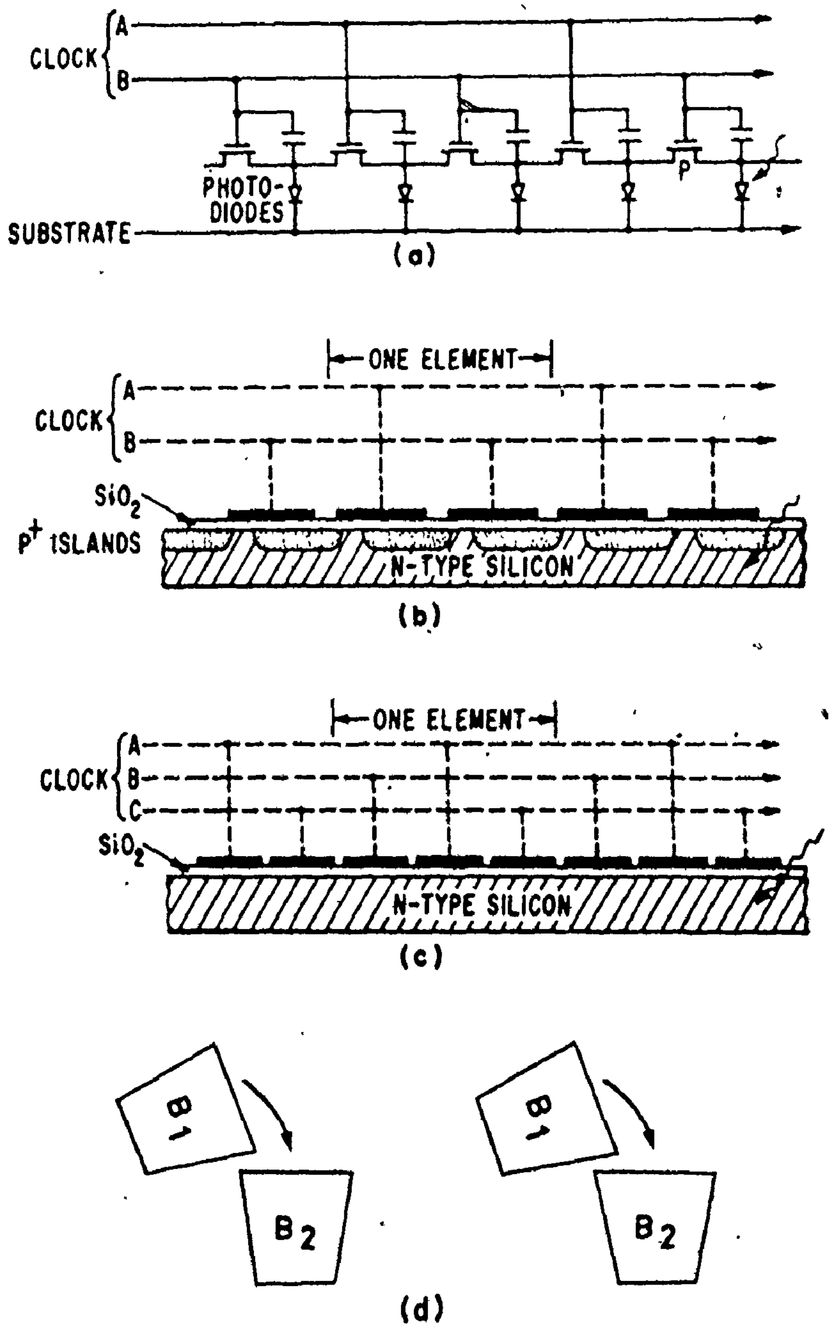

Fig. 4.1. Schematic and structural comparison of:
(a) Discrete MOS bucket-brigade;
(b) Integrated MOS bucket-brigade cross-section;
(c) Charge-coupled register cross-section;
(d) 2-phase clock model for charge transfer, employing water buckets.

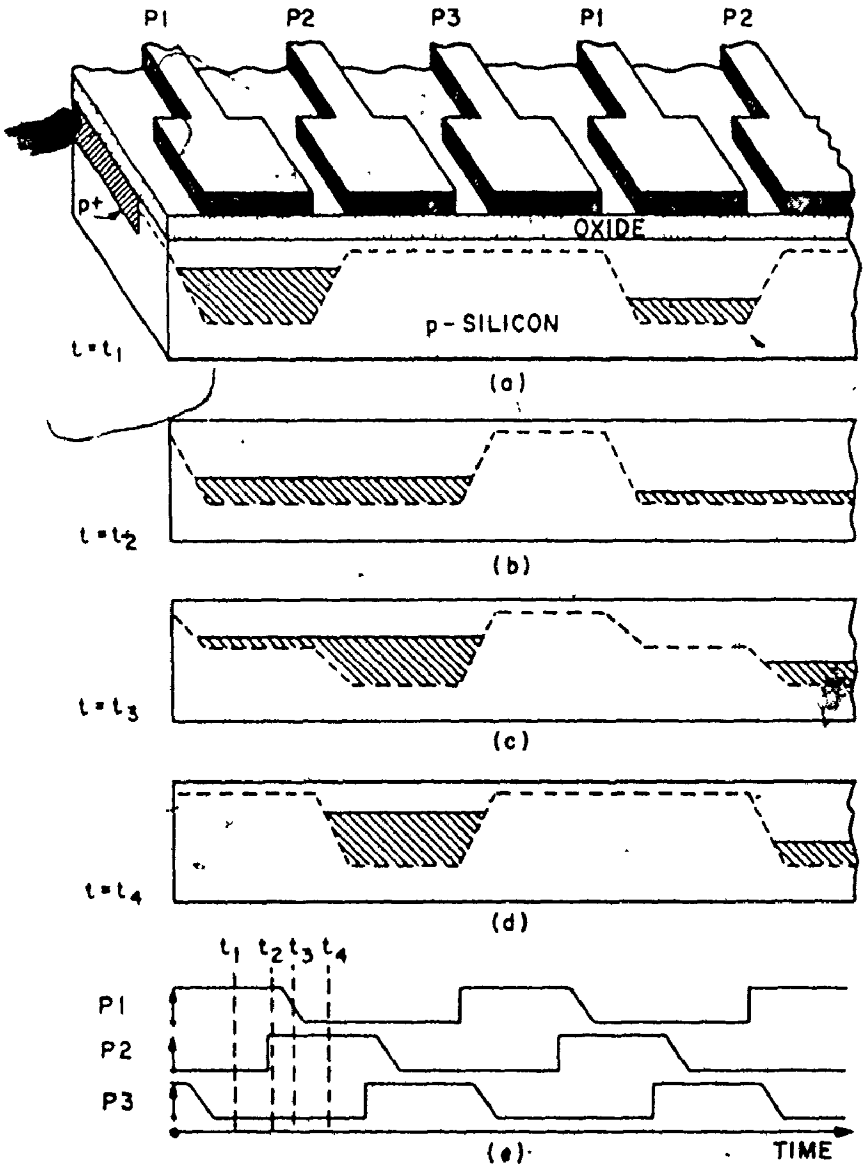

Fig. 4.2. (a) 3-phase charge-coupled register cross-section
(b,c,d) potential well structure shown at different time intervals with
(e) corresponding time slots marked in the diagram of the waveform.

(from Sequin and Thompsett (1975))

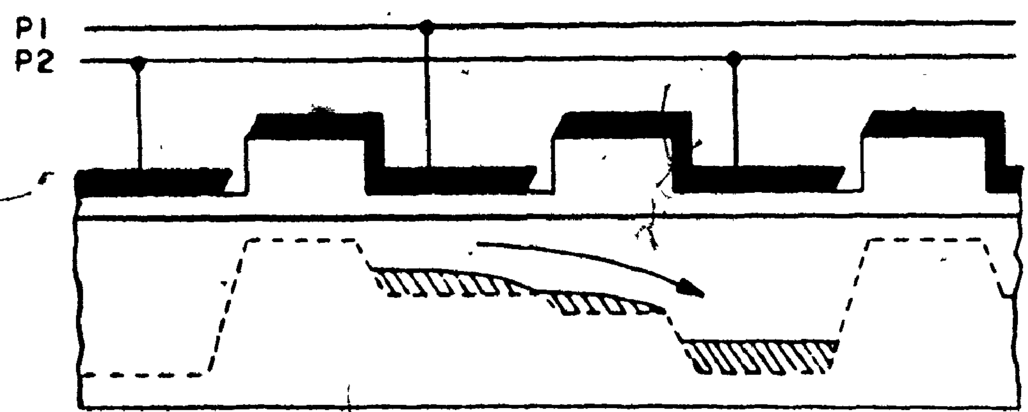

Fig. 4.3. 2-phase charge-coupled register with stepped electrodes, showing, schematically, the potential well structure.

(from Sequin and Thompsett (1975))

signal, by shifting the charges through the register, by applying the clock voltages to the electrodes and collecting the charges emerging from the end of the register. If light falls onto the silicon, the optical photoeffect will release minority carriers, which are trapped at the surface under the electrodes whose voltages form the deepest potential well. In this way, a charge-coupled register can become a line-image-sensor, but, in practice, a charge-coupled linear image-sensor is more complex. It will consist of a photosensor array for accumulating the photo-charge pattern, plus an associated charge-coupled shift register with one charge-coupled element for each photo-sensor element in order to move the resulting charge packets to an output point. A 2-dimensional layout of a photosensor array, together with the transport registers, will form an area-image-sensor. The transfer from the photosites to the transport register and, finally, to the output register can be done in many different ways. The two more important ones, which are also the ones to be found in commercially available products, will be discussed in section 4.2.

From Figs. 4.1. and 4.2., the basic structural details of a CCD can be seen. The channels can be either p- or n-silicon. Not shown are the confining barriers along the sides of the channel, which can be constructed by, e.g., n^+ or p^+ channel stops (usually introduced by a diffusion process), or conducting shields with a fixed bias located between the gate-electrodes, but insulated from the substrate. The electrodes, usually aluminum, are insulated from the channel by a SIO_2-layer.

Practical problems for the 3-phase structure are the required close spacings between electrodes to permit efficient charge-transfer. The simpler construction of the 2-phase CCD-register cannot always be achieved because the asymmetry, which must be incorporated into each potential well, may actually increase the complexity of fabrication.

4.2. Sensors and readout schemes.

The readout sequence from an area-image sensor will have to match the format of a line-scanned television display in order to obtain compatibility with conventional TV-systems. This is a very important factor from the manufacturer's viewpoint, because the ultimate application for the CCD-image sensors is the commercial and consumer television market. Other factors, such as minimizing optical smearing, which will result if the integrated charge pattern is moved across illuminated regions of the array, also restricts the number of possible layout and readout schemes. A straightforward approach from a linear sensor will be to assemble the linear sensors with illuminated charge-transfer registers in a two-dimensional array. An addressing circuit switches the clock pulses to a certain line. In order to compensate for the variable delay in the vertical readout register, each line has to be started with proper timing.

4.2.1. Frame/field transfer.

A better approach which is formed in a commercially available product (RCA SID 52501 image sensor) has the illuminated charge transfer channels running in the vertical direction, placed side by side and operated with common electrodes. An additional buffer area of the same size as the imaging area has to be added to it (Fig. 4.4).

The charge pattern accumulated in the imaging area is shifted into the buffer area during the period of the television retrace. Upon completion of the transfer, the imaging area is returned to the integrating mode. The charge pattern in the storage area is shifted, one line at a time, into the horizontal readout register, during the horizontal blanking period. During the active line time, this information is shifted through the horizontal readout register into the output-amplifier, which generates the video signal.

Disadvantages are the need for the additional storage area required, as well as the possibility of blooming and smearing, because the charge gets shifted through the illuminated areas. However, the advantages of the simplicity of the electrode structure and compact transfer cells may very well offset these disadvantages. Interlacing can be obtained by shifting the centre of each integration site by half a cell dimension. Since a 3-phase structure is used, one field is integrated under a single set of electrodes, and the other field jointly under the other two electrodes sets by holding either the one electrode or the two others at high clock level.

4.2.2. Interline transfer.

Image and storage area can be integrated within the same area, and the storage sites also function as the vertical transport elements, resulting as the interline transfer structure.

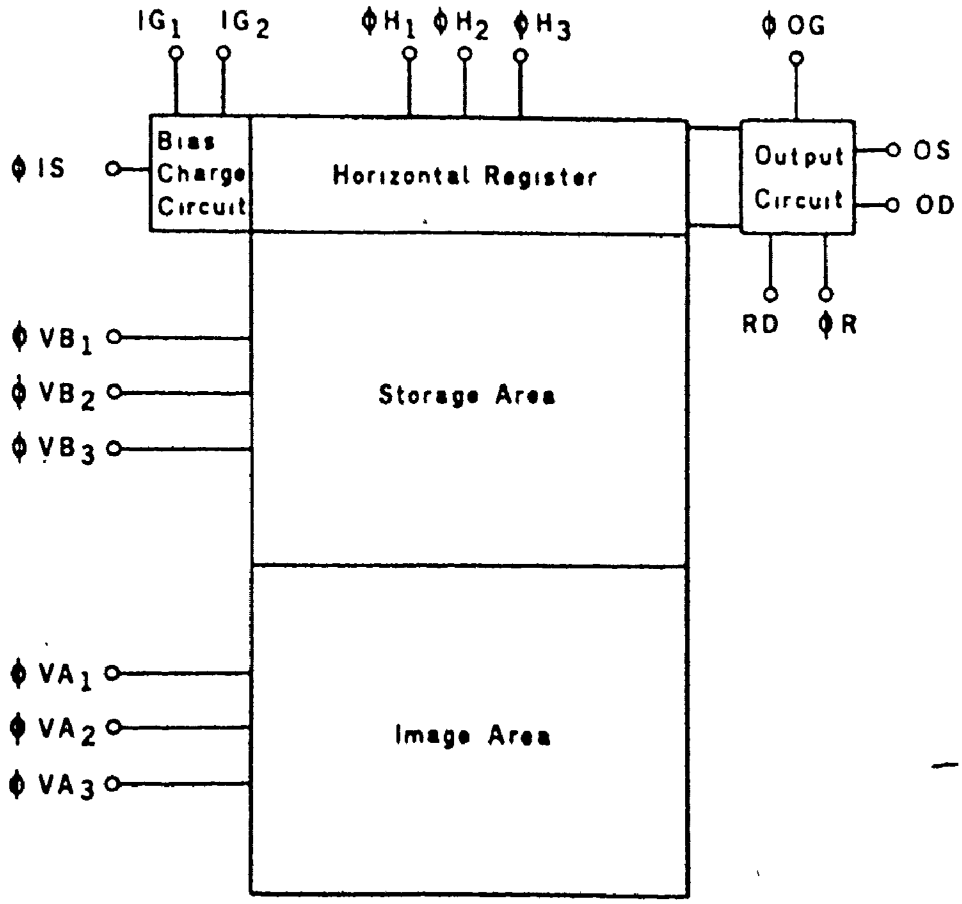

Fig. 4.4. Frame/field transfer and readout scheme (from RCA SID 52501 data sheet)

The layout can be seen from the blockdiagram in Fig. 4.5.

The charge is accumulated in alternate lines, while the others, forming the previous field, are simultaneously shifted along the vertical channels. Two photosites for each element of the vertical registers are used, and the information is shifted out in interlaced format directly by this method. In addition, if a 2-phase clock structure is used, these devices become very simple to operate.

A more complex cell design and a reduction of the light sensitive area by approximately 30% - 50%, due to the light shields over the transfer channels, are negative factors. However, it is this shading which acts to eliminate image smearing. The first charge-coupled image-sensor to become commercially available with 100 x 100 elements is based on this interline transfer principle with a 2-phase clock. It was mainly the availability of this device which led to the decision to employ it for interfacing with a minicomputer.

Practical details regarding the operation of these devices are to be found in section 4.3.

4.3 Implementation and results.

When the CCD 201 became available, a first prototype camera was built, based on a drive-circuit furnished by FAIRCHILD. This circuit includes the digital drive logic, the clock drivers, an analog part for an oscilloscope display, and a video-amplifier. For the CCD 211, where no standard circuit was available, circuitry was developed based on the results obtained with the CCD 201. A description of the clock-drivers will be given in the following; the com-

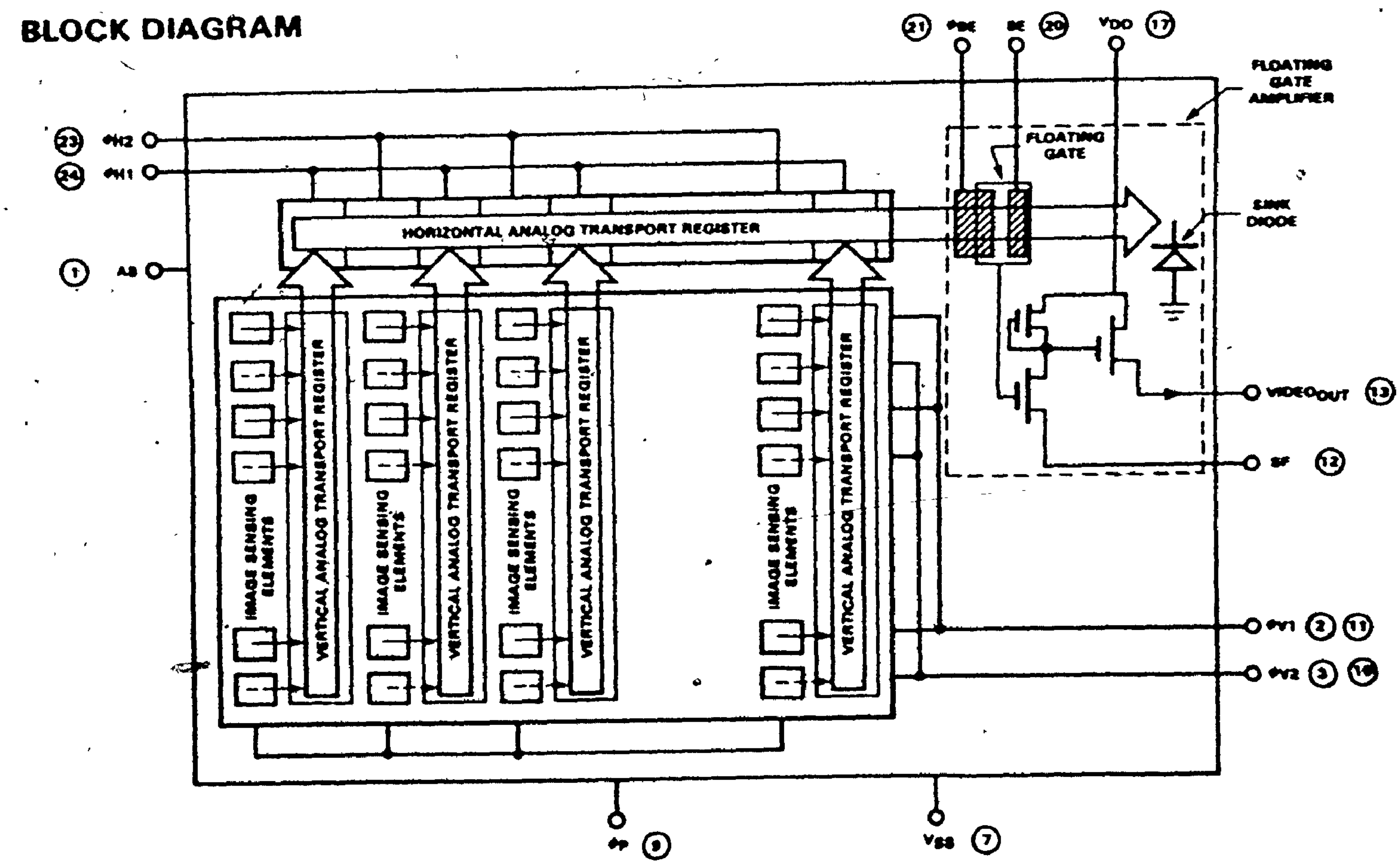

Fig. 4.5. Interline transfer structure (from Fairchild CCD 211 data sheet)

plete drive circuitry is to be found in Appendix A.

The MOS-nature of the CCDs requires almost no power to drive the inputs, but the clock-inputs have a high capacitive input impedance and the clock-frequencies are relatively high (1 - 15 MHz), requiring a low impedance drive.

Both the CCD 201 and CCD 211 are 2-phase clock-devices, which means, each clock signal has to be a pair, one being the exactly inverted version of the other (see also Fig. 5.5., Chapter 5, Timing signals). The basic drive signals required are as follows (nomenclature adopted from the manufacturer):

horizontal clock : ϕH_1, ϕH_2

vertical clock : ϕV_1, ϕV_2

photogate clock : ϕP

bias electrode clock : ϕBE .

Although high frequencies are required for the clocks, rise and fall-times should not be less than 15 ns. Since high speed switching circuitry was used, a matching resistor is used in the ouput stage of the driver. This also minimizes ringing effects on the lines.

In addition to the low impedance drive, each signal high and low level has to be uniquely adjusted between -10 V and +15 V for a particular device. It was found, especially for the CCD 201, that these levels are very critical; no operation was obtained over a large range and optimum performance only in a very narrow range.

These requirements led to the design of the clock driver with the adjustable high and low levels. It was noticed that certain blemishes of the device could be made to disappear by adjusting the clock levels, a setting which was not necessarily the same as the one for best image quality. Since the devices were to be used for tracking illuminated targets, a compromise had to be made.

4.3.2. Chip deficiencies.

The "white video defects" or blemishes, caused by dark current spikes or completely defective regions, which were found in all the devices examined, are of particular concern in a computerized data acquisition system. It will be seen in Chapter 6 that no time is available for a software suppression of blemishes during real-time data acquisition. Therefore, suppression by hardware had to be as good as possible. It was noted that most of the blemish-levels are below video-saturation level, and discrimination was possible by threshold setting of the amplifier (see section 4.3.3.). This resulted in a great loss of dynamic range, because dynamic range is given now by the difference betweeen video-peak and dark signal peak voltages, and not the dark signal RMS voltage.

Due to edge effects, one of the devices showed badly blemished lines, which were the two outermost ones on one side of the chip. A "logical" suppression of these lines was done in the digital part (see Chapter 5).

4.3.3. Video amplifier.

Data sheet specifications guarantee typical video saturation voltage of 200 mV and a minimum of 100 mV for the CCD 211. The devices now implemented in the present camera system meet these specifications, where an earlier device had to be rejected, having less than 50 mV video peak-signal.

The voltage levels, obtained by the on-chip floating gate amplifier, are not critical for further necessary amplification. Adjusting the clock-levels for optimum quality requires a display device. For simplicity, a standard oscilloscope (TEKTRONIX 7004) was used. Two saw-tooth generators were built (see Logic Diagram, Appendix A, Fig. A3) for the deflection of the oscilloscope beam in X- and Y-direction, synchronized with the scanning clocks. The pattern obtained on the oscilloscope screen is modulated with the video signal through the Z-modulation input of the oscilloscope. For suitable modulation, a voltage of about 5 V was required, and the video amplifier was designed accordingly. The image obtained is of acceptable quality, and can be used for adjusting the CCD-clock levels, setting up the camera system, and observing the data acquisition. In fact, the setup can be used as a closed-circuit-TV-system, no computer being required at this stage.

4.3.3. The marker detector.

The "labels" whose motions are to be tracked can be of reflective material, incandescent light sources, or infrared LED's. It is essential that the light levels generated by labels exceed that generated by the background or the object itself. Fulfilling this made it possible to use simple threshold detection to identify the labels in the output signal from the CCD. As mentioned in section 4.3.2. , dark current spikes in the video-signal limit the useful range for label-detection.

A one-stage transistor amplifier was designed to amplify the signal coming from the CCD. Portion of the horizontal clock ϕH_1 is used for biasing the transistor. The "steep slope" characteristics of the following TTL-gate, together with the set gain of this amplifier-stage (see Appendix A, Fig. A5), form the threshold characteristics of the label-detector-amplifier. The output signal controls the logic for the coordinate determination, and also generates an interrupt to the computer. A detailed description will follow in Chapter 5.

CHAPTER 5

SYSTEM DESIGN

CHAPTER 5

5.1. Camera drive logic.

The data sheet specifications for the CCD 211 define the required clocking signals (see Fig. 5.1. :Timing diagram drive signals).

It should be noted that the horizontal readout register consists of 200 elements, although the device itself has only 190 vertical columns. The required 200 horizontal clock pulses provide some blank information at the beginning of each line.

In the vertical direction, 125 vertical shifts provide one blank line at the beginning and 2 blank lines at the end of each half-frame.

At the end of a field (half-frame), when the photogate voltage ϕP is lowered, the vertical clock ϕV is held either high or low, determining the odd or even field to be moved into the vertical transport register.

A complete description of the logic is to be found in Appendix A Figs. A1 and A2.

Basically, it consists of a master clock, driving a row of binary counters. Loading a selected 2's complement number into these counters gives the necessary counts of the individual stages to obtain the horizontal and vertical counts. Two integrators, reset by the vertical and horizontal blank pulses, respectively, provide the

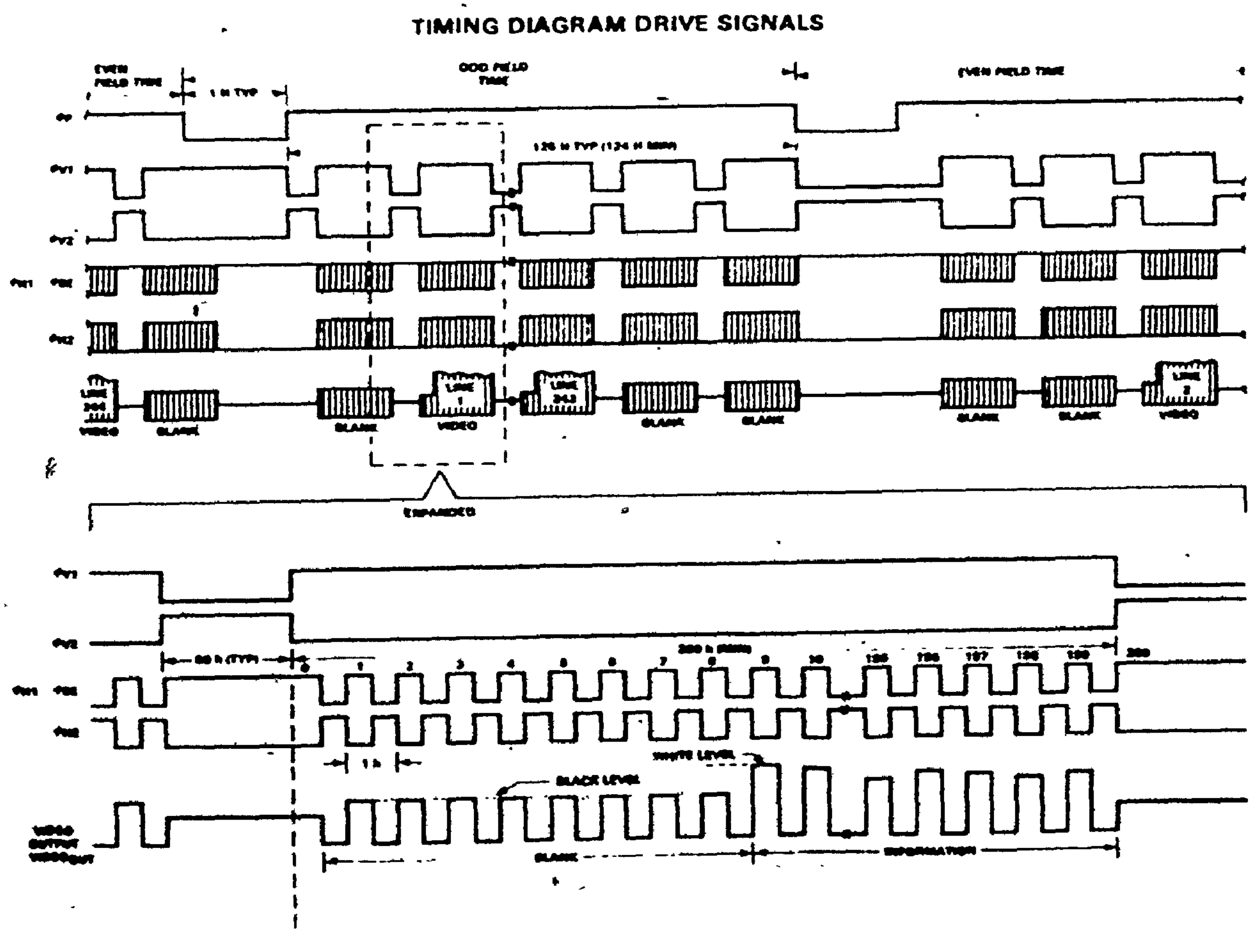

Fig. 5.1. CCD 211 timing diagram drive signals (from Fairchild data sheet)

vertical and horizontal sweep signals for the oscilloscope display. An interlace signal is also used to determine the odd or even field. These signals are summarized in the block diagram of the drive logic (Fig. 5.2.).

5.2. Interface to a computer.

5.2.1. Operation principle.

The circuitry described in section 5.1. (circuit diagrams Appendix A, Figs. A1-A5) permits operation of the CCD 211, and enables one to obtain an image on an oscilloscope used as a monitor. From Fig. 5.1. it can be seen that the relationship between horizontal and vertical clock pulses determines the scanning state of the device, or: the actual horizontal and vertical counts, with regard to the photogate clock, determine the coordinates of that charge packet being shifted into the floating gate output amplifier at this state. Therefore, by keeping track of the horizontal and vertical counts being applied to the CCD, it is possible to assign planar coordinate information to the video signal.

The discrimination on the video-signal is done only on one level: the transition between black and white, white being information from the illuminated labels. Upon the occurrence of the "label-detection", the coordinates are transferred to the computer by sending an interrupt signal to the machine. The computer then reads the input lines given by the output of the horizontal and vertical counter and

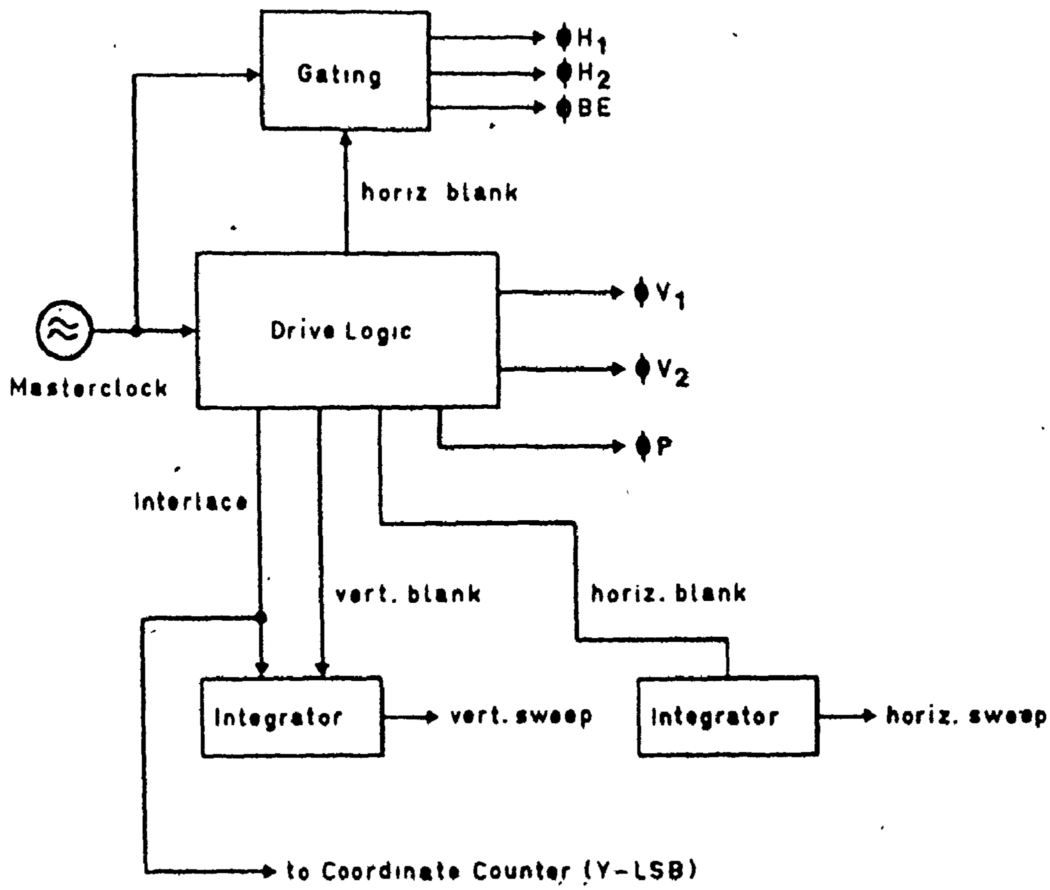

Fig. 5.2. Blockdiagram of the drive logic for the CCD 211 area image sensor.

stores the information. Since odd- and even-frames alternate, end-of-frame information is contained in the least significant bit of the vertical data. Therefore, no "end-of-frame" signal has to be transmitted to the computer. The way in which this can be exploited will be shown in Chapter 6. This basic principle of interfacing was utilized in a first prototype employing the CCD 201 running at a clock frequency of 1 MHz.

5.2.2. Timing relations.

Despite the relative low clock frequency, it was only possible to detect more than one coordinate point on one line if they were 35 cells or more apart, because the time for the computer to store one coordinate pair involved 35 µs for the fastest possible interrupt routine. For the CCD 211, in order to get the same frame rate, a higher clock-frequency had to be utilized. Experiments performed with the system (gait studies, and spinning wheel experiments, which are described in Chapter 6), showed a half-frame-rate of 100 Hz to be adequate, requiring a clock-frequency of 4.1 MHz. This means that points with the same Y-coordinate have to be separated more than half the image-width in order to be picked up by the processor.

In the sagittal plane, this problem will occur only if the heel marker swings as high as the knee, which will be, normally, not the case, or if the foot is fitted with markers on heel and toe. The backplane view will have this problem in all the cases where both sides of the body are fitted with markers. In general, the body size will not be large enough to provide enough time during the scan to enable the required separation. A faster computer, obviously, would reduce this time involved, but it is not possible to detect 2-points next to each other with this high clock frequency.

This problem can be overcome by an elegant solution, and, at the same time, it is possible to increase the basic resolution of the system, as will be shown in the following.

The work of Winter and Reimer (1972) shows that the error between the calculated centre and actual centre for a marker can be reduced by increasing the diameter of the body marker (Fig. 5.3.). A marker is represented by those points (coordinate pairs), whose video-light-levels exceed the set threshold, and, therefore, define the size and shape of the marker. In Fig. 5.3. the size of the marker is, therefore, expressed in terms of these points within and representing the marker. Therefore, the larger the marker, the larger the number of points.

These points are accurate only to a certain degree (quantisation error), but calculating the actual centre of the marker by means of averaging the X-coordinates of all points within the marker to get an averaged X-coordinate, and repeating this for the Y-coordinate, yields an error which is less than the original quantisation error. Fig. 5.3. shows the results obtained, where the mean of this error is plotted as a function of the marker diameter.

It is possible, to store the data in a temporary fast buffer and transfer during the inactive line-blank period to the computer.

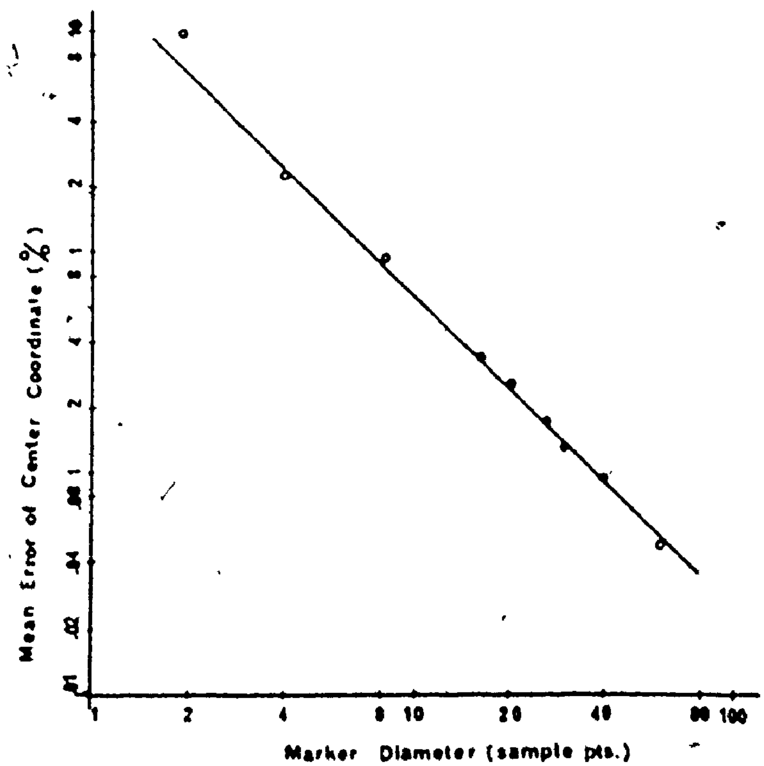

Fig. 5.3. Error in centre coordinate vs. marker diameter (sample points within the marker)

(from Winter and Reimer (1972))

Since the algorithm to average over the X-values can be realized with a hardware segment, only the resulting X-value has to be transmitted to the computer. The description of this, which was successfully implemented in the CCD 211-computer interface, is given in the next section (5.2.3.).

In order to take advantage of this method, it is necessary to detect points next to each other. In the system used by Winter, this is very simple, because all the video information is stored prior to processing, including all the redundant black-levels.

Since probably no computer at present is capable of keeping track of the signal rate on a horizontal line-scan (approximately 4 MHz for the CCD 211 at 100 frames/sec. or standard television), other techniques have to be incorporated.

5.2.3. Label midpoint determination.

The circuit-segment, described in this section, was developed to make it possible to calculate the "centre of gravity" of an illuminated label. In order to obtain the centre it is necessary to average the X-coordinates of all the points within the label and the same for the Y-coordinate. The hardware-segment performs this operation for the X-coordinates on the same line only, the resulting X-Y-pairs are averaged by the computer.

For one single line, the operation to be performed can be described as follows: if, for one particular line, the shape of the marker covers X-values from N to N + K, then the averaged X-value, $\bar{X}$

becomes

$$\bar{X} = \frac{1}{K} \sum_{i=n}^{n+K} X_i \quad , \tag{5.1.}$$

but since the values within the labels are linearly increasing equation 5.1. can be simplified to

$$\bar{X} = X_n + \frac{K}{2} \tag{5.2.}$$

or

$$\bar{X} = \frac{X_B + X_E}{2} \quad , \tag{5.3.}$$

where : $X_B = X_n$, and $X_E = X_{(n+K)}$.

This operation is performed in the hardware element (see Fig. 5.4. and Fig. 5.5.). Equation 5.3, shows that only the first or beginning point (X_B) and last or end point (X_E) of a line belonging to a label (label begin and label end) have to be detected and the midpoint of this "illuminated line" calculated. In practice, this is achieved by a retriggerable monostable multivibrator, triggered by the video signal above the selectable threshold-levels (see also circuit diagram Appendix A, Fig. A7). This forms the signal "label" in Fig.5.5.

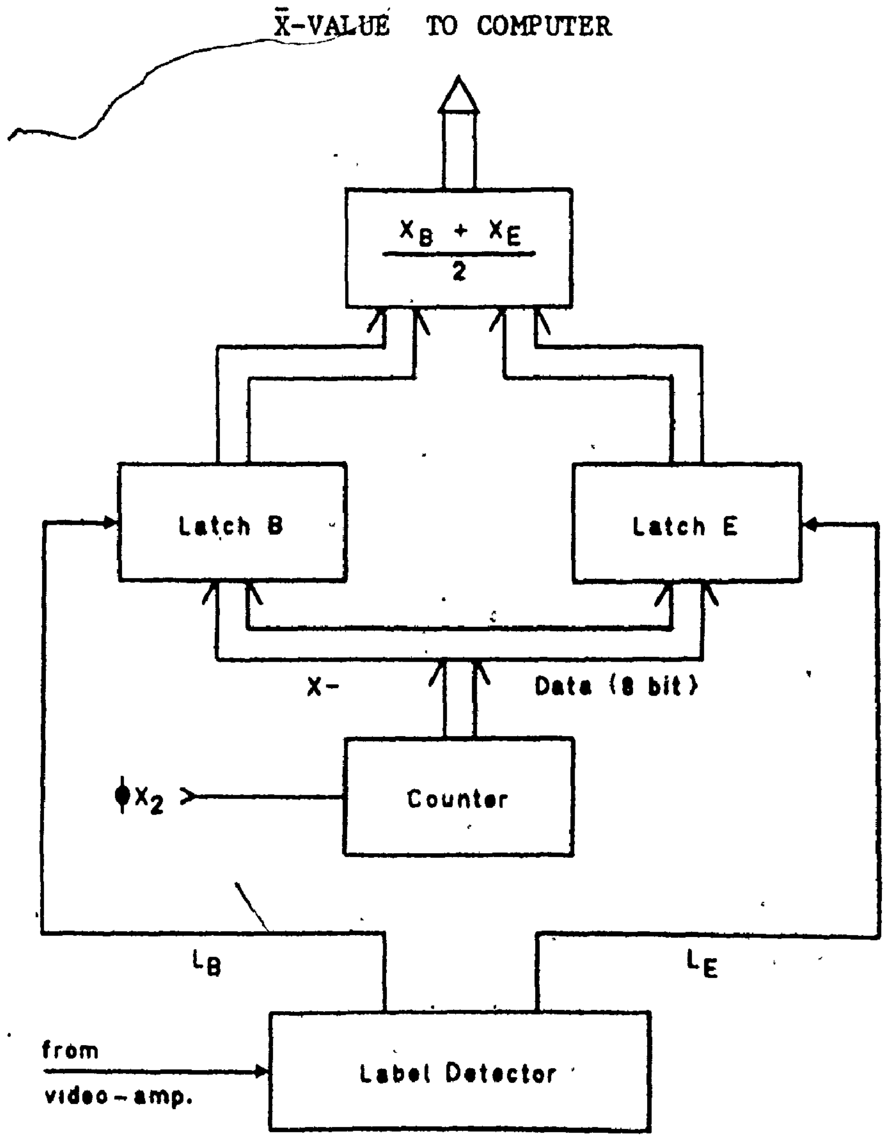

Fig. 5.4. Label midpoint determination (X-averaging).

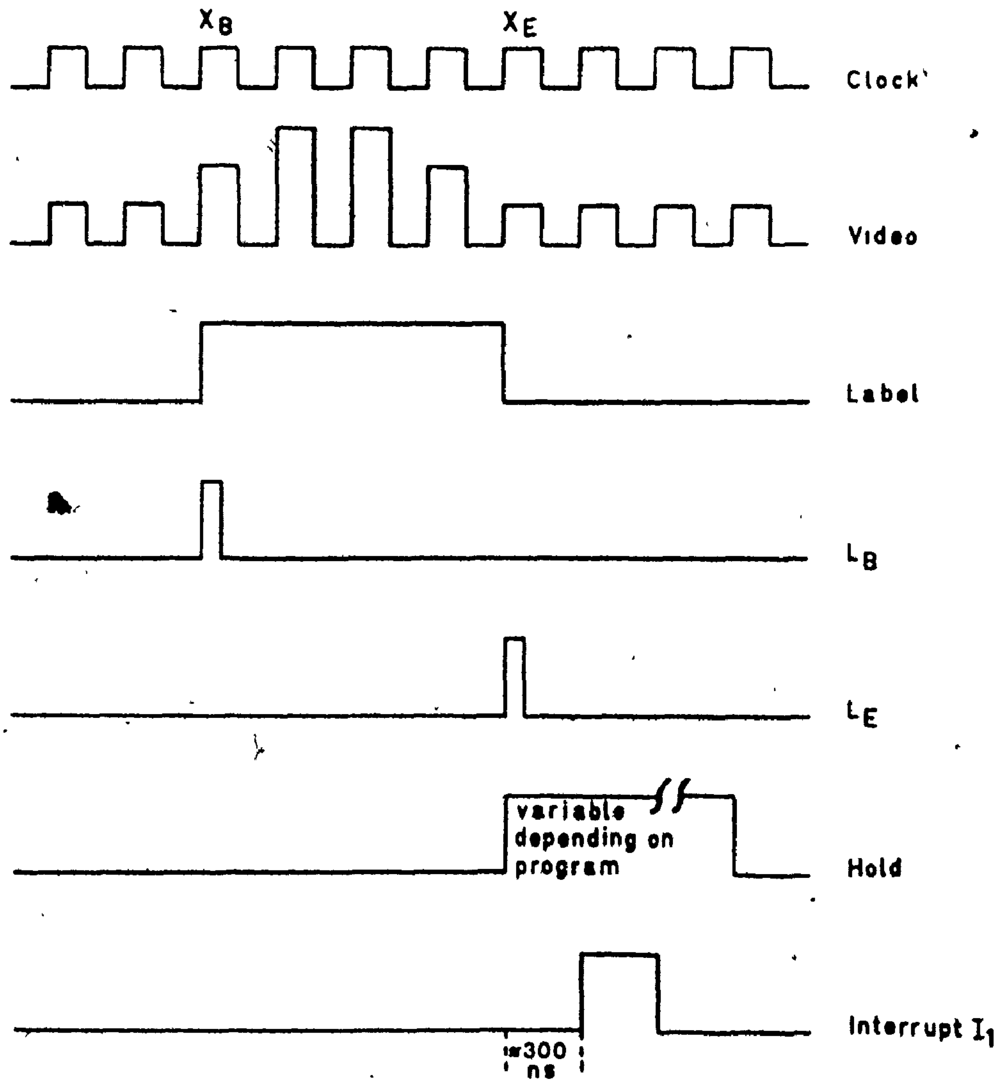

Fig. 5.5. Timing and signals for the interface control.

This coordinate pair (averaged X-value, Y-value) is transmitted to the computer. For the PDP 11/10 presently being used, it takes approximately 35 μs to store this coordinate pair. If no intermediate storage is provided, any other label falling within this 35 μs-range will get lost. A simple way to overcome this problem was to disable the master clock for this time period (signal "HOLD" in Fig. 5.5.), which means no other label-signals are generated, but data is not lost.

This is an advantage of the CCD-device over TV-tubes because a simple control over the scan can be achieved. This switch selectable option of the system allows the generation of virtually any number of labels on any one scanning line, limited only by the software separation algorithm (see Chapter 6).

5.2.4. Interrupt control.

After completion of the averaging process by TTL-arithmetic-logic, which takes about 12 ns, data is available at the camera output to be read by the computer. The machine requires 300 ns settling time and, therefore, this delay has to be provided before the interrupt signal is sent to the computer. The sequence of operations to store the data in the computer is discussed in Chapter 6. The overall layout of the interface system is given in Fig. 5.6.

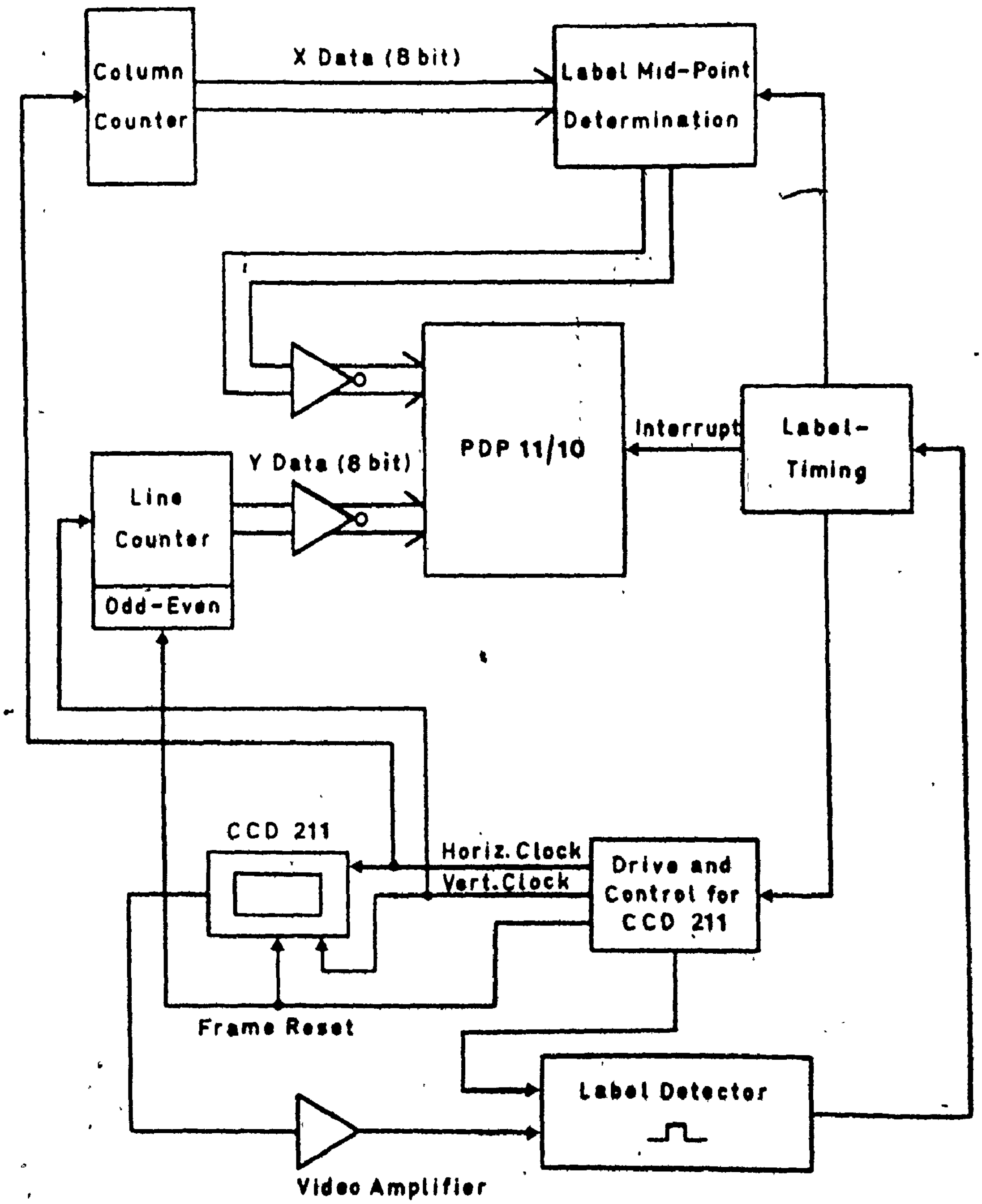

Fig. 5.6. CCD area image sensor - computer interface system for optical data collection.

5.2.5. Cable drive.

The distance of the computer from the camera required a cable connection of approximately 15 m. In order to transmit the data without crosstalk and ringing effects, a special cable drive had to be built. It was found necessary to use a cable with individually shielded twisted pairs for the signal lines, with a differential drive and receive circuit. The circuit of the cable drive is given in Appendix A, Fig. A10.

5.3. 2-camera system.

5.3.1. Expanding from one camera.

The 3D-recording of spatial data requires two 2-dimensional camera-systems. In order to relate the data obtained by the 2 cameras, they have to be synchronized. Several ways of doing this are possible. If the cameras are built as identical units, they have to run at the same master clock frequency, which can be achieved by supplying each camera with this clock signal. This will result in the same frame rate, but the frames have also to be synchronized, i.e., the frames have to change at the same time. This can be accomplished by a general reset signal to start both systems at the same time, or simply by sending the frame reset signal from one camera to the other.

Another possibility is to have one central logic unit including the counters for the interface and two identical remote cameras. Since one camera was built already, it was, from a practical standpoint, the easiest way to run the 2 CCD's from the same clock. Since all the clock-signals are available from the drive module for camera #1, they have to be transmitted only to the other CCD-camera system over a suitable cable. The same cable-drive circuitry as used in the data link between camera #1 and the computer was used. Therefore, the components for the second camera could be reduced to the cable receiver, the CCD-driver, video-amplifier, label-amplifier and power-supply. The TTL-level "label"-signal is sent over the same cable to the control module (Fig. 5.7.).

5.3.2. The control module.

The control module for the two cameras has to perform the following functions:

- send to and receive signals from camera #2
- track the coordinates of camera #2
- multiplex the data from the two cameras to the computer and send the interrupt signal.

The coordinate counters, arithmetic unit, timing and interrupt generation are identical in function to camera #1. In addition, a 2-to-1 multiplexer connects the data of the particular camera to the computer line, which was sending a "label"-signal. At the same time, the master clock is disabled ("HOLD"), so that no label-generation from the other camera is possible. This will essentially slow down the frame rate, but practically, the "HOLD"-times are short enough that even in a case of, e.g., 10 labels within one frame the frame rate will be affected by less than 2%.

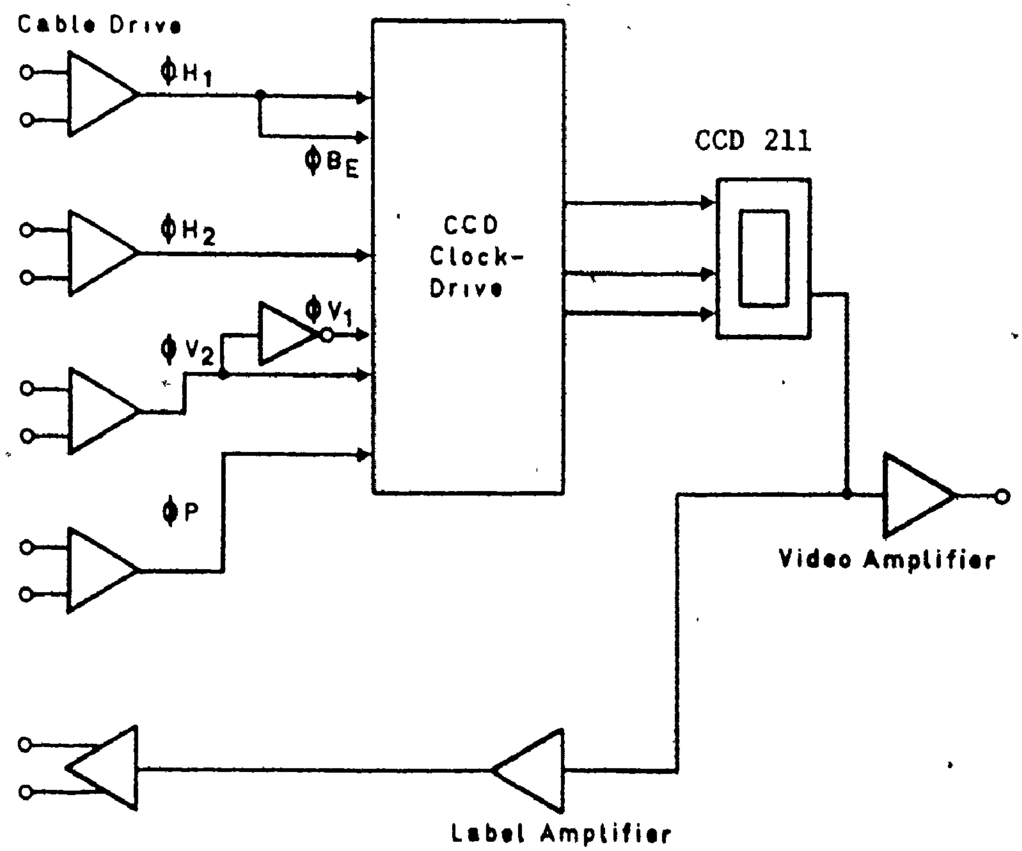

Fig. 5.7. Blockdiagram for the slave-camera module (camera #2), including the differential cable drive.

In the event of the simultaneous occurrence of the label-signals from the two cameras, there will result a loss of the data from camera #2 because camera #1 has priority in the multiplexer select.

The two interrupt signals are sent on different lines to the computer, which makes the soft-ware differentiation between data from the two cameras very easy.

Summarizing, the function of camera #2 and control module are identical to the main unit with the addition of a data multiplexer. A block diagram description of the control module is given in Fig. 5.8, the complete circuit in Appendix A, Fig. A2.

The cable connections and related arrangements were designed in such a way that camera #1 can be used alone for 2D-recording only. In this case, the control module does not have to be connected to the camera, and the camera can be used in this "stand-alone" fashion. Connecting the control unit and the other camera gives the full 3D-recording system. Different software programs have to be used for the 2D or 3D version. Descriptions follow in Chapter 6.

5.4. A general 2-camera system design proposal.

The existing system was originally built expanding from one camera to two cameras. The results obtained are very promising for this fashion of interfacing charge-coupled device image sensors with a minicomputer. By combining the functional modules and centralizing them, the overall system design can be simplified. The satisfactory

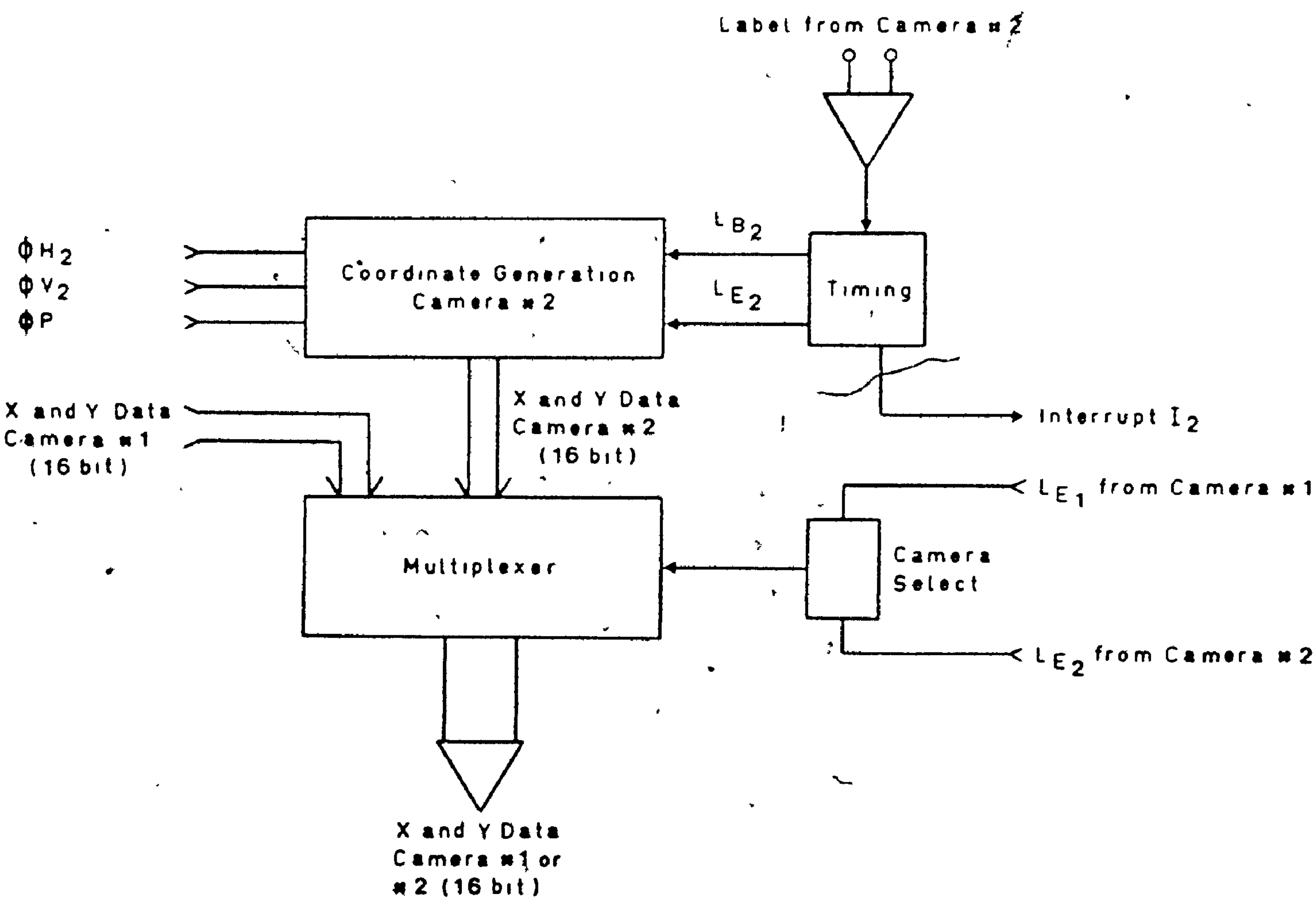

Fig. 5.8. Blockdiagram for the 2-camera control module.

results with the cable drive used for camera #2 make it possible, that both cameras can be driven through such a cable and thus the remainder of the interface and control logic can be close to the computer so that the special cable drive for the data becomes unnecessary. A general functional system will look like Fig. 5.9.

The individual modules such as drive logic, counters, midpoint determination, etc., can be identical to the system previously described in this chapter.

It can be seen that the data multiplexer becomes unnecessary, camera selection being done by the interrupts alone.

Although for 3D-reconstruction only 2 cameras are necessary, it can be advantageous to employ more than 2 cameras for a more complex data analysis (e.g., both sides of the body at the same time). Since the cameras are just handled as input devices to the computer, basically, any number of cameras could be employed, where the number of available hardware interrupts and core-space would constrain the maximum possible number of cameras in such a system.

This general approach is possible with any kind of CCD-sensor where the counting principle can be applied. It was during 1977, that CCD-TV cameras, made by RCA, became commercially available. Implementing these self-contained cameras for interfacing would simplify the construction considerably. The same principle as shown in Fig. 5.9. could still be applied but elements such as the CCD-clock drivers, and video-amplifiers are already contained in the cameras. Because the cameras are not driven centrally, clock synchronizing

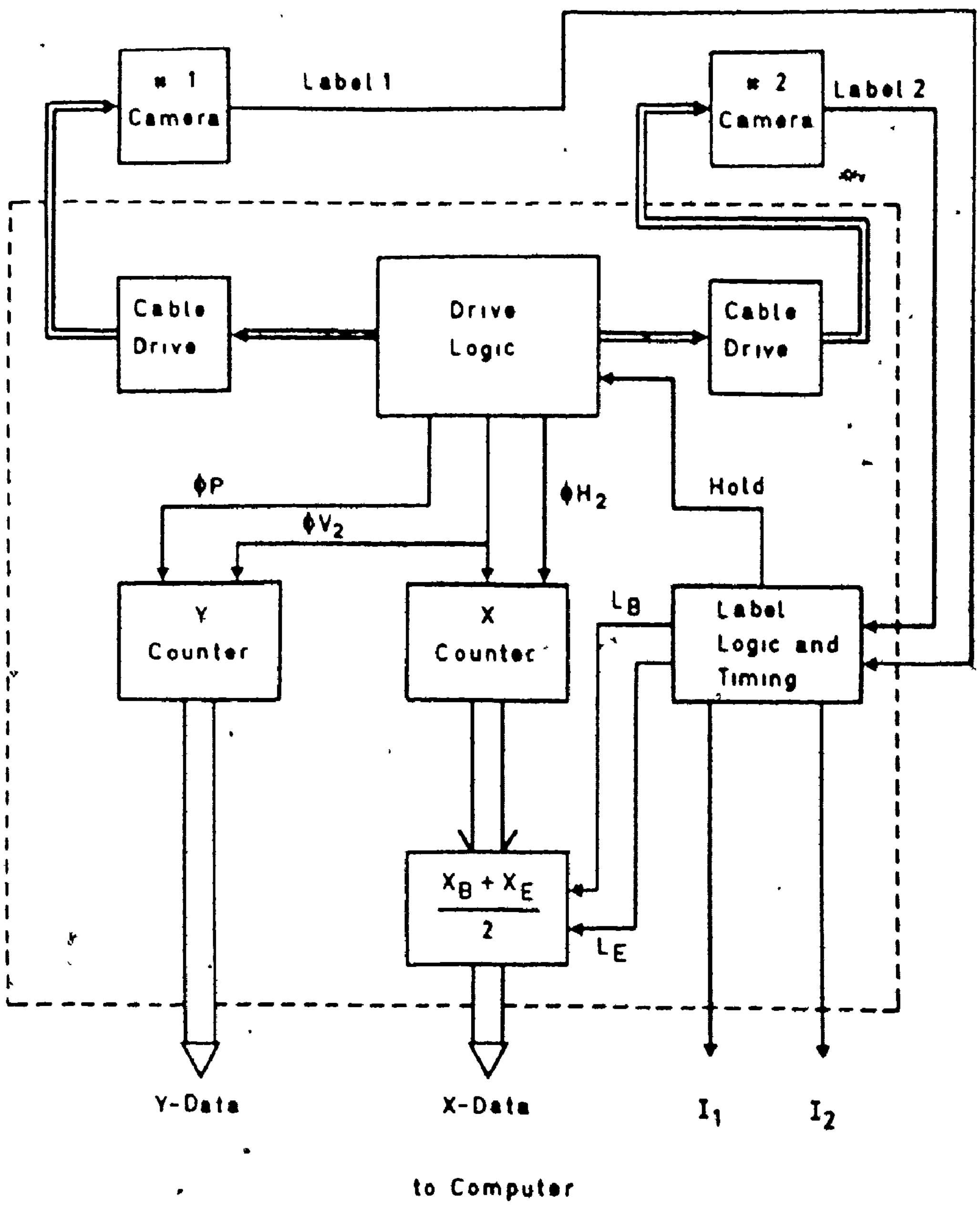

Fig. 5.9. Blockdiagram for a general CCD 2-camera drive-, control- and computer interface-system.

would have to be applied instead.

At present, CCD-sensors and cameras are still expensive, not easily available, and not always at expected quality, in respect of both image blemishes and photo-response uniformity. The fabrication of CCD-sensors is based upon silicon integrated circuit technology, in which the manufacturing costs have decreased at the remarkable rate of almost an order of a magnitude within the last 6 or 7 years. Although a definite trend cannot be foreseen, the prospects for cost reduction are very good. If high resolution sensors become available, the CCD's will be a powerful tool even in a general computer image processing or optical data acquisition system.

CHAPTER 6

DATA COLLECTION AND PROCESSING

CHAPTER 6

6.1. Data collection under program control.

6.1.1. Program language considerations.

The operation of the camera-system requires that trajectory data from the CCD-cameras be acquired under program control, with the elementary programs (drivers) written in machine language (MACRO-11) for the computer available.

This machine consists of a PDP 11/10 CPU with 28 K core memory and extended arithmetic (integer) hardware. A 1.2 Megaword moving-head disc (RK05) and dual magnetic-tape system (DEC-TAPE) were available for mass storage.

A multifunctional I/O-unit (LPS-11) with A/D and D/A-facilities (8 A/D-channels, and D/A-channels), 16 bit digital in- and output, real-time-clock, Schmitt-trigger input and relay-output are part of the system.

The 16 bit digital input was ideally suited for the interfacing of the cameras, except that no internal latch was provided.

The fast real-time operating system (RT-11, V02B) permits very efficient programming and running of the programs. The MACRO-11 Assembler is based on the earlier PAL-11R assembly language, but with macro-coding capability.

Only these sections of the programs, where severe speed constraints existed (or non I/O-drivers were available), were written in machine code, which is machine dependent, and would have to be changed for other computers. However, the general principles involved are still applicable to most mini- and even micro-computers with interrupt facilities. The program control, data storage and processing was done under FORTRAN.

Utilizing a controlling program written in a higher level language offers many advantages. Usually, compilers are available for most computers, and it is much easier to write a program in a higher level language, or to modify it, than is the case for machine language. Disadvantages such as more core requirements and slower execution time have to be considered. FORTRAN IV was chosen for these programs because of its virtually universal acceptance and availability.

6.1.2. Data format and machine characteristics.

The data available from the cameras is represented in 8 bit words for the X- and Y-values. The PDP 11/10 is a 16 bit-machine with byte-addressing capability. Therefore, the two 8 bit words from the cameras were transmitted and read by the computer as one single 16 bit word from the digital input, and separated using the byte addressing feature of the machine. It is not within the scope of this thesis to give a complete description of the machine language and the LPS-system, which are, respectively, to be found in the PDP-11 Handbook (1973) and the digital input in the LPS-11 User's Guide (1973).

The digital input did not provide an internal latch requiring data to be present at the input for the time while being read under program control. The most efficient way to do this was to use the interrupt facility of the computer. The program steps within the interrupt-loops have to be kept to a minimum, in order to maximize speed. Therefore, the input-data is read and stored only; separation of X- and Y-values and data-checking have to be performed upon completion of the data-collection.

Two substantial programs in machine language were written for operating the CCD-camera system:

- A program for an on-line, true real-time display of the data from the cameras on a display-monitor (oscilloscope), and
- a driver for on-line data acquisition under FORTRAN program control with optimized speed.

Both programs exist in two versions, for running either the one- or two-camera systems.

Although the momentary data-rate can be very high (if two points are next to each other on the same horizontal line), the average rate is low, and other data acquisition during this idle-period is possible. This maximum rate equals the horizontal clock-frequency (4 MHz for the present system), but points that are close to each other cannot be separated by the software routine; a spacing of approximately 5 cells or more is required for separation, which will result in 800 KHz for the data rate.

The average rate for one frame is obtained by the product of frame rate, number of labels, and number of vertical lines occupied by one label. For 5 labels, as an example, 2 KHz would result as the average rate.

Con had to be

because no interruption of the service-routine is permitted, since no time is available to save and restore the general registers. Therefore, the line clock, used by the operating system, had to be disabled, and camera #1 was given priority over camera #2. The assembly program descriptions in the following sections can only serve to demonstrate the general principles applied. For more information, reference should be made to the actual listing in Appendix B. For a complete understanding of the machine language, the interrupting and the LPS 11, the appropriate manuals will provide the additional information.

6.1.3. Real-time display.

This program (see program listing Appendix B, program B1) performs a direct on-line display of the data obtained from the CCD-cameras. No data storage is done, the program is mainly used for setup and checking of the system. The principle of data collection can be shown illustratively with this program (see Flowchart Fig. 6.1.).

After the initializing procedure, the computer goes into a WAIT mode to minimize latency time. The occurrence of an interrupt from the camera transfers the program counter to the actual display routine, which performs the reading of the digital input, unpacking X- and Y-values, loading the analog X- and Y-outputs, and plotting the data on the oscilloscope-screen.

Summarizing, with the CCD-camera and its interface sending the appropriate interrupt signals, the CCD-camera can be treated as any other input device to the computer, which simplifies the programming considerably. The 2-camera-version (listing in Appendix B, program B2)

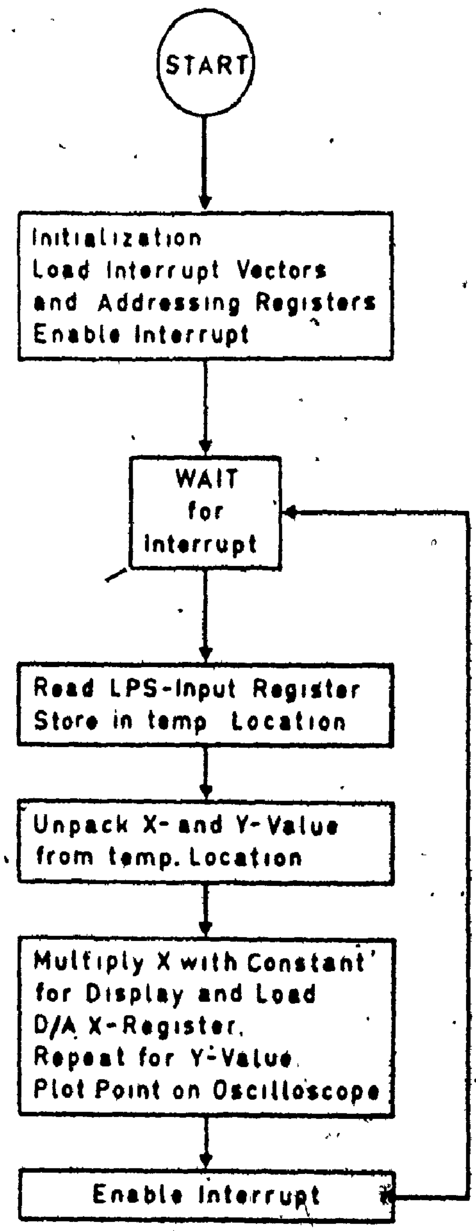

Fig. 6.1. Flowchart for the real-time display of the CCD-camera data.

signals on two different lines, allowing the computer to distinguish between the cameras.

For the PDP-11 with the LPS-system the interrupt line for the digital output was used for the second camera because the "interrupt enable" belongs to the same control and status word of the LPS-system, but with different interrupt vectors. This made it possible to operate the 2 cameras independently, although synchronized by the hardware system. During the WAIT-cycle it is also possible to acquire data from other sources, such as e.g. the A/D input, if interrupt priority is given to the cameras. Simultaneous recording of, e.g., electromyographic and trajectory data, is, therefore, possible.

6.1.4. The Camera driver (data collection).

This program (Appendix B, program B5 and B6) is a FORTRAN callable subroutine which stores the data picked up from the camera in an array of the FORTRAN-program. Information, such as array addresses and lengths, is passed to the subroutine.

The data acquisition is started by an external event (operator control) and terminated by reaching the end of buffer space or another external event. Control is then returned to the FORTRAN-program, where further processing of the data and displays can be done.

The operation of the subroutine in the interrupt-routine section is similar to the real-time display, with the difference that data is stored in core memory. If operator control terminates the acquisition, the [illegible] is [illegible] to the

6.1.5. The controlling program and core requirements.

The main purpose of the main program is to pass required information to the subroutine (the actual camera driver), call it, and upon return, continue with displays and further processing. It was found that further processing for the 2 camera system was not possible within the same program due to core restrictions.

With the computer configuration available for these studies, a maximum of 28 K core-memory was available, leaving approximately 24 K for programs and data buffer. With a minimum FORTRAN-program, 22 K of memory was available for buffer space. This results in a 5500 word-buffer for X- and Y-data for the two cameras. This data is written on the mass storage device (disc or tape) and read back separately for each camera in a subsequent program. For the one-camera-version, this intermediate step is not required because more core is available for program code.

The received data, as it comes from the camera, has to be identified with regard to the labels, if more than one label is involved. This separation process is described in section 6.2.

6.2. Trajectory identification.

6.2.1. Frame separation and the identification problem.

The sequential scanning operation of the CCD-cameras results

These time-relations within one frame can be associated with coordinate-information for the image generating the video-signal. If more than one light-source is generating the video-signal, identification of these sources becomes necessary. Since the interrupts to the computer are given in order of occurrence, storage of the data is done in the same order. The physical size of one label, resulting in a number of X-Y pairs per label (see also Chapter 5), requires a number of storage locations per label. For more than one light source, the order of the data values being stored in core depends on the position of the light sources generating the image on the sensor, which means, if e.g. 2 labels are positioned on the same Y-coordinates, partly or fully, the data storage sequence will alternate between the 2 labels.

Before averaging of the individual labels is possible, an identification of the label data, with regard to each label, is required.

6.2.2. Separation routine.

As described in Chapter 5, the interlacing provides a simple method for detection of the frame-boundaries in the data stream. Data within one frame has to be averaged for each label within this frame. A frame identifier in the form of a subroutine has been written in machine language (Appendix B, program B8) to increase computation speed, since this subroutine is called many times during a separation process. This subroutine takes advantage of the interlaced format of the CCD-camera-data, where data belonging to the same field will always have the same LSB (odd or even) for the Y-values. This permits recognition of the fra

The actual separation routine (Appendix B, program B8) has to perform the following tasks:

- detect the first full frame
- detect the labels in the first frame, average and use it as reference for the following process
- use the reference to separate the next field and update the reference.

False information due to chip deficiencies, reflections in the room, etc., will be rejected during the separation process. If information is missing (label obscured), a prediction based on the previous data is made and used to fill the "gap". The separation process is shown in block diagrams (Figs. 6.2.1. and 6.2.2.). Only the principles are given by the block diagrams. Some of the more complex operations such as comparing last and present frame information ("New data good"), are done by separate subroutines. For complete information, refer to the program listing in Appendix B.

6.2.3. Quantization effects and format representation.

The limited number of elements in the CCD-sensor (244 x 190 for CCD 211) which determines the resolution of the system has to be considered for the processing. The input data, as well as results for subsequent display, are represented in one word integer format (16 bit). From the size of the CCD 211, where 244 is the largest number, the quantization step is 1:244. The averaging process to determine the centre of a label, as well as the extrapolation process, is done in floating point

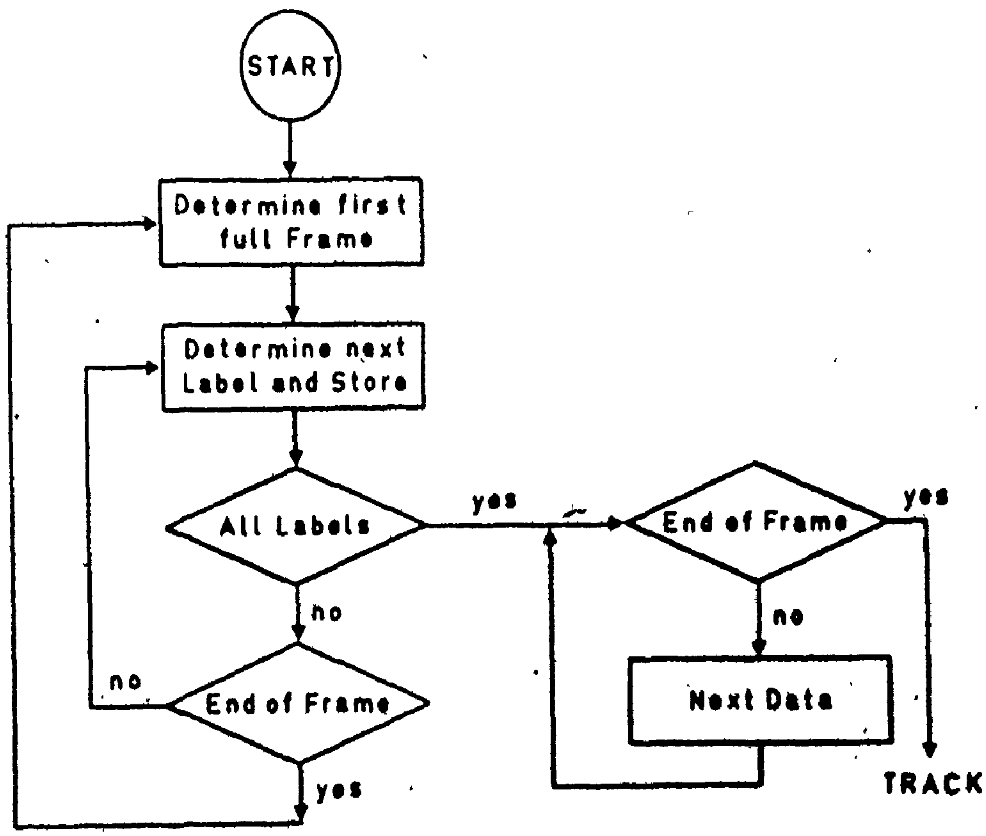

Fig. 6.2.1. Flowchart for the separation subroutine, detection of the first frame.

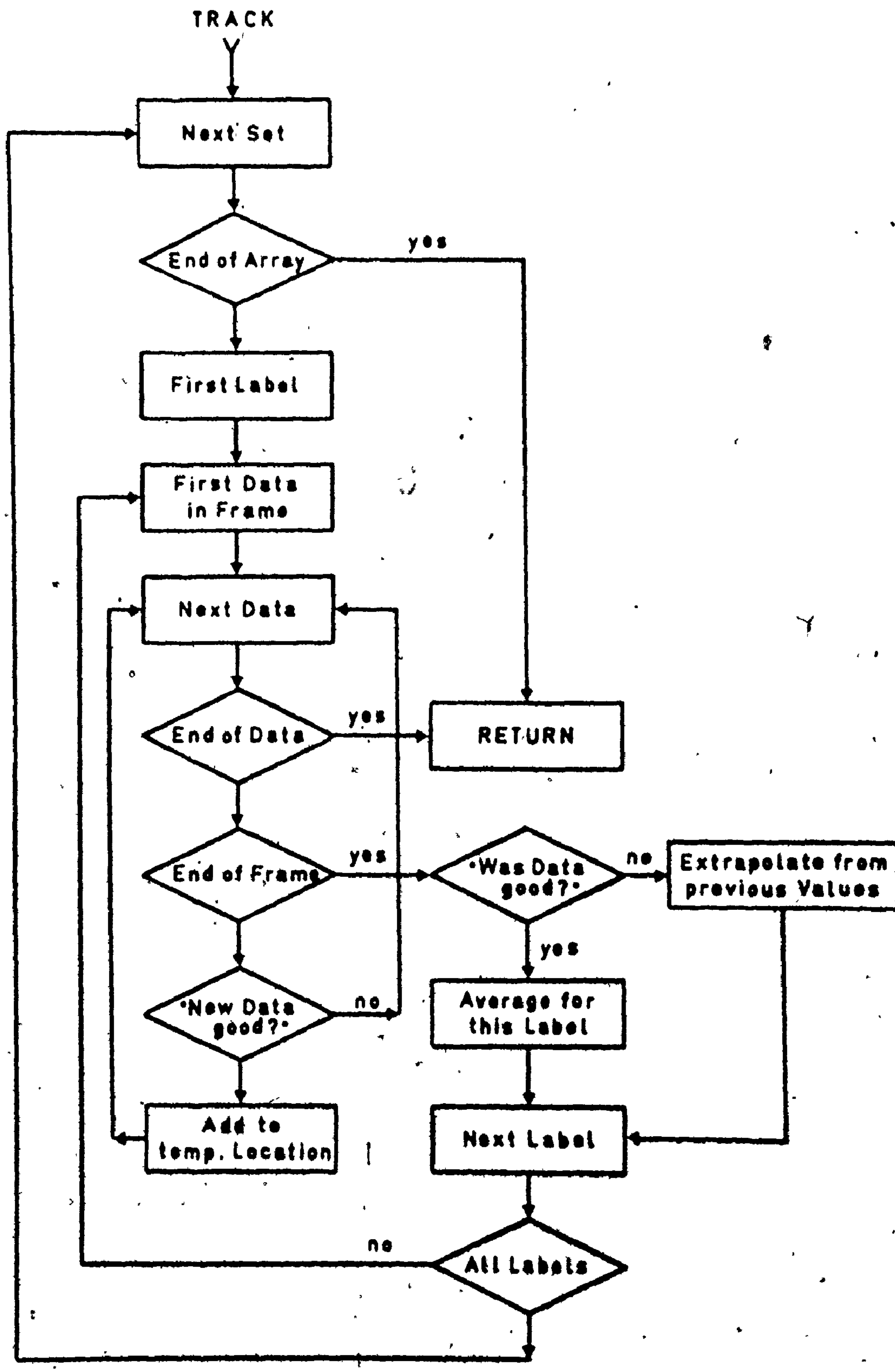

Fig. 6.2.2. Flowchart for the separation subroutine, separation of the labels.

format. For data storage and display, results are converted back to integer format to reduce storage requirements, but are multiplied with a sufficiently large scale factor to minimize the introduction of additional quantization error. If the data is manipulated, (e.g. averaged), fractions of the original quantization steps can be obtained, but this advantage is lost, if data is stored back into integer format of the same value. Multiplying the data with a large enough scale factor to take advantage of the 16 bit size of the machine reduces this quantization, which occurs upon the conversion into the integer format. For display purposes, data has then to be adjusted to match the display format of the device being used. After calibration, the scale factor can be chosen to represent the data, e.g., in millimeters.

6.3. Calibration and errors.

6.3.1. Sources of error.

Compared to television-systems, where deflection nonlinearities have to be considered, the CCD-sensor does not introduce any error or distortion, since the geometric accuracy for the diode matrix in the sensor is much better than the obtainable resolution. No figures are given by the manufacturers for the matrix layout, which is claimed to be "accurate". From a physical standpoint, it is certainly possible that the cell-centre spacings are sufficiently accurate with regard to the cell-dimensions, that the error might be neglected. In this case, the main linearity errors of the system are given by the optical system alone. Calibration procedures, such as described in section 6.3.4., are possible but will in general be valid only for the one particular lens being used. Then, the limited resolution of the sensors will introduce an uncertainty in the determined coordinates of the targets (quantization error).

The moving label, with its spatial coordinates varying with time t, can be represented by the coordinates X(t), and Y(t). Therefore, the quantization through the discrete CCD-sensor, is just another form of A/D-conversion, where white noise adds to the signal, due to the quantization process.

The basic resolution of the sensor can be enhanced by the procedure described in Chapter 5, additional improvements can be done only by signal processing procedures such as filtering and smoothing. Some of these filtering procedures are described in Andrews' (1976) and Woltring's (1977) work. The method being used for this system, with the advantages of little computer core requirements (only one data array required), and a minimum of processing time is described in the following.

6.3.2. "Window-averaging".

Since the sampling rate of this system can be selected to be

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with the sampling frequency fs of the camera system and K as the number of samples within the window.

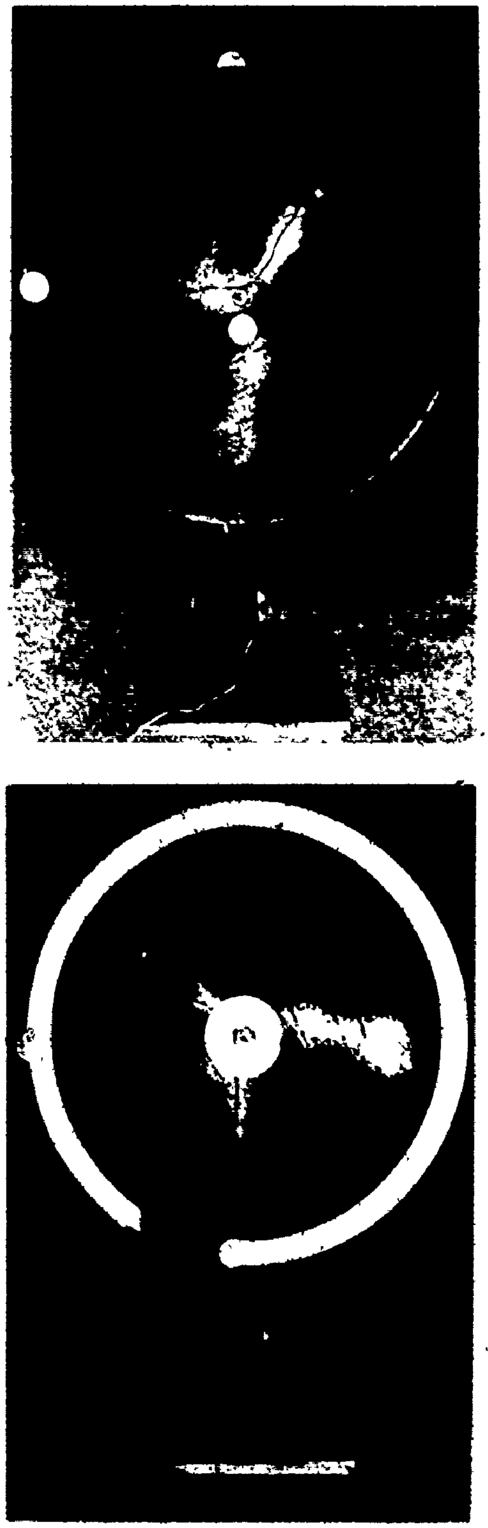
Equation (6.4.) makes it convenient to estimate the filtering characteristic for the selection of a window length for the particular applications (slow walk, fast walk, etc.).

6.3.3 Experimental and theoretical errors.

Testing the system in a dynamic fashion required trajectories of known characteristics. A rotating wheel, with lightbulbs placed at different positions on the wheel (see Fig. 6.3.), was used to investigate the overall dynamic characteristics of the camera system.

One full rotation of the spinning wheel was used, with one or more lightbulbs generating the trajectories. Computations of the centre of the obtained circle, as well as the radii for each sample point, were done. By investigating the results obtained, it was seen that the error can be held within the spatial equivalent of ± 1 element sensor spacing.

Originally, odd- and even-frame samples were averaged to obtain one data point. These data were smoothed by the process described in section 6.3.2. The visual inspection of the displays showed, that the same results can be obtained by keeping the data in its original form, and increasing the size of the smoothing-window by a factor of two. This way, twice the data points are available for visuals displays, which is advantageous, especially for point-plotting devices such as storage oscilloscopes.



(a)

(b)

Fig. 6.3. Calibration wheel setup with table tennis balls (illuminated inside), representing the labels.
(a) - standing
(b) - rotating

Calculating the distance between two light sources of the spinning wheel confirmed the results in calculating the radii.

A more qualitative analysis of the frequency response of the system was performed by tracking the light spot (beam) on an oscilloscope screen. Test signals for the deflection of the oscilloscope beam such as: sine-, square- and triangular- waveforms were used. For the sinewave, a signal up to approximately 40 Hz can be detected, with the camera frame rate of 100 Hz. A similar performance in tracking the squarewave was observed, although no points were detected during rise- and falltime, where the shape of the triangular- wave gradually changed into its fundamental with increasing frequency of the signal, a result to be expected.

In conclusion, it can be noted that the tracking performance of the system is good, and comes close to the Nyquist limit (50 Hz), although, for a general signal with high and low frequency components, the possible range of illumination causes a problem, since slow movements may cause blooming of the image, where very fast movements might not be detected at all.

6.3.4. Lens errors

The determination and classification of the individual lens errors, such as barrel or pincushion distortion, astigmatism and centering accuracy are relatively complex, but examination in detail is not necessary because of the global character of all these errors, which can be concluded by inspection of a regular distribution of control points.

In general, these errors have a radial symmetrical character, which would require only a one-dimensional compensation, either in a closed form approximation or calibration table, based on the obtained observations.

The lens testing was performed using the camera system and moving 2 lightsources separated by a fixed distance within the measuring field.

The Canon 6 mm lens, designed for the 16 mm movie-format, showed up to 10% barrel-like distortion towards two corners, and less than 1% barrel in the other directions. No radial symmetry as mentioned above was found, the large errors seemed to be manufacturing errors and it would be difficult to set up a compensation table, because the characteristics change with the focusing of the lens. As an accurate measuring device, such lenses have to be rejected, but a calibration method described in section 6.3.6. can still be applied.

6.3.5. 2-camera set-up and spatial resolution.

It is possible to reconstruct the 3-dimensional spatial coordinates from the obtained observations of the 2 cameras. The choice of camera parameters depends on the application, with restrictions such as room size, lenses and camera positions. A setup was selected as shown in Fig. 6.4. with the optical axes intersecting at 90^{o}, which simplifies the solving of the equations, and also will give optimum accuracy, since observed distances (internal camera values) are maximum. These internal camera values are the ones which are obtained in the imaging plane,

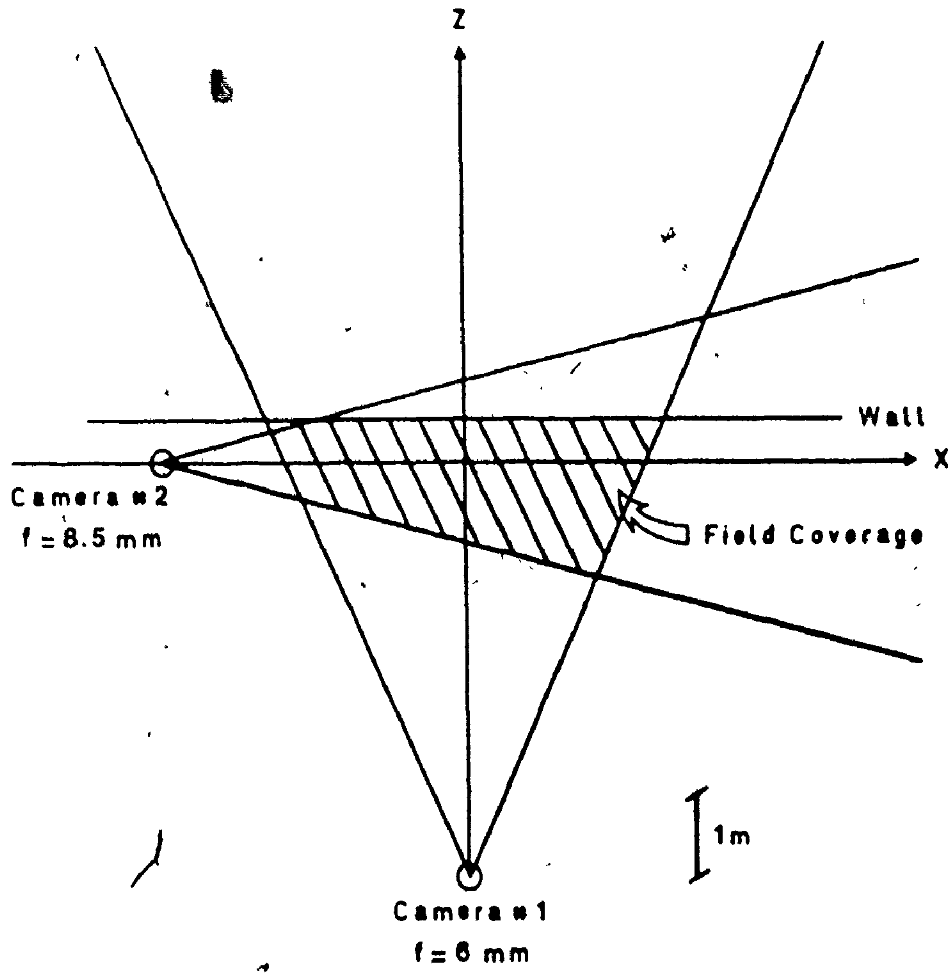


Fig. 6.4. Setup configuration of the CCD-cameras for 3D-recording, with the resulting field coverage for the selected lenses.

and are, of course, for a fixed external distance between two points a maximum, if this line is at an angle of 90° with regard to the optical axis. Since quantization error of the sensor is a fixed value and independent of image size, the relative error gets minimized by maximizing the image size. A range of approximately 5 m in the walking direction is highly desirable, yielding about 3 consecutive footsteps in the field, but the obtained resolution is relatively low for the CCD 211-sensor. Better absolute accuracy can be obtained by reducing the field size.

For a camera setup as per Fig. 6.4., and invoking the lens equation 2.3. using the camera coordinates:

camera #1 $(D_1,0,0)$

camera #2 $(0,0,D_2)$,

the true coordinates can be expressed as follows:

$$X = (X'_1 \cdot Z/f_1) + D_1$$

$$Y = (Y'_1 \cdot Z/f_1) \qquad (6.5.)$$

$$Z = (Z'_1 \cdot X/f_2) + D_2 \quad ,$$

with the primed values indicating camera values, and the subscripts referring to the camera numbers.

Since all the final values are not known a priori, the equations have to be solved as follows:

$$X = \frac{f_2\ (D_1 f_1 + D_2 X_1')}{f_1 f_2 - X_1' Z_2'}$$

$$Y = \frac{Y_1'\ (D_2 f_2 + D_1 Z_2')}{f_1 f_2 - Z_2' X_1'} \qquad (6.6.)$$

$$Z = \frac{f_1\ (D_2 f_2 + D_1 Z_1')}{f_1 f_2 - Z_2' X_1'} \quad .$$

The above equations permit the determination of the spatial coordinates from the camera observations alone.

Errors made in the X or Z values will affect all three coordinate values. A "worst case" estimate, based on a quantization error of one element both for X and Z values, is tabulated in Appendix C. It can be concluded that for one coordinate, the major contribution of error will come from the error made in measuring this particular coordinate. This will be worst for the X direction because the actual spatial spacing is the widest, due to the minimum number of elements (190 for CCD 211) and the aspect ratio of 4:3 in the sensor. For camera #2, this direction was chosen to be the Y direction, and the Z direction being obtained with the higher resolution direction (244 for CCD 211).

6.3.6. Compensation by calibration input.

Using the method described in section 6.3.5., the camera positions were assumed to be correct. It was found that a small setup error in one of the camera positions will introduce a relative error of less than half this setup error for the coordinates. Since it seems to be not difficult to measure the camera positions with an error of less than 1 cm, for the setup, the error resulting from this will not be critical. If the Z-coordinate is not available for image size compensations, as in the case of the one-camera-system, an alternate method for calibration has to be applied. Because of its simplicity, the same method was also used for the 2-camera version. The procedure applied will be shown in the following:

The simple principle is to introduce a known geometry, e.g., the distance between shoulder and hip, for calibration into the system. In this way, lens and distance parameters are not required; a scale factor is determined by comparison of the actual value and the camera data. This scale factor is recalculated for each frame, where the camera data is averaged over a suitable window to reduce quantization noise and then compared with the calibration input data. This process is repeated for all the data points within the frame. The next time sample (frame) is then taken and the above process repeated. This, again, is repeated until all frames are compensated. Since the data is compared with a known value and accordingly adjusted, the source of the error of the data is irrelevant, which means that perspective compensation is also possible in the same way.

The disadvantage of this method is that error is introduced, if the calibration segment on the body is not perpendicular to the optical axis. Nevertheless, these errors can be expected to be small (less than 4%) for angular deviations not exceeding e.g. 15°, which would be expected for the shoulder-hip segment during normal walking.

The advantage of this calibration method is certainly evident:

- Any camera distance can be selected without recalibration (important for a non-fixed setup).
- Lens distortion is automatically compensated.

If large angular movements are observed, the camera parameters can be calculated from the calibration input and coordinates calculated by the method of section 6.3.5. A practical measurement was done on a walking subject, where the shoulder-hip distance was used as calibration distance. The walk covered the whole X-range, and the ankle-knee distance was entered, this being selected because the fastest movements occur for this segment. Then, the error obtained was calculated. The results showed an error of less than 3 cm for the distance ankle-knee during a walk covering approximately 80% of the field. This is within the expectations predicted by the theoretical values.

This error is unacceptable for trajectory data which shows that, for a sensor of this given resolution, a field, where 3 or more footsteps are possible, is too large and has to be reduced to obtain better results. Implementing large sensors, which were not available at the beginning of construction of the system, would be highly desirable.

6.4. Displays for clinical use.

6.4.1. Drivers for the hardware.

Initially, there was only a storage oscilloscope available together with the PDP 11/10 computing facility. The D/A-converters within the LPS-module permit computer-controlled analog outputs suitable for deflecting an oscilloscope. An assembly-subroutine, (listing Appendix B) callable by FORTRAN, was written to plot one or more data points on the oscilloscope screen in a repetitive or storage mode. The data is passed from the FORTRAN main program to the subroutine fast enough to permit a flicker-free display in repetitive mode. In the nonrepetitive mode, data is displayed in storage-mode of the oscilloscope, and the computer is released to perform other functions. The subsequently acquired graphics-terminal (TEKTRONIX 4006) plots data or alphanumerics on a large screen (17 x 24 cm). This serially interfaced device requires ASCII-code for the addressing of the X- and Y-directions. A driver was written (listing Appendix B, program B4) to accept the data in the same format as for the oscilloscope. The data is scaled first to match the display-format of the device, and then converted into ASCII-code.

These display-devices were used to display the acquired and processed data from the camera-system.

6.4.2. Trajectory-displays.

The trajectories are generated by fitting the subject with internally illuminated table-tennis balls on the anatomical landmarks (usually joints). Fig. 6.5. shows such a marked subject, where the optical traces obtained in a walk can be seen in Fig. 6.6. The camera data is generated by the threshold detection of the lightsources alone, as described in Chapter 5. Unwanted ambient light and reflections in the room are eliminated by filtering the visible part of the light spectrum. An infrared filter (Kodak Wratten No. 89B) was selected to match the spectral response characteristic of the device (see Fig. 6.7.).

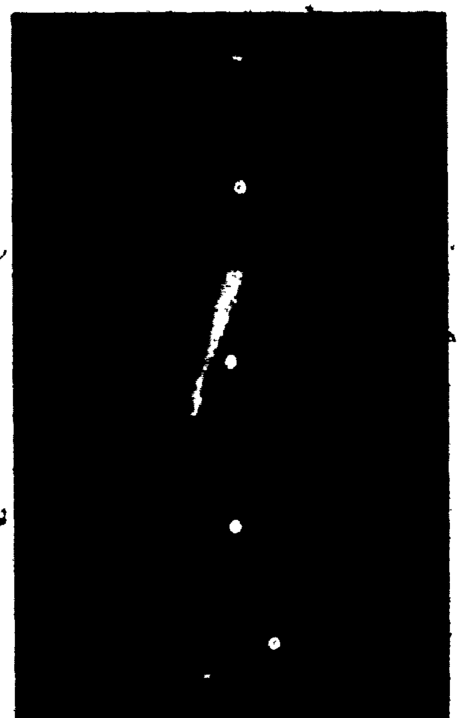
Therefore, the room lighting-conditions (fluorescent light) do not affect the cameras, the room can be kept at normal illumination, which is of importance for clinical studies.

Fig. 6.8. is a typical example of the raw data obtained from one camera in the sagittal plane, Fig. 6.9. shows the same data after elimination of the quantization-noise by the filtering method described in section 6.3.2. The original concept devised by Marey (1894) on an abstract form of limb representation ("stick-diagram"), can be easily obtained by interconnecting the data points within one frame.

The resulting stick-figure (Fig. 6.10.) is very illustrative, especially when observed while being generated on the display-screen, since an almost real-time playback of the walking can be reproduced.

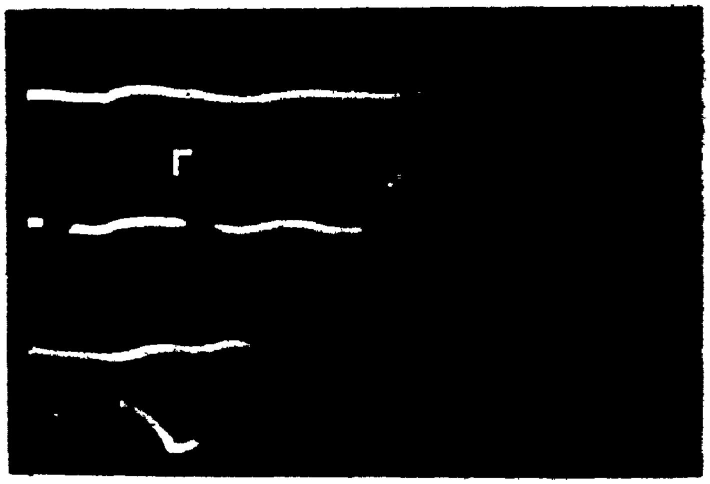
Displays from camera #2, which is aimed in the walking direction, are somewhat less illustrative. An example of the pattern obtained is shown in Fig. 6.11., where the actual size of the image reduces, as the subject walks away from the camera. The marked joints in this example were: the 2 shoulders and hips, knee and ankle on the right side only. No segments were connected in this figure. Therefore, camera #2 "sees"

(a)

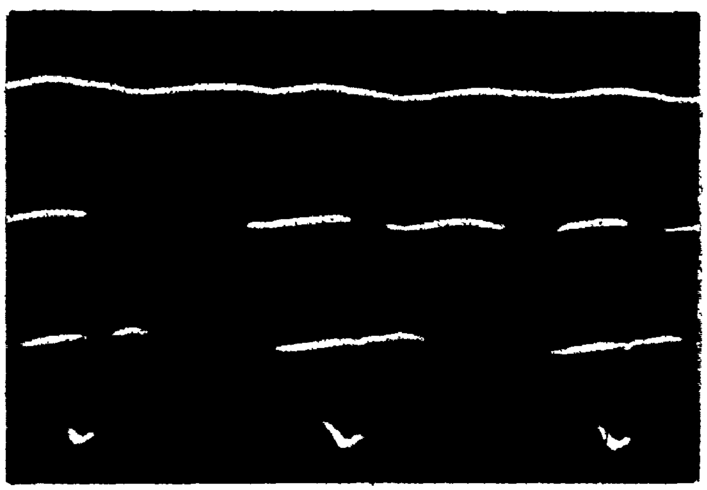


(b)

Fig. 6.5. Subject marked with illuminated table tennis balls on shoulder, hip, knee and ankle.
(a) - frontal view
(b) - side view



(a)



(b)

Fig. 6.6. Optical traces obtained from a marked walking subject.
(a) - with the subject illuminated at several time intervals
(b) - traces only

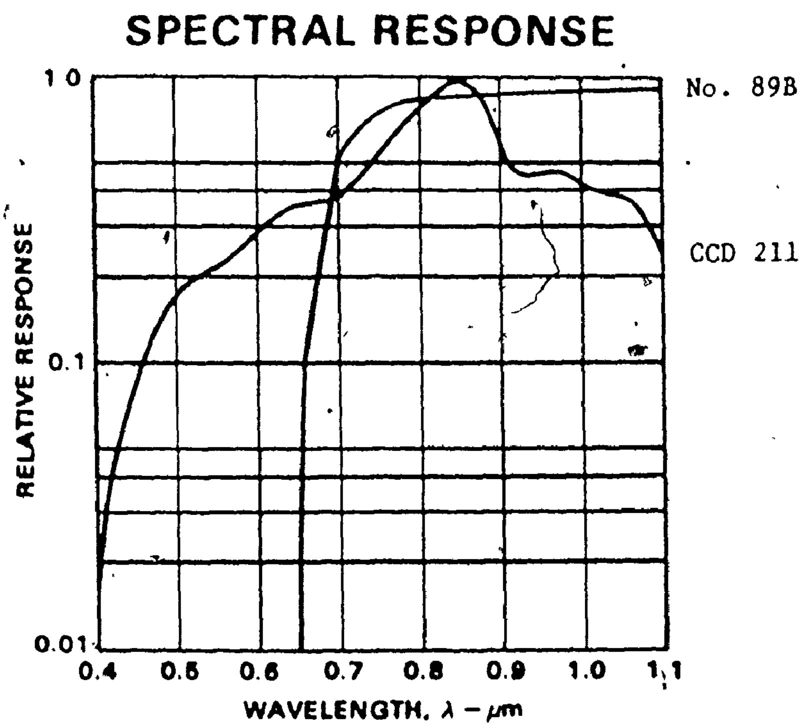


Fig. 6.7. Relative spectral response of the CCD 211 area image-sensor and Kodak Wratten filter No. 89B.

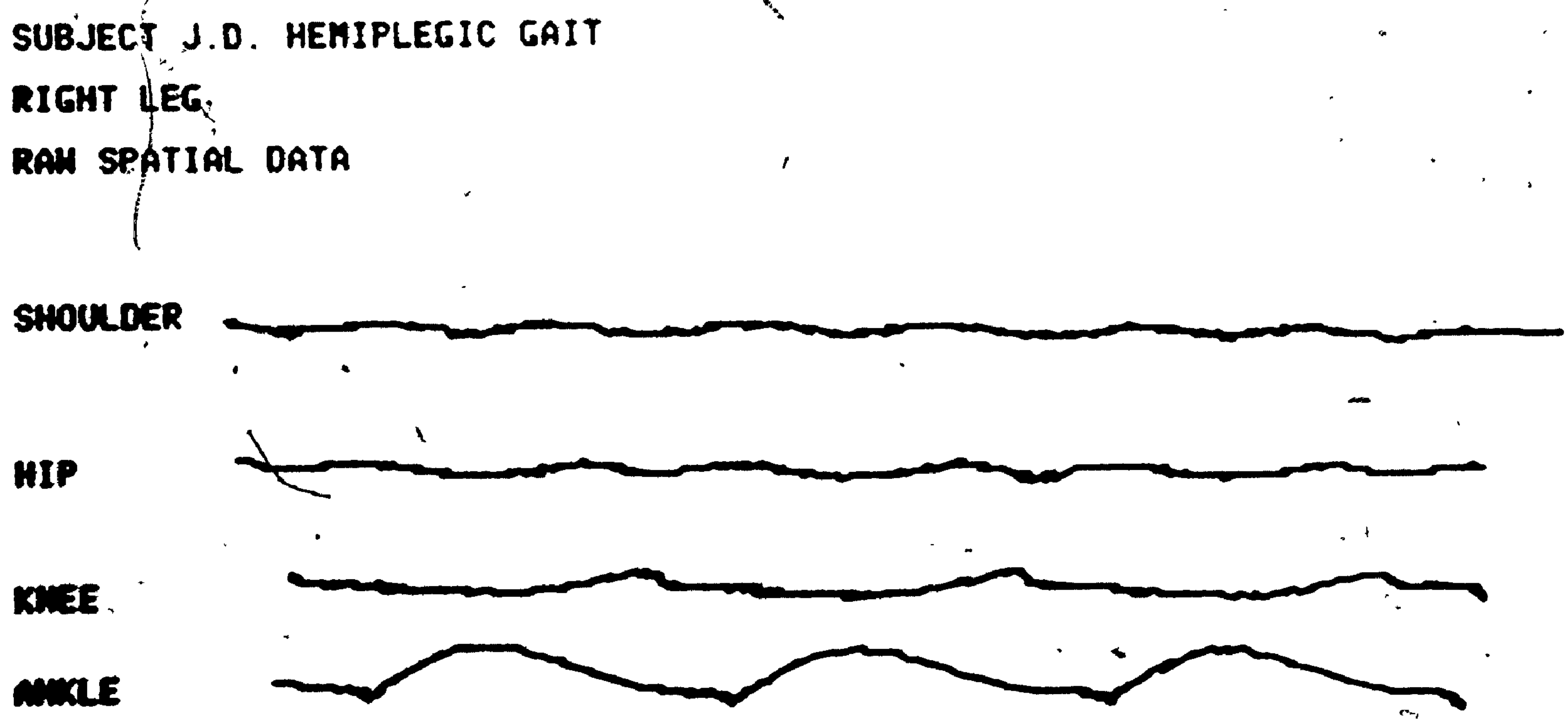


Fig. 6.8. Raw spatial trajectory data from one CCD-camera in the sagittal plane.

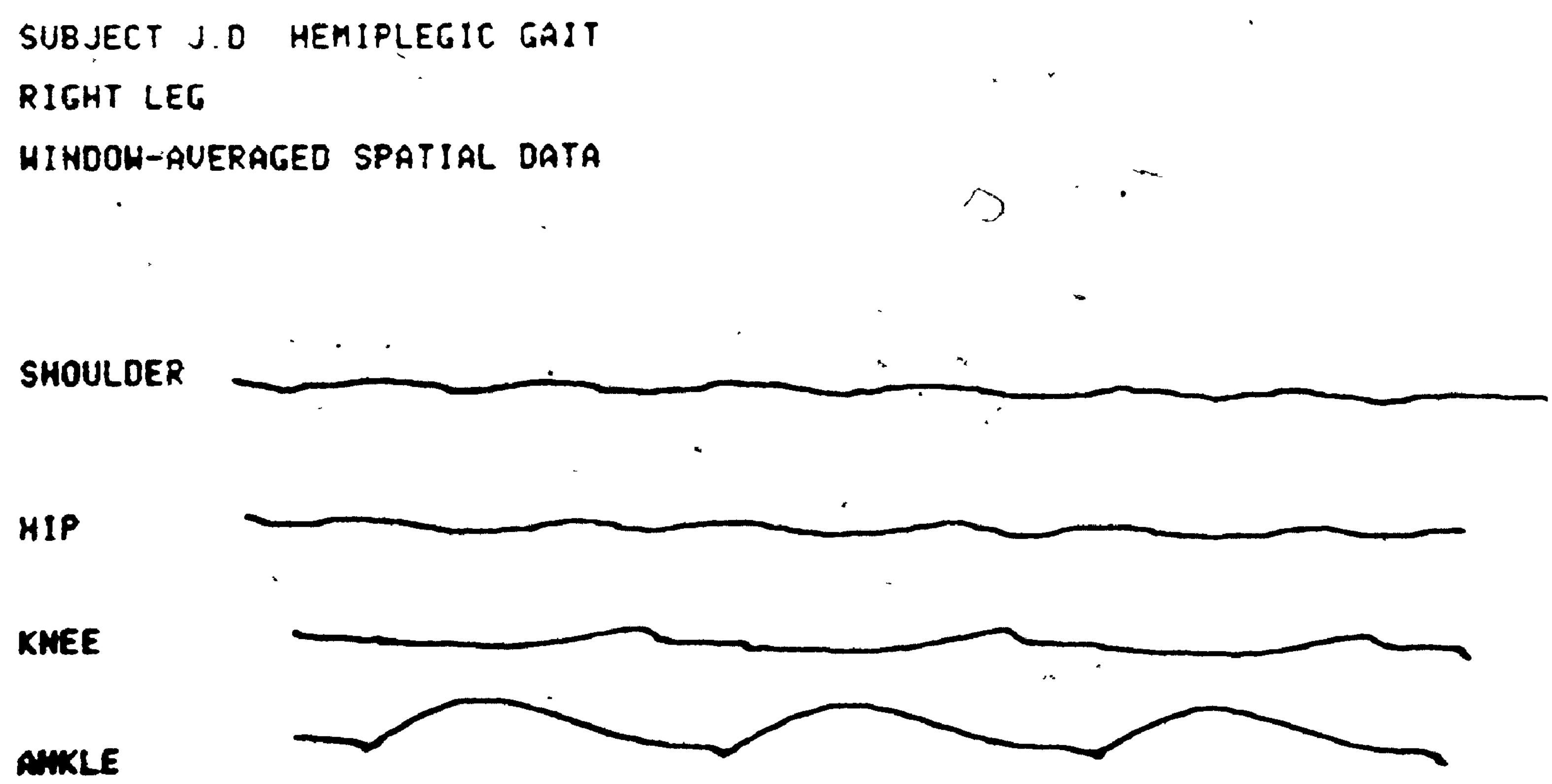


Fig. 6.9. Window-averaged spatial trajectory data from one CCD-camera in the sagittal plane.

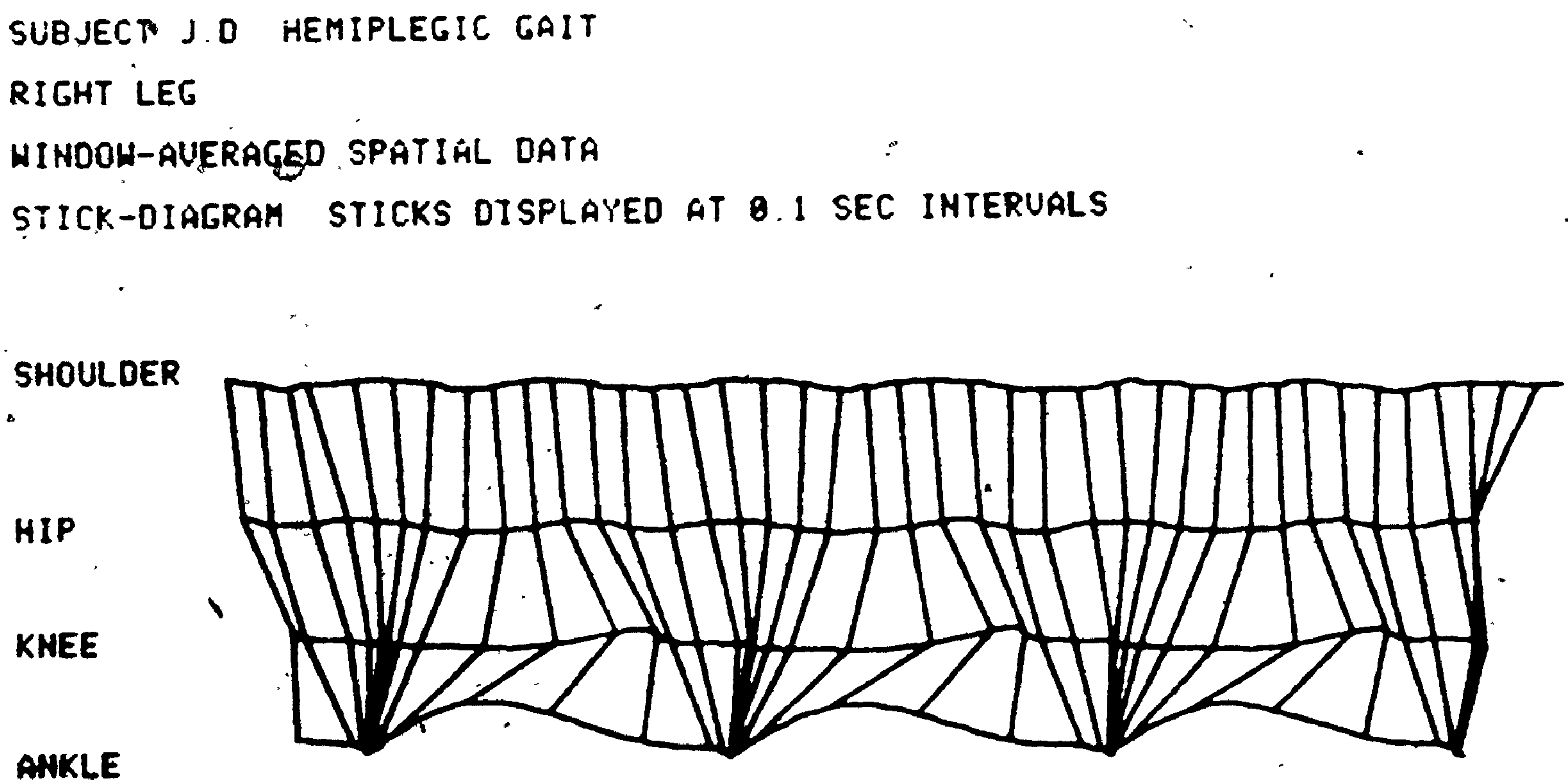


Fig. 6.10. Computer drawn "stick-figure" to represent limb segments.

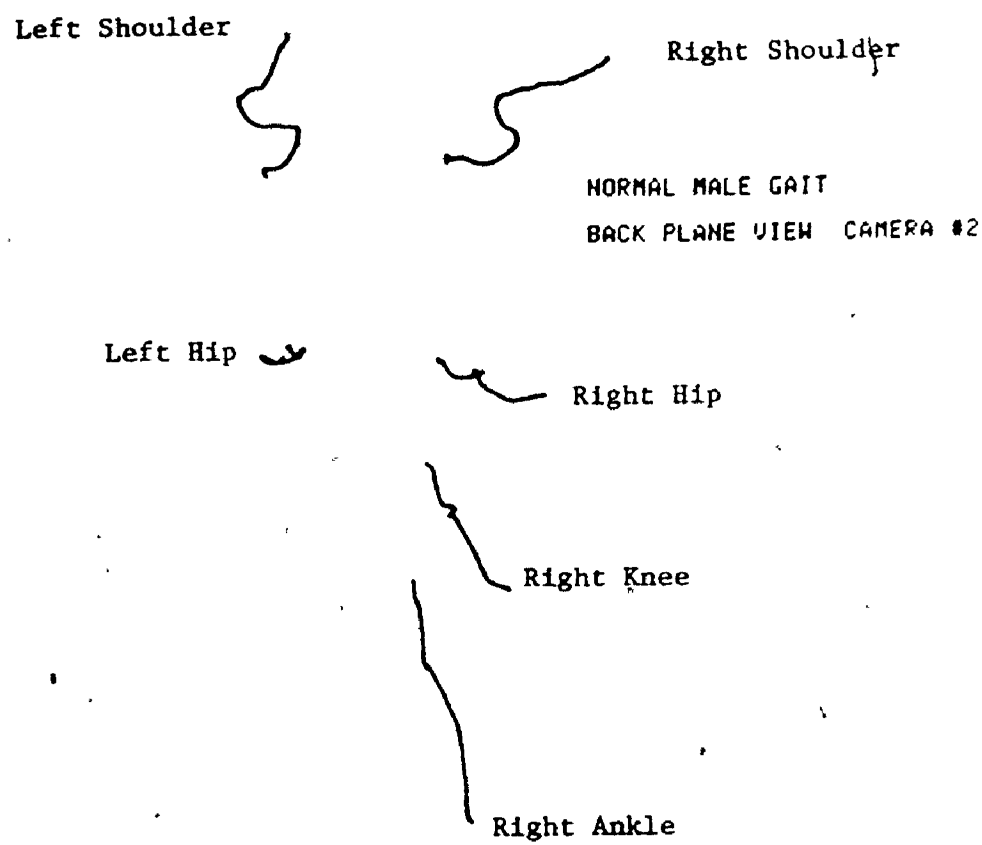


Fig. 6.11. Spatial data display as obtained from camera #2, no compensation. (Labels for each trajectory are inserted at their commencement, e.g., "Right Ankle" marks the start of the trajectory for the right ankle).

6 points, where camera #1 only looks at the 4 points, which are identical to those in Fig. 6.8.

An approach to a more illustrative display is given in Figs. 6.12. and 6.13. Fig. 6.12. displays only the hip and shoulder points, with the two hip-shoulder segments and the shoulder-shoulder segment connected. In order to prevent the segments from lying on top of each other, a fixed shift in X-direction from frame to frame is artificially introduced. As an alternative, Fig. 6.13. represents a dotted line for the segment not visible from camera #1. In both cases, knee and ankle are omitted.

If the reduction in image size is compensated, as described in section 6.3.6. (perspective compensation), the display in Fig. 6.14. results (the dotted line example is preferred here).

An approximation of a top view (X-Z-plane) can be obtained by using the X-coordinates derived from camera #1. An example is given in Fig. 6.15. Horizontal shoulder movements (perpendicular to the walking direction) can be seen, but it is not possible to detect shoulder rotations, because the X-coordinate is the same for both shoulder points as detected by camera #1.

6.4.3. Angular displays.

The original concept of Grieve (1968), of displaying hip-angle vs. knee-angle in an angle-angle diagram, has shown its effectiveness in the assessment of locomotor function as shown by Milner et al (1973), where extensive studies on normals and patients were done. Data capture

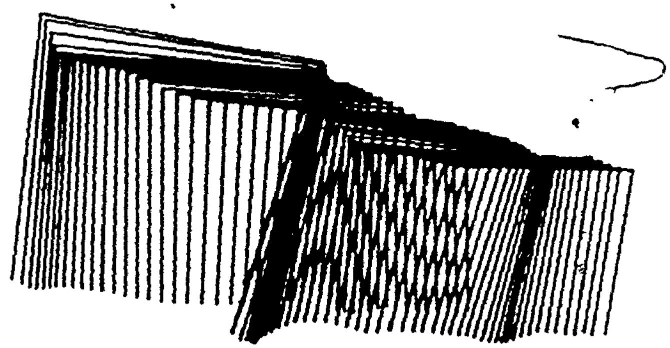


Fig. 6.12. Hip and shoulder display, no compensation. (The X-shift between the segments is artificial, the timing is selected similar to the "stick-figure" Fig. 6.10.).

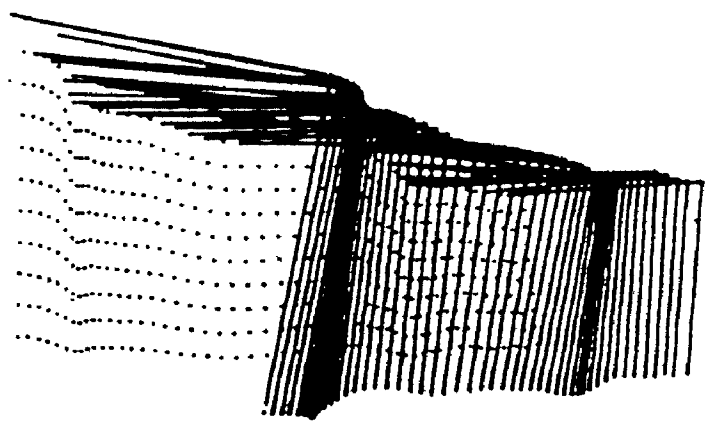


Fig. 6.13. Hip and shoulder display, no compensation, segment not seen by camera #1 dotted.

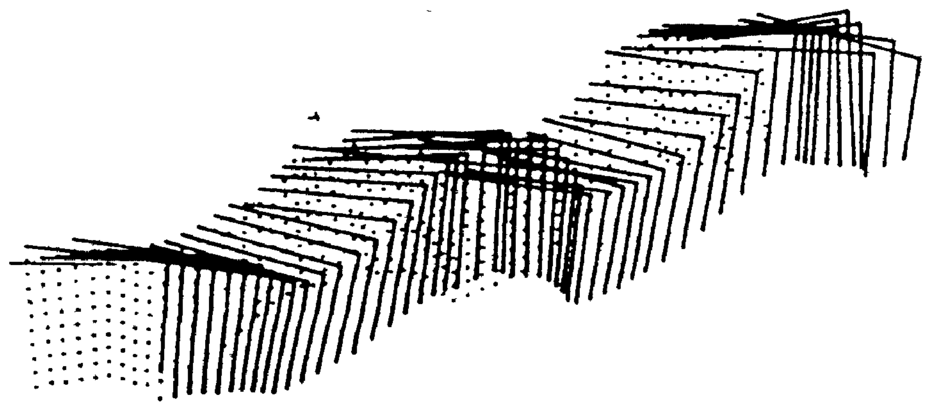


Fig. 6.14. Display of the hip and shoulder segments after compensation for image size reduction (perspective compensation), female walk with artificial limp to accentuate shoulder movements.

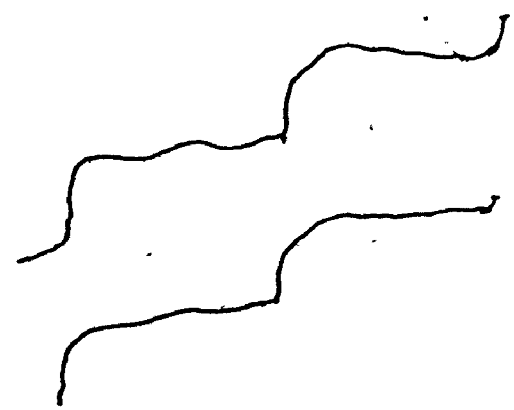


Fig. 6.15. Display of the shoulder point trajectories in an approximation of a top view (X-Z-plane), X-coordinate identical for both shoulders.

was done with stroboscopic flash photography The flash-rate is approximately one order of magnitude lower than the sampling-rate of the CCD-system.

By calculating the angles from the obtained trajectory data in the sagittal plane, the same angle-angle diagrams as in Milner et al's work (1973) can be obtained. An example of such a pattern is shown in Fig. 6.16. Approximately 3 full footsteps were captured (see also trajectories Fig. 6.10), yielding 3 angular loops. The repetitiveness of the gait can be seen from the relative deviations of the individual loops from each other.

Since one might be interested in the individual footsteps, separation can be done on a heel-minimum-criteria, which will occur approximately when the heel touches the ground (heel-strike).

By applying this method, the gait from Figs 6.10. and 6.16. can be separated into the individual footsteps. The first two steps are shown in Figs. 6.17., 6.18. For additional information, the "stick-diagram" of this particular footstep is included in the display, where a visual comparison of the angles can be done. This is helpful in cases where the loops do not "close", meaning that the body-configuration is not identical at the beginning and the end of the particular footstep, (e.g. Fig. 6.19.).

The mathematical process in obtaining the angular information is similar to a differentiation where the undesired enhancing of the noise component in the signal becomes apparent. Therefore, filtering of the signal with the method described in section 6.3.2. was required, and satisfactory results could then be obtained.

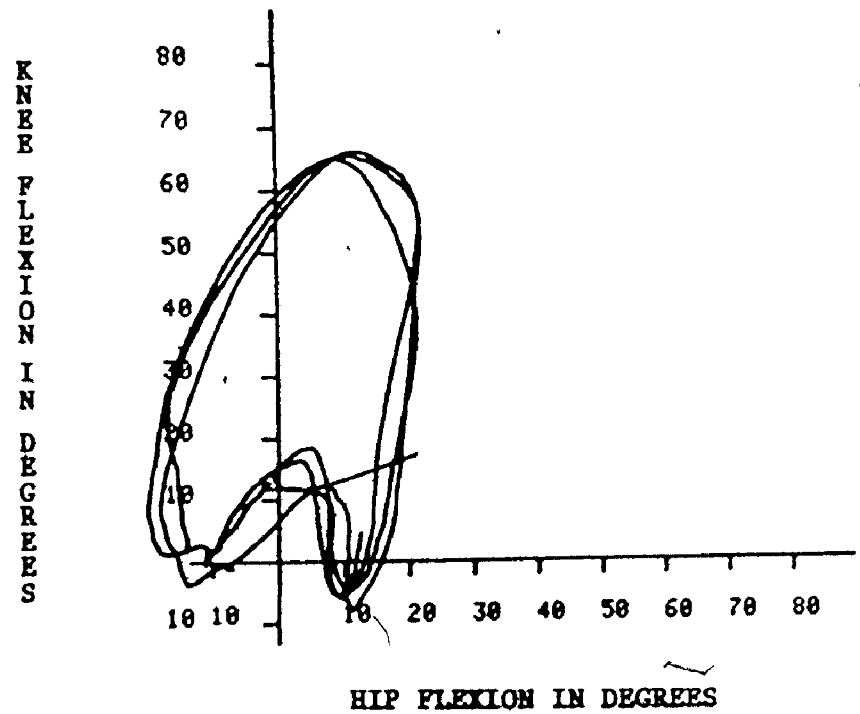


Fig. 6.16. Angular display of hip-angle vs. knee-angle of a walk covering approx. 3 footsteps.

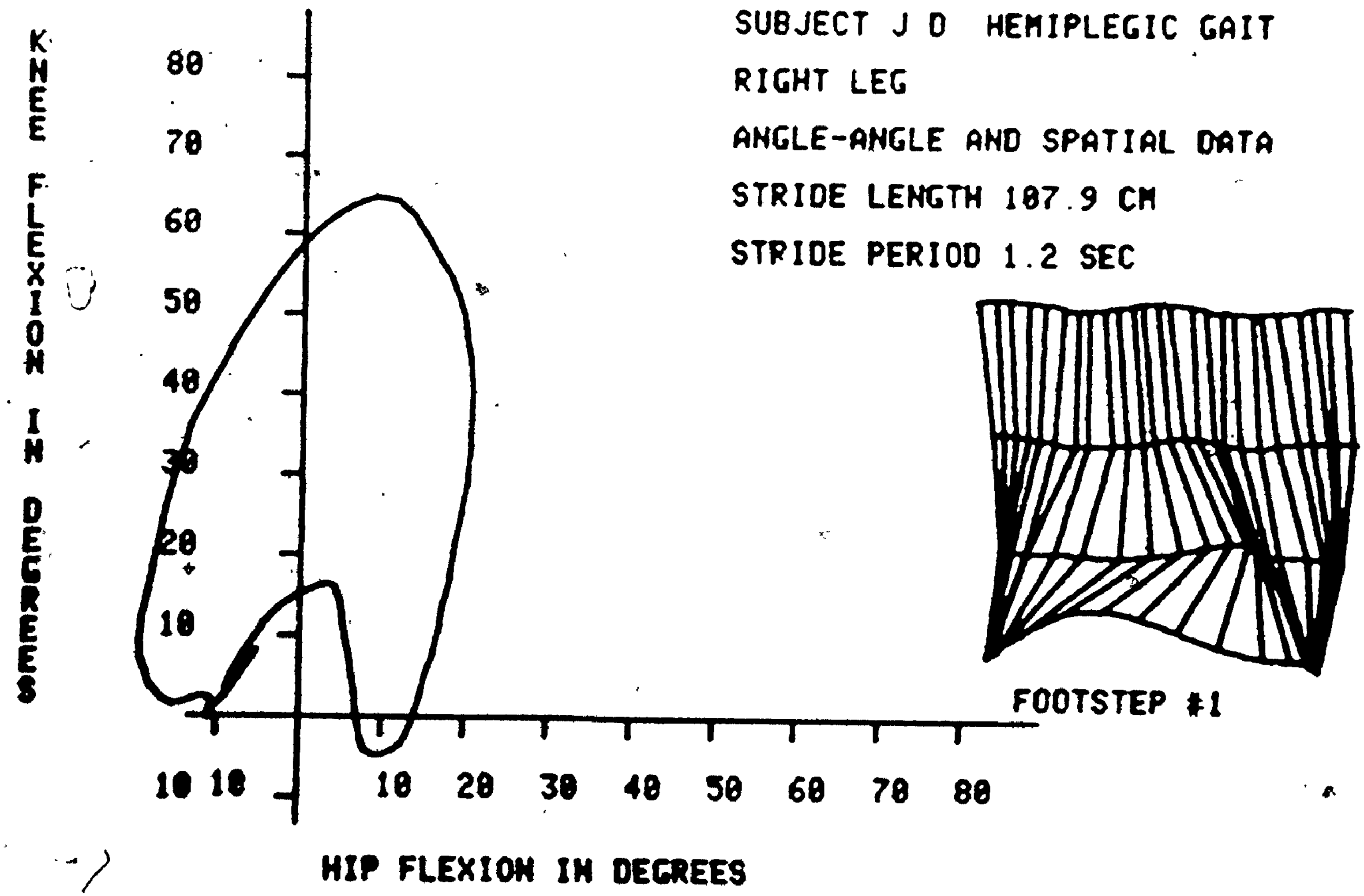


Fig. 6.17. Angle-angle and spatial data of a selected footstep.

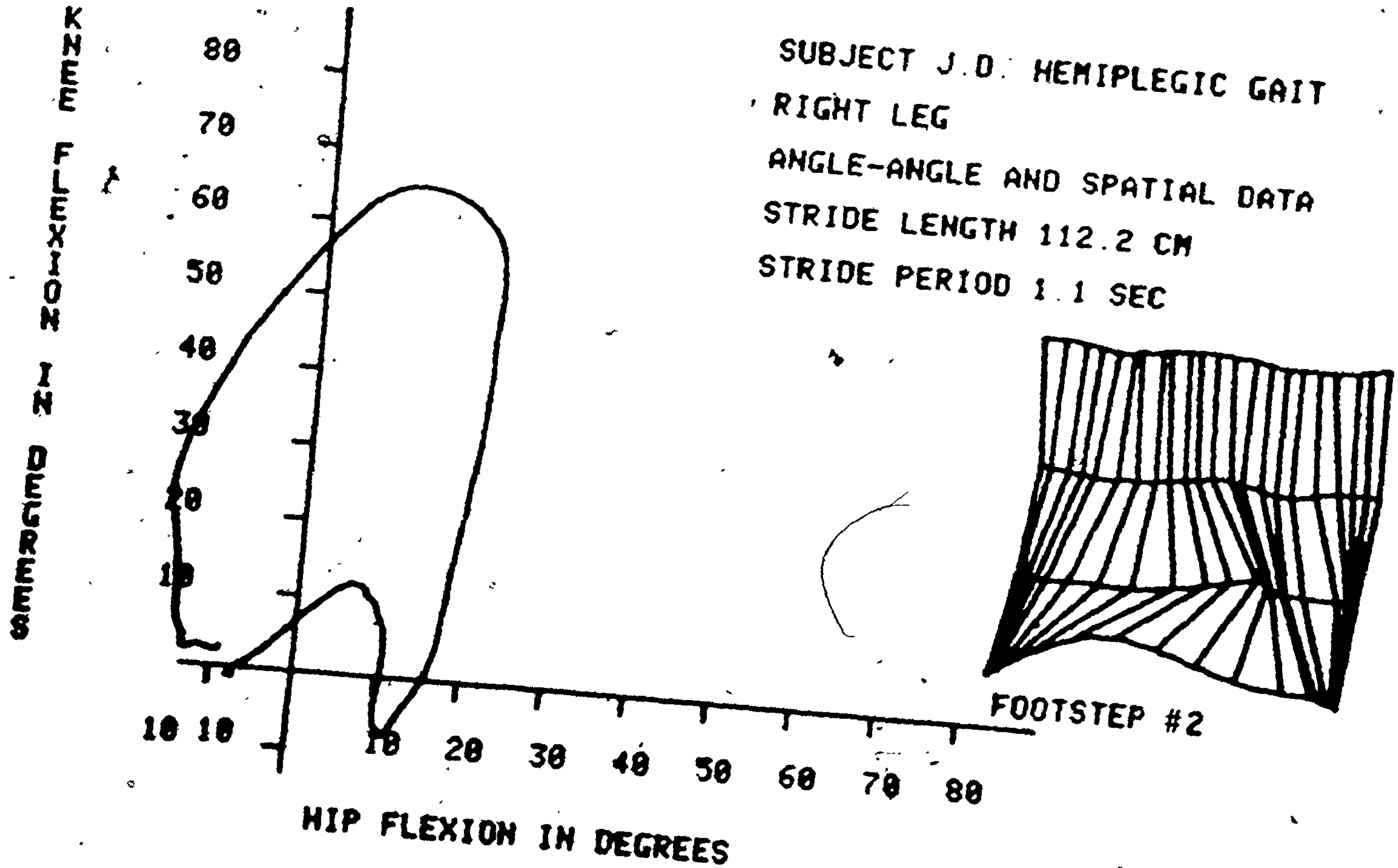


Fig. 6.18. Angle-angle and spatial data of a selected footstep.

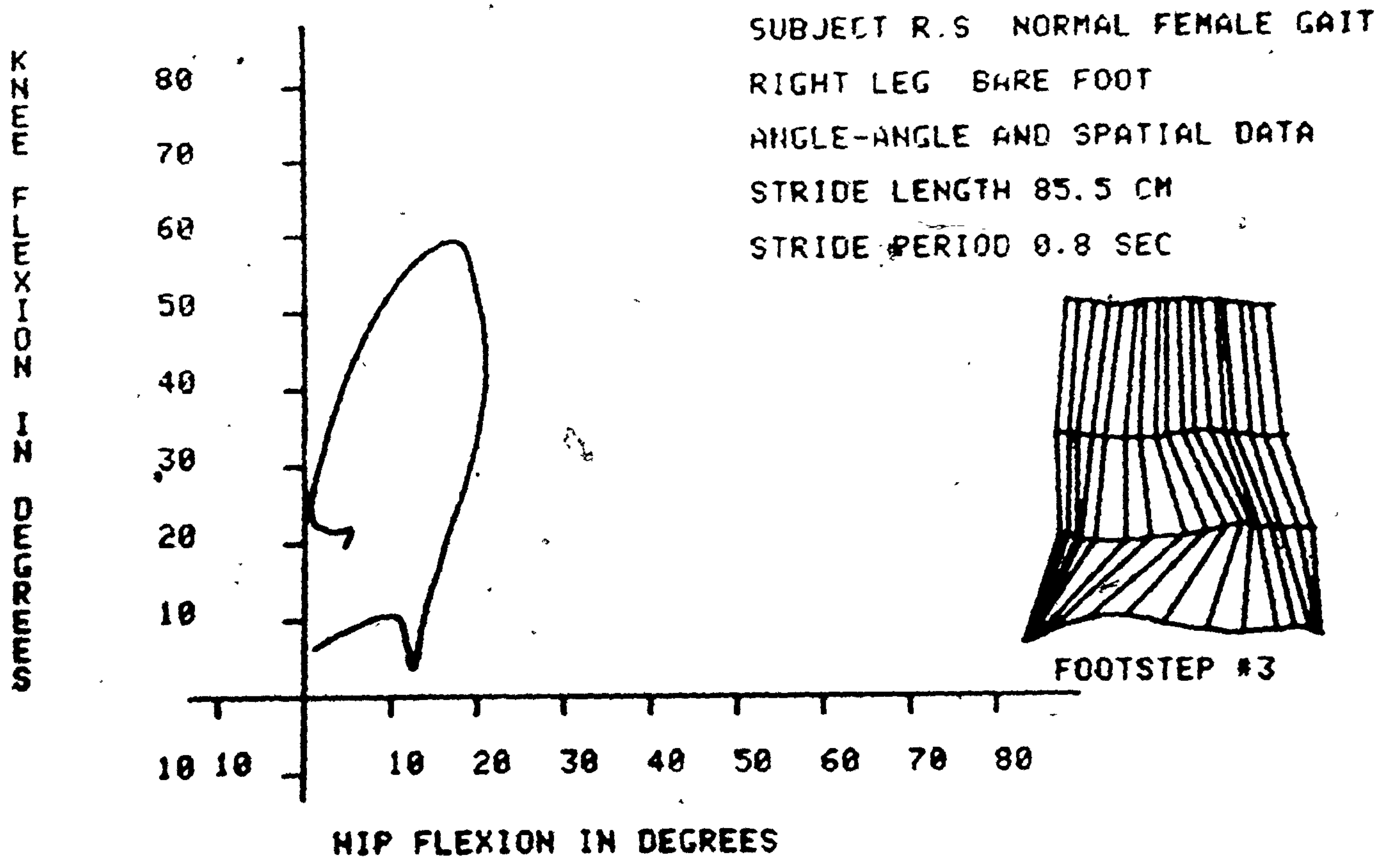


Fig. 6.19. Angle-angle and spatial data of a selected footstep.

Nevertheless, for operations like the angle computation and possibly other similar calculations, it would be desirable to have a higher resolution system available. This, because in the process for computing the angles, the difference between two coordinates is taken, which results in a reduction of significant figures in the result, which means, that the error or the noise of these results gets enhanced.

However, on the other hand, it is apparent from this, that the angle-angle display is a sensitive process for an effective display of locomotor performance and disorders where the reduction of redundant data is a very helpful method for clinical applications.

In conclusion, it could be shown that with CCD-image sensors, an effective optical sensing instrument can be built, which is extremely easy to link with a computer. At the beginning of, and well into this study, sensors with the desired resolution were not available. Nevertheless, it was possible to prove the idea of interfacing CCDs with a computer, where the results of this prototype system with the limited resolution sensors (CCD 211) are of very acceptable quality.

CHAPTER 7

CONCLUSIONS

CHAPTER 7

7.1. Summary of contributions of this work.

From the introductory Chapters 1 and 2 of this work, it can be seen that great importance is allied with the study, measurement and recording of the kinesiological aspects of human locomotion, especially in the clinical and rehabilitation field.

The clinical needs, which stimulated the development of the system designed, include: the design and evaluation of prosthetic and orthotic devices; follow-up of the dynamic performance of patients undergoing therapeutic or surgical treatment, such as major joint replacements; biofeedback relating to human movements and facilitated by on-line displays; general use in studying human movements.

Important factors for such a system should take cognisance of the following:

- The patient or the subject should be influenced as little as possible by the instrumentation set-up.
- For comprehensive data collection, several body points have to be recorded simultaneously.
- Spatial information is required in three dimensions.
- Visual real-time (or virtually so) displays of body movements should be produced.
- Data storage and processing with inexpensive mini- or micro-computers should be possible.

This thesis deals with a solution which addresses itself to the aspects outlined above.

The work constitutes a significant advance in, and realization of, a 3-dimensional optoelectronic camera system, embodying recently available charge-coupled devices of the area-image-sensor variety. Fig. 7.1. shows the 2 camera modules, interface and control, and the cable drive board. The cameras are interfaced to a minicomputer, and appropriate software (programmes) have been developed to permit relevant processing and achieve pertinent displays of the kinesiological data acquired. A major concern was to generate results which are of substantial use to clinicians. The "clinical digestibility" feature has been incorporated wherever possible.

Although the needs for the clinical environment predominated during the design and development of the system, a general optical computerized tracking instrument has emerged where key factors, such as the real-time computer application, the simplicity in using, and the fast turnaround time in processing and displaying the results, enable the usage of the system in almost any environment, where the optical tracking of objects or points is of concern, and where the frequency-range of the movements stays within the frequency limitations of the system (presently 50 Hz).

Although the practical design ended with a 2-camera system, allowing 3D-recording, it is possible for virtually any number of cameras to be incorporated, and interconnected with the same computer. This would enable, together with appropriate processing, such as, e.g.,

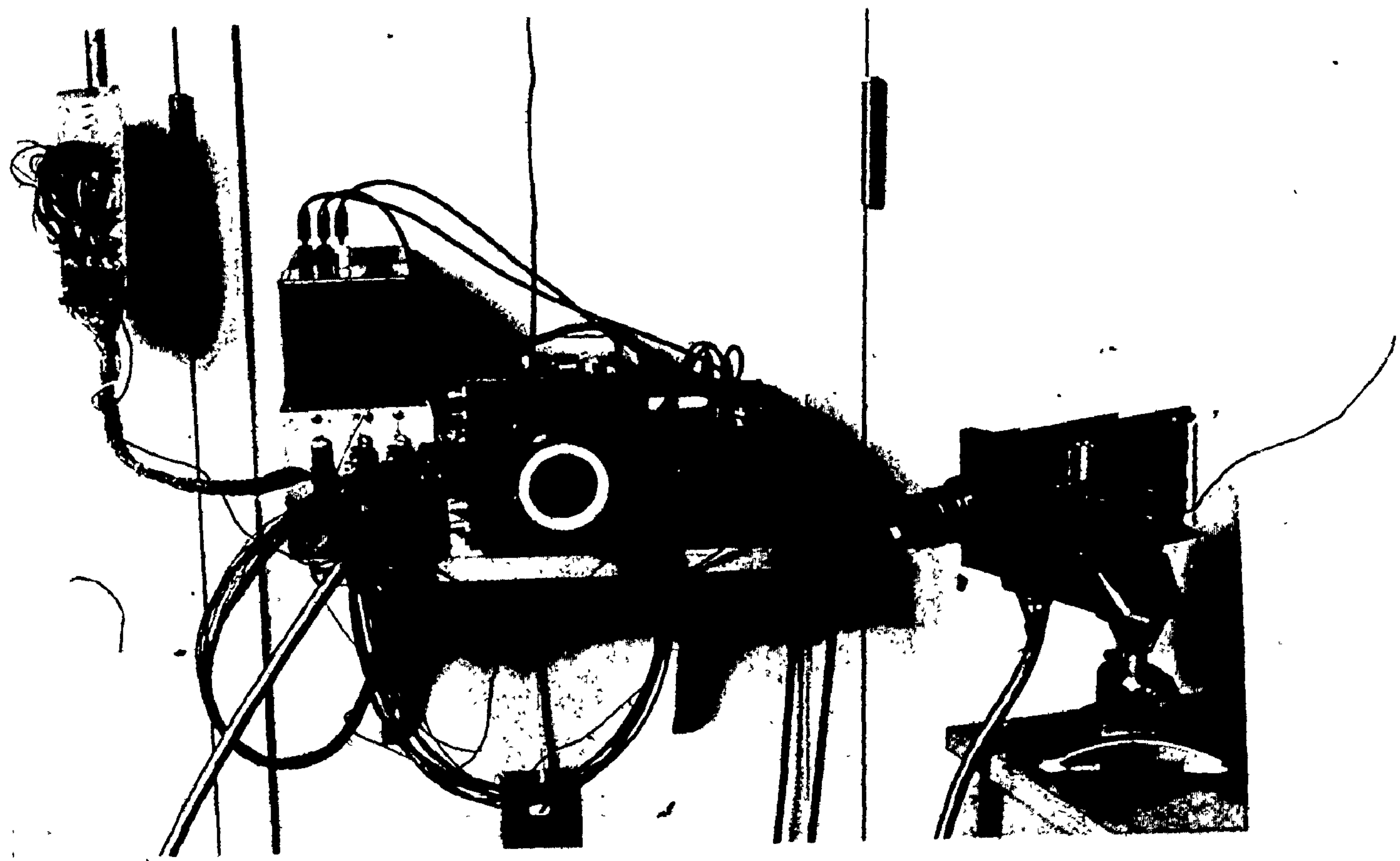


Fig. 7.1. The 2 CCD-cameras with control module and cable drive.

pattern recognition, a very general application of the system, where surveillance or monitoring of any kind of process is just one of many possible examples.

For the particular clinical application, it is believed that the specifications alluded to above have been met and pertinent analysis procedures for the clinical gait data are incorporated.

The thesis embraces detailed information to enable developmental work on further prototype camera systems to be undertaken. In its present form, the system appears to meet the essential needs and future refinements, such as implementing larger sensors and expanding the software routines to produce a wider variety of analysis display possibilities are indicated.

7.2. Future directions.

Although this work has been taken to the stage of being a viable clinical research tool, sensors of the desired quality and resolution could not be incorporated because of their nonavailablility. Presently, sensors and even complete CCD cameras with approximately 500 x 500 elements are available which would improve the resolution over the existing system by a factor of more than 2 in both X- and Y-directions. The commercially available RCA CCD-camera, which meets the above-mentioned resolution, has been examined with regard to other quality aspects, such as blemishes, and was found to be a definite improvement over the FAIRCHILD CCD 211 sensor.

Nevertheless, it has been possible to develop the present system in such a way that acquired data are useful for a number of current clinical applications. The experience and results obtained during design, construction and application of the present system can now fruitfully be implemented in a version where larger sensors, or, possibly, complete CCD-cameras could be implemented.

Since gait data acquisition can now be performed in a time-frame hitherto impossible, a broad range of motion studies involving normals and pathological conditions can lead to processing techniques and statistical analyses with a view to eliminating redundant data and creating readily diagnosable results easily interpretable by clinicians.

APPENDIX A

CIRCUIT DIAGRAMS FOR THE CCD 211 DUAL-CAMERA COMPUTER INTERFACE SYSTEM

General

All logic is standard TTL, unless specified. All resistors are 1/4 W, unless specified. Power supplies for the logic and standard operational amplifiers are not shown; the voltages are +5V and ±15V.

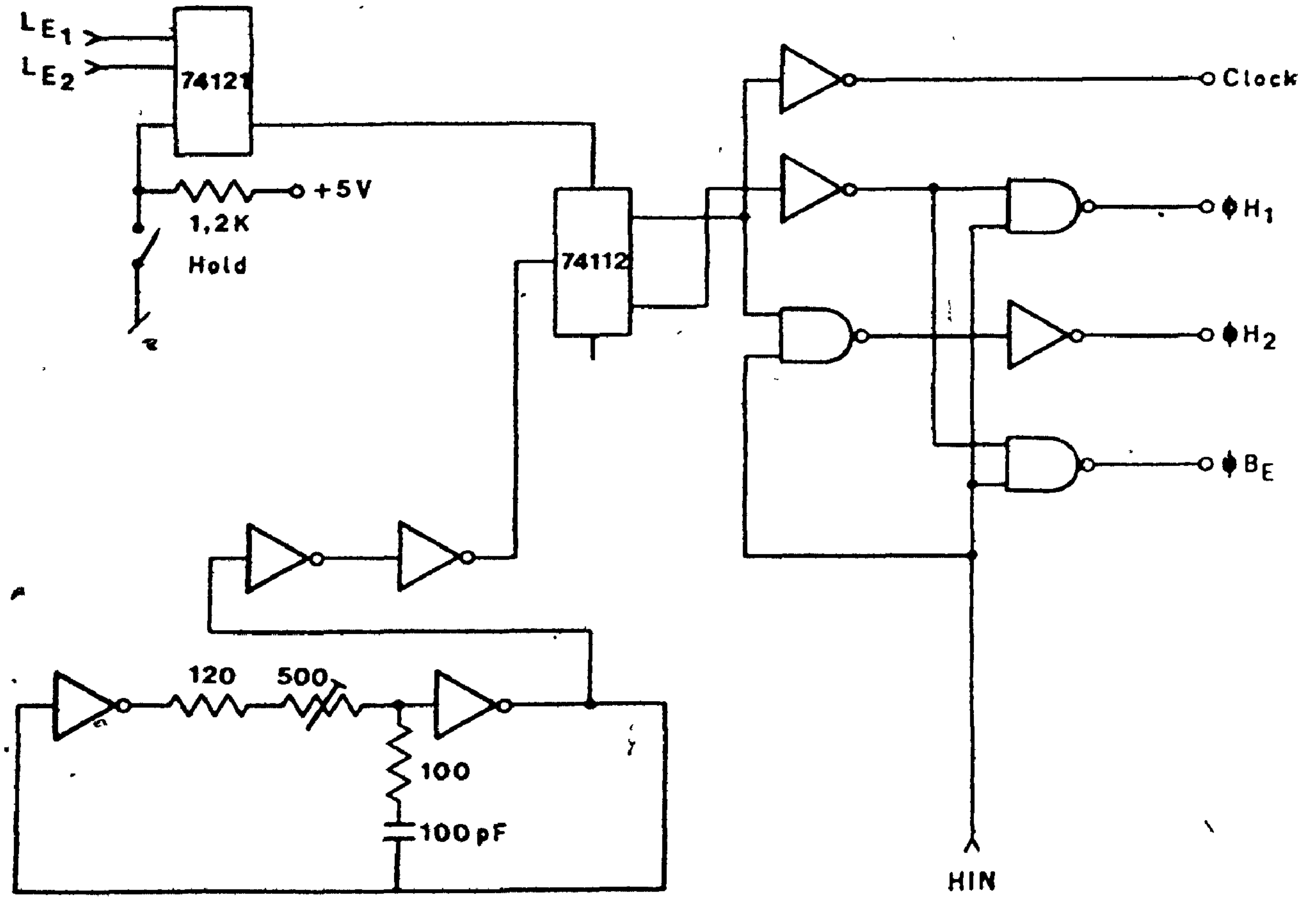


Fig. A1 Master and horizontal clock generation.
(all gates are Schottky-TTL)

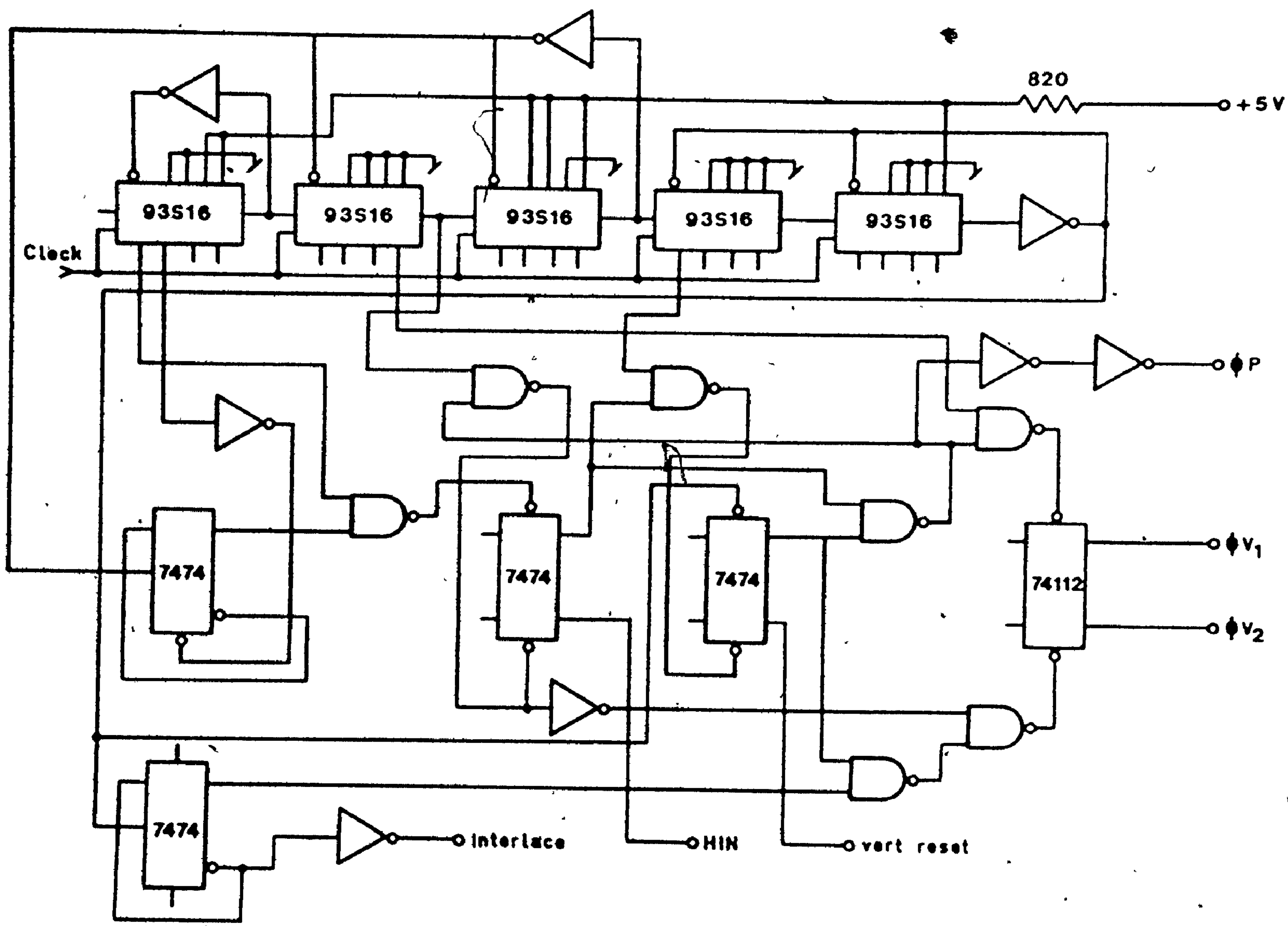


Fig. A2 Drive logic for the CCD 211

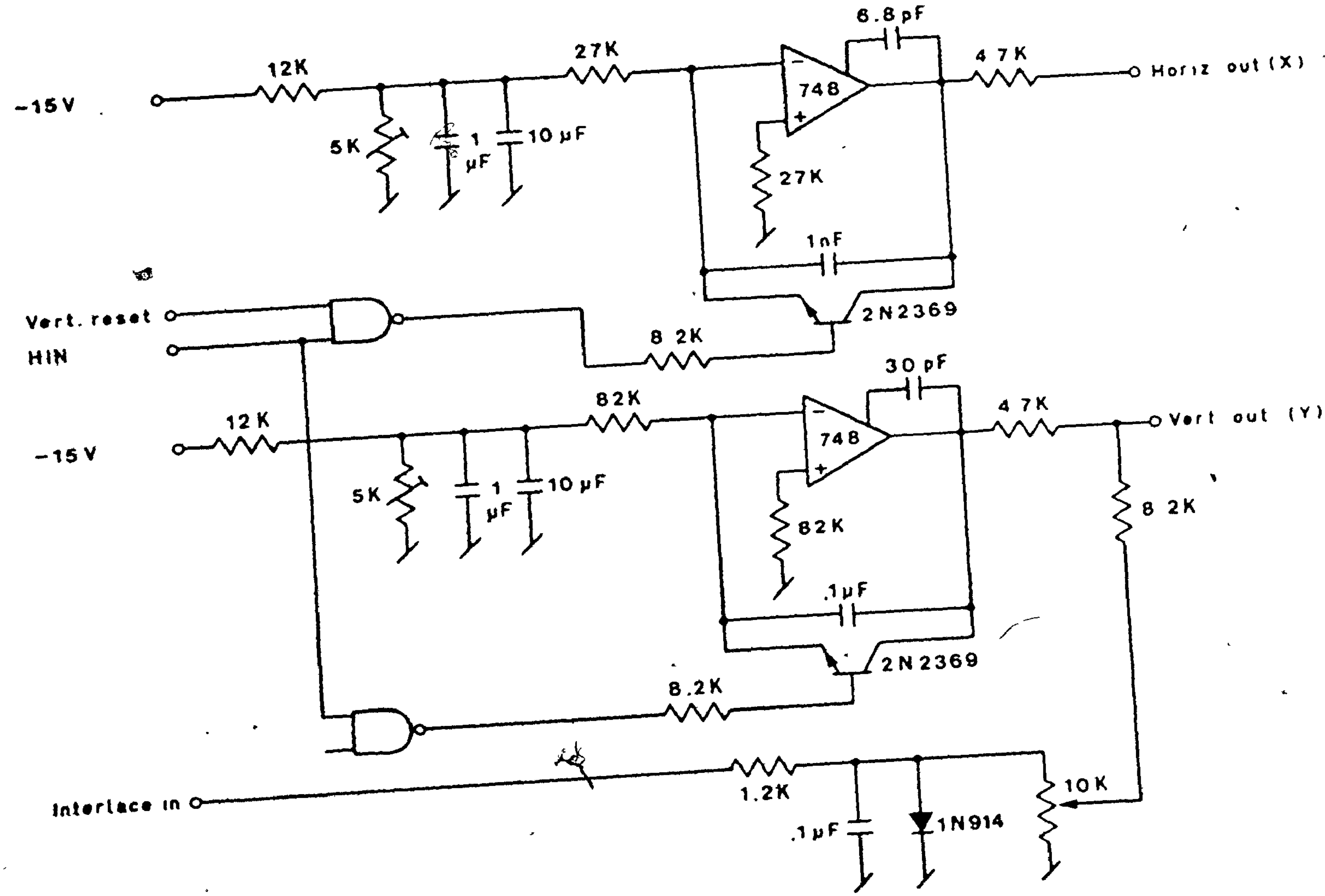


Fig. A3 Oscilloscope deflection for the CCD 211 video-display.

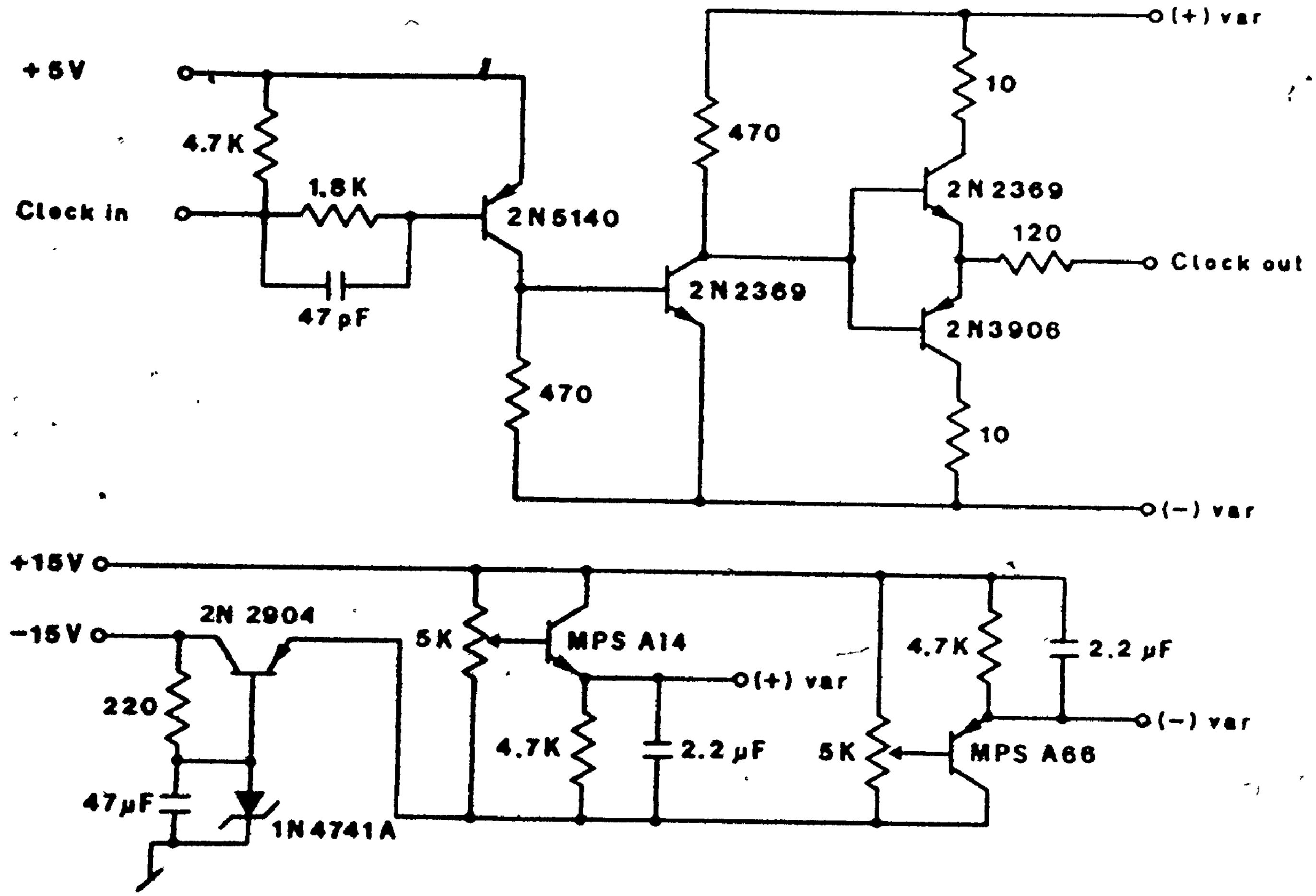


Fig. A4 Clock-driver circuit for the CCD 211 clock inputs and high and low level regulator. Shown for one signal.

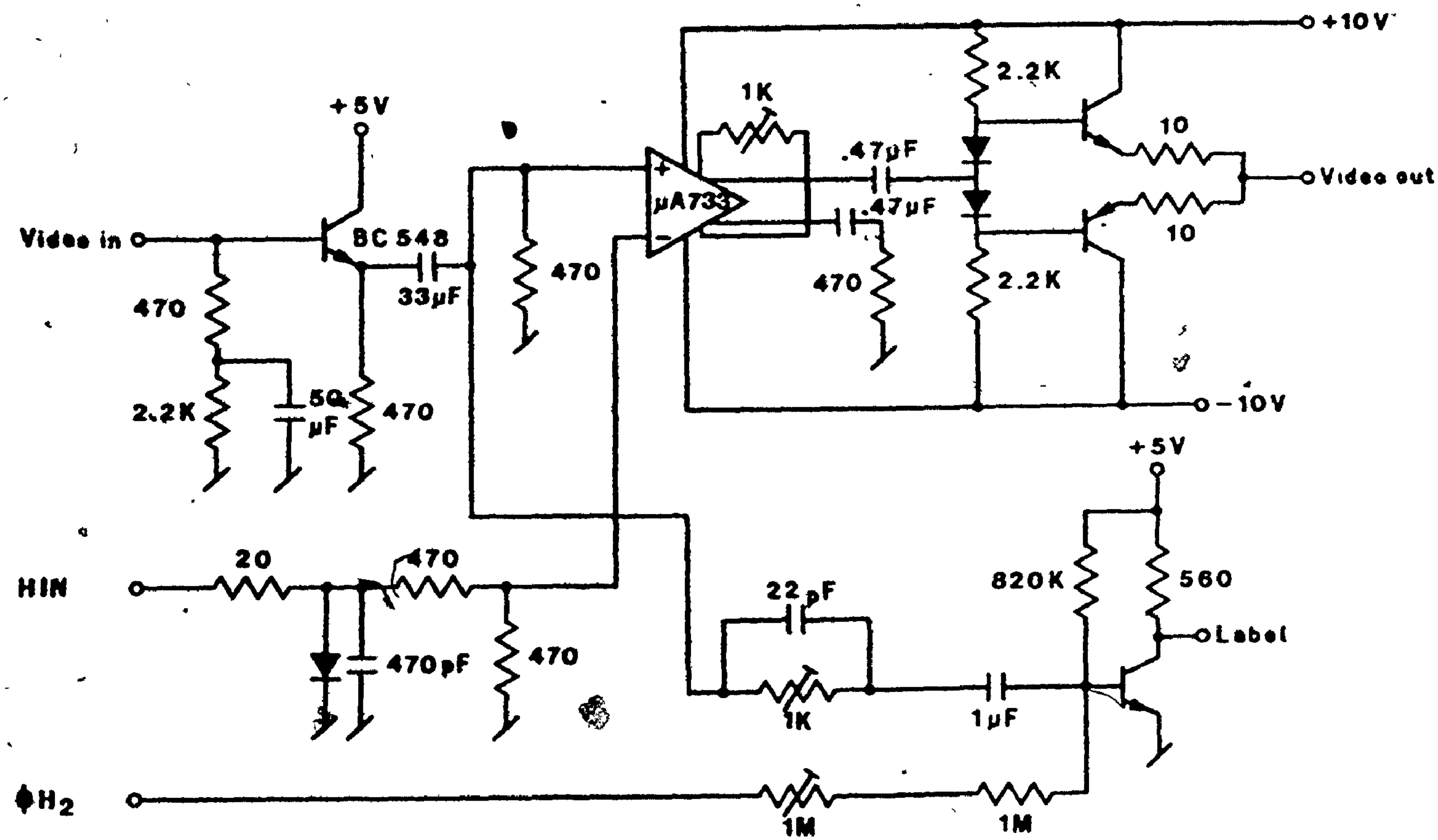


Fig. A5 Video- and label-amplifier

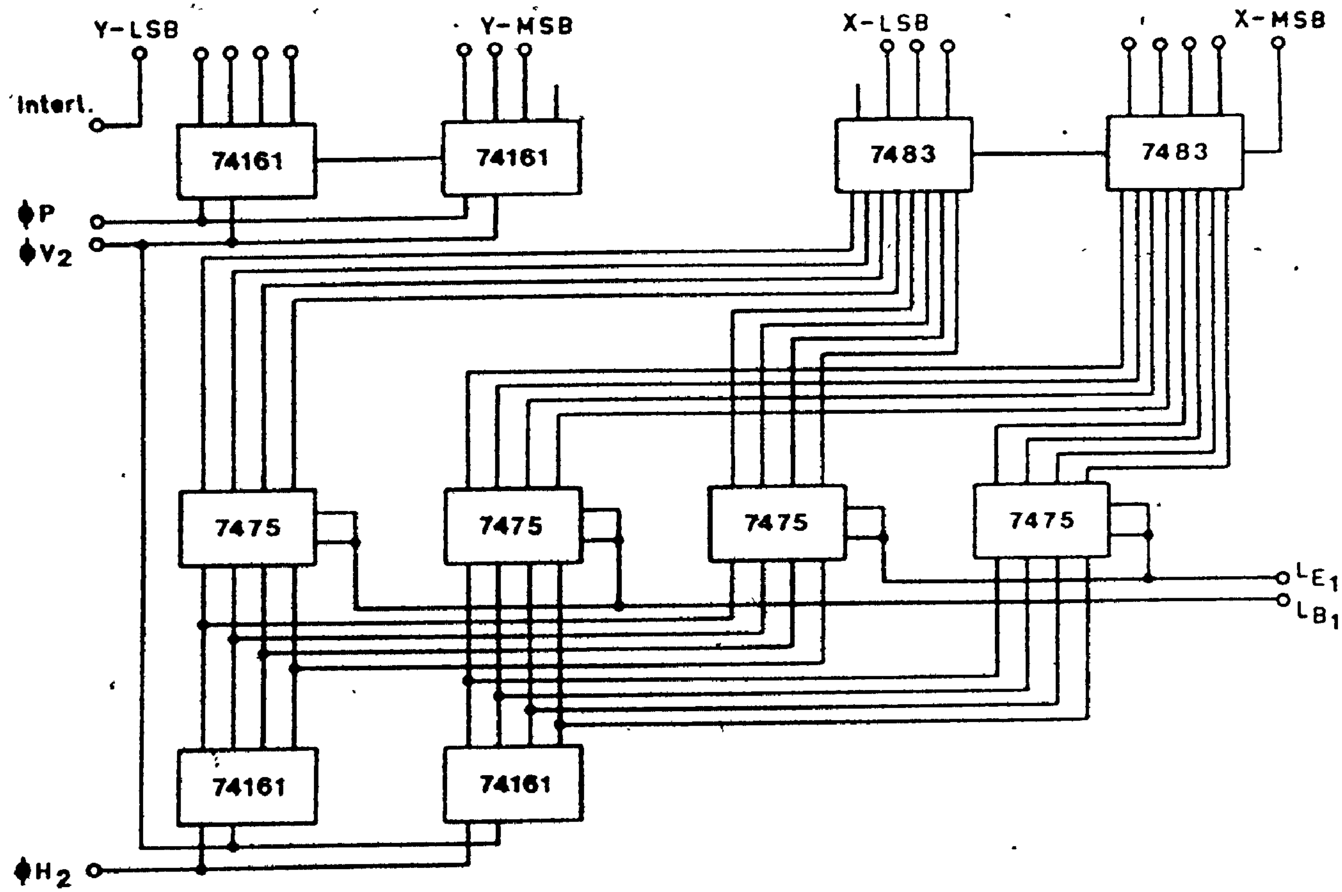


Fig. A6 Coordinate discriminator camera #1.

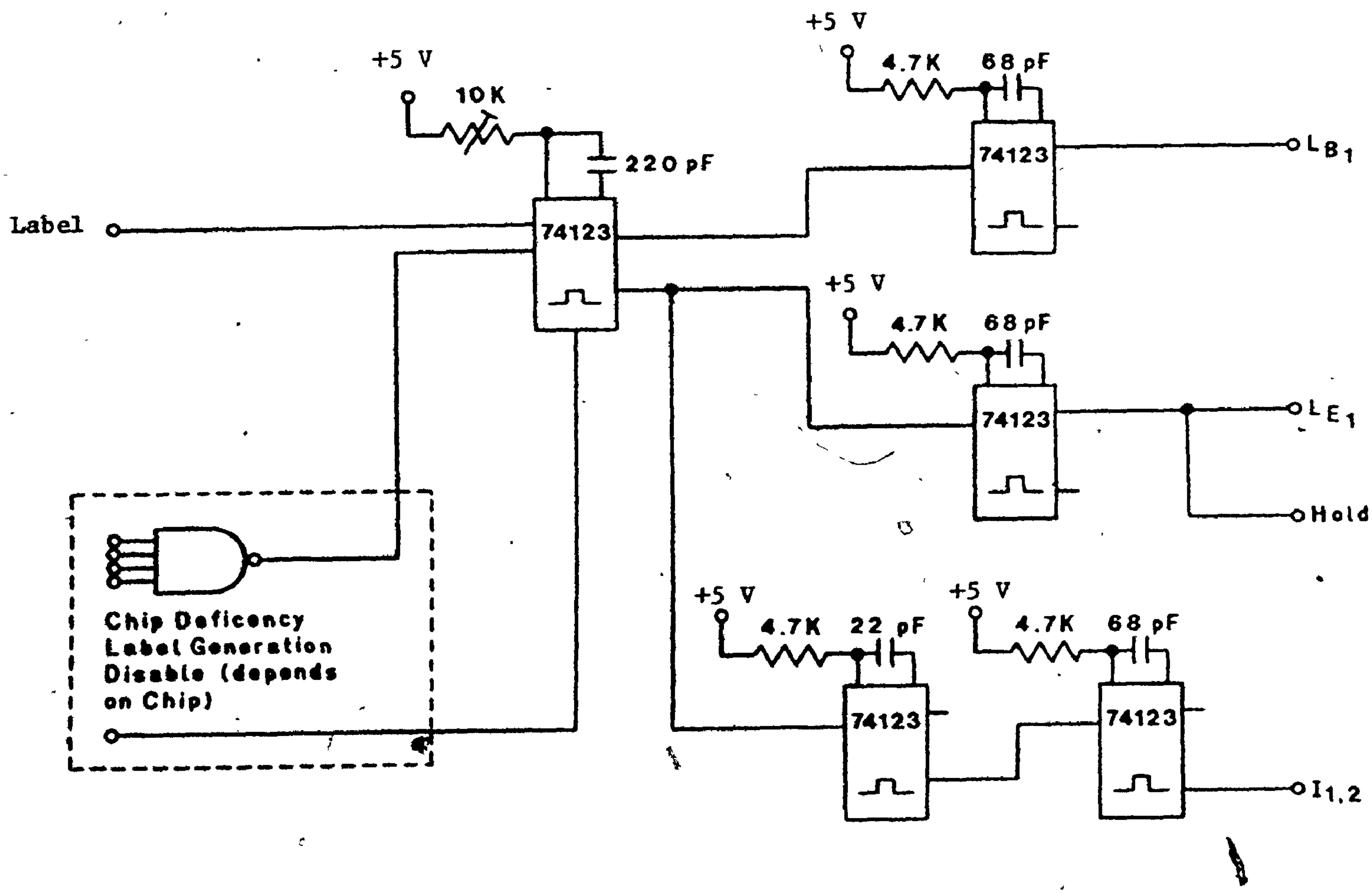


Fig. A7 Label timing and interupt generation.

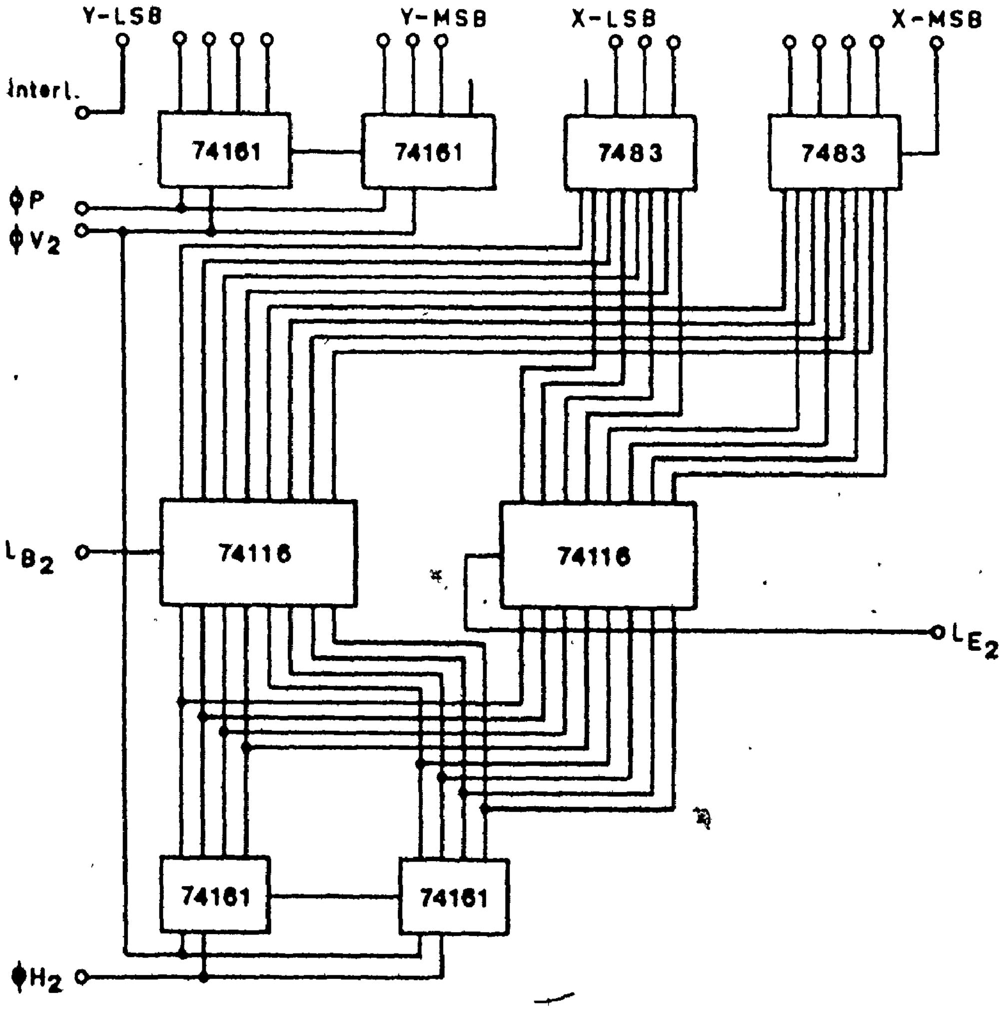


Fig. A8 Coordinate discriminator camera #2.

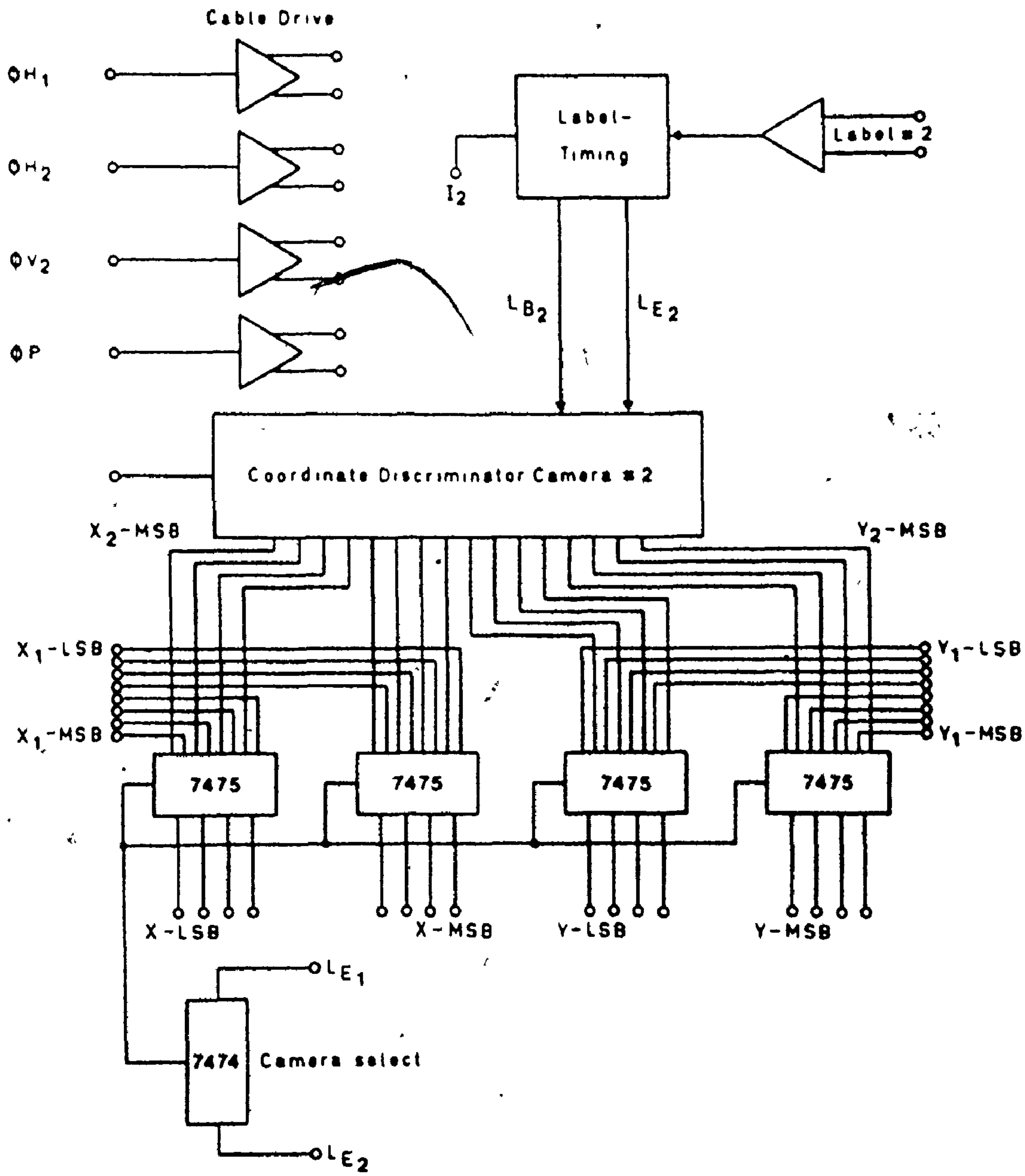


Fig. A9 Control module for the 2 CCD-sensor-systems.

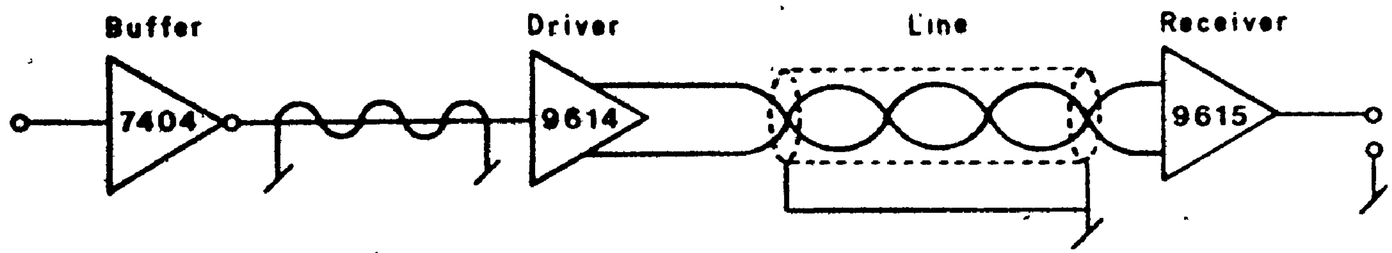


Fig. A10 High speed differential cable drive and receive circuit, employing twisted pair individually shielded cable (Belden #8774). Circuit shown for one signal only.

APPENDIX B

PROGRAM LISTINGS

General

All programs were written under the RT11 single job monitor version V02B-05 with a PDP 11/05 CPU and the LPS interface system.

Appendix B contains some of the programs and subroutines required to operate the CCD-camera system. The source-files and the current file names are given.

Summary

Program	Source file	Function
B1	DID211.MAC	On-line display for one CCD-camera
B2	DID2C.MAC	On-line display for two cameras
B3	DISV.MAC	Display-driver for 2-dimensional display on an oscilloscope
B4	PLOTEK.MAC	Display-driver for the TEKTRONIX 4006-1 graphics terminal
B5	DIGIN1.MAC	Digital-input driver for one camera
B6	DIGIN2.MAC	Digital-input driver for two cameras
B7	FRAME.MAC	Frame boundary detector subroutine for the CCD-data
B8	SEPAR.FOR	Separation subroutine for the identification of several labels within the CCD-input data

```
;                  ******************************
;                  ON-LINE DISPLAY FOR CCD-CAMERA
;                  ******************************
        .MCALL  .REGDEF
        .REGDEF

START:  CLR @#177546
        MOV #INT,310
        MOV #300,312
        MOV #DISBUF,R5
        MOV PNTCNT,R0
        MOV #16.,R2
        MOV #100,LPSCSR
INP:    WAIT
        BR INP
        BR INP
INT:    MOV LPSINP,DAT
        CLR M0
        MOVB DAT,M0
        MOV R2,MUL
        MOV M0,DAX
        CLR M0
        MOVB DAT+1,M0
        MOV R2,MUL
        MOV M0,DAY
        INC DACSR
        MOV #100,LPSCSR
        RTI
DAT:    0
        .END START
*
```

Program B1 DID211.MAC

```
;******************************
;ON-LINE DISPLAY FOR 2 CAMERAS
;******************************

;AUTHOR : W.BRUEGGER
;BIOMED.ENG.DEPT
;MC MASTER UNIV. HAMILTON

        .MCALL .REGDEF
        .REGDEF

START:  CLR @#177546
        MOV #11,DACSR      ;INT ON Y
        MOV #INT,310
        MOV #300,312
        MOV #INT2,314
        MOV #240,316
        MOV #16.,R2
        MOV #LPSCSR,R1
        MOV #LPSINF,R0
        MOV #DAX,R3
        MOV #DAY,R4
        MOV #40100,R5
        MOV R5,@R1         ;INT EN CAM 1+2
INP:    WAIT
        BR INP
        BR INP
INT:    MOV @R0,DAT
        CLR MQ
        MOVB DAT,MQ
        MOV R2,MUL
        MOV MQ,@R3
        CLR MQ
        MOVB DAT+1,MQ
        MOV R2,MUL
        MOV MQ,@R4
        MOV R5,@R1
        RTI

INT2:   MOV @R0,DAT2
        CLR MQ
        MOVB DAT2+1,MQ
        MOV R2,MUL
        MOV MQ,@R3
        CLR MQ
        MOVB DAT2,MQ
        MOV R2,MUL
        MOV MQ,@R4
        RTI

DAT2:   0
DAT:    0
        .END START
```

Program B2 DID2C.MAC

```
;                   ******************
;                   *DISPLAY OF ARRAY*
;                   ******************


;FORTRAN : CALL DISV(XADDR,YADDR,NR.OF PTS,SIZE,ERASE(=0))

;AUTHOR:            W.BRUEGGER
;                   MC MASTER UNIV. HAMILTON,ONT


        .GLOBL DISV
        .TITLE DISV

                .MCALL .REGDEF
        .REGDEF

DISV:   TST (R5)+
        MOV (R5)+,DBX
        MOV (R5)+,DBY
        MOV @(R5)+,PNTCNT
        MOV @(R5)+,SIZE
        MOV @(R5)+,R1     ;ERASE?
        BEQ NOER
        MOV SIZE,R2
DIS:    MOV #10000,DACSR            ;ERASE
        CLR DELAY
        INC DELAY
        BVC .-4
        INC DELAY
        BVC .-4
NOER:   MOV SIZE,R2
        MOV PNTCNT,R0

        MOV DBX,R3
        MOV DBY,R1

DIS1:   MOV (R3)+,MQ
        MOV R2,MUL
        MOV MQ,DAX
        MOV (R1)+,MQ
        MOV R2,MUL
        MOV MQ,DAY
        INC DACSR
        TSTB DACSR
        BGE .-4
        DEC R0
```

Program B3 DISV.MAC

```
        BGT DIS1
        RTS PC
DBX:    0
DBY:    0
SIZE:   1
DELAY:  0
FNTCNT: 0
.END
*
```

Program B3 DISVC.MAC (cont.)

```
;DISPLAY FOR TEKTRONIX 4006-1 GRAPH.TERMINAL
;FROM FORTRAN: CALL PLOTEK(XADDR,YADDR,NO.OF PTS,ISIZE,,NEWVEC,
;                   IPPLT(=1),ERASE(=1))

;AUTHOR:            W.BRUEGGER
;                   BIOMEDICAL ENGINEERING
;                   MCMASTER UNIV. HAMILTON



        .GLOBL PLOTEK
        .MCALL .REGDEF
        .MCALL ..V2..
        .REGDEF
        ..V2..

PLOTEK: TST (R5)+
        MOV (R5)+,DBX
        MOV (R5)+,DBY
        MOV @(R5)+,PNTCNT
        MOV @(R5)+,SIZE
        MOV @(R5)+,ALPHA
        MOV @(R5)+,PPLOT
        TST @(R5)+          ;ERASE?
        BEQ PLOT

ERASE:  MOV #27.,R5         ;ERASE
        JSR PC,SEND         ;-----
        MOV #12.,R5         ;-----
        JSR PC,SEND         ;SCREEN
        CLR DELAY
        INC DELAY
        BVC .-4

PLOT:   TST ALPHA
        BEQ PL1
        MOV #29.,R5
        JSR PC,SEND         ;GRAPH MODE
PL1:    MOV PNTCNT,R0
        MOV #ECHO,70
        MOV #300,72
        CLR TEKCSI
        CLR TEKBFI
        MOV #100,TEKCSI ;INT EN KB OF TEK
        MOV DBX,R3
        MOV DBY,R1
MULT:   MOV SIZE,R2
        MOV (R3)+,M0
        MOV R2,MUL
*
```

Program B4 PLOTEK.MAC

```
        MOV #4,DIV
        MOV MQ,XVEC
        MOV (R1)+,MQ
        MOV R2,MUL
        MOV #4,DIV
        MOV MQ,YVEC
CODGEN: MOV #32.,R2

        CLR AC
        MOV YVEC,MQ
        MOV R2,DIV
        MOV MQ,R5
        ADD #32.,R5         ;ASCII OFFSET Y
        JSR PC,SEND         ;HI Y
        MOV AC,R5
        ADD #96.,R5         ;ASCII OFFSET LO Y
        JSR PC,SEND
        CLR AC
        MOV XVEC,MQ
        MOV R2,DIV
        MOV MQ,R5
        ADD #32.,R5
        JSR PC,SEND
        MOV AC,R5
        ADD #64.,R5
        JSR PC,SEND
        TST FPLOT
        BEQ C2
        CLR FPLOT
        JMP CODGEN
C2:     DEC R0
        BGT MULT
C1:     CLR TEKCSO
        RTS PC

SEND:   TSTB TEKCSO
        BGE .-4
        MOV R5,TEKBFO
        RTS PC

ECHO:   TSTB @#TEKCSO
        BGE .-4
        MOV TEKBFI,TEKBFO
        MOV #100 ,TEKCSI
        RTI

FPLOT:  0
DBX:    0
DBY:    0
PNTCNT: 0
*
```

Program B4 PLOTEK.MAC (cont.)

```
SIZE:    0
ALPHA:   1
DELAY:   0
XVEC:    0
YVEC:    0
         .END
*
```

Program B4 PLOTEK.MAC (cont.)

```
;        *************************
;        *DIGITAL INPUT DATA COLL.*
;        *************************

;AUTHOR:           W.BRUEGGER
;        MC MASTER UNIV. BIOMED ENG.
;        HAMILTON,ONT

;DATA COLLECT. FROM LPS DIG.INP IN 2 BYTES.
;FORTRAN : CALL DIGIN(XADDR,YADDR,NO.OF PTS.)
;START AND STOP WITH ST1

        .TITLE DIGIN
        .GLOBL DIGIN

                  .MCALL .REGDEF
        .REGDEF

DIGIN:  CLR CLCSR
        MOV 177776,SPTEMP
        TST (R5)+
        MOV (R5)+,DBX
        MOV (R5)+,DBY
        MOV @R5,PTADR
        MOV @(R5)+,PNTCNT
        CLR @#177546
        MOV #INP,310      ;DIG INP VECT
        MOV #240,312      ;BR5
        MOV #ENDAT,304    ;SCHM VECT
        MOV #200,306      ;BR4
        TST CLCSR
        BPL .-4           ;WAIT FOR ST1
        MOV #7,@#177566   ;BELL
        MOV #40000,CLCSR          ;INT EN
        MOV DBX,R5        ;ADDR OF X-BUF F INP DAT
        MOV PNTCNT,R0
        MOV #32.,R2
        MOV #LPSCSR,R1
        MOV #LPSINP,R3
        MOV #100,R4
        MOV #100,LPSCSR

 I:     WAIT
        BR I
 *
```

Program B5. DIGIN1.MAC

```
        BR I
INP:    MOV @R3,(R5)+
        DEC R0
        BLE ENDAT
        MOV R4,@R1
        RTI

DI:     CLR CLCSR
        MOV #7,@#177566
        MOV DBX,R3
        MOV DBY,R1
        MOV PNTCNT,R0
DISC:   MOV (R3),DAT
        CLR (R3)
        MOVB DAT,(R3)+
        INC R3
        CLR (R1)
        MOVB DAT+1,(R1)+
        INC R1
        DEC R0
        BPL DISC
        TST (SP)+
        TST (SP)+
        MOV SPTEMP,177776          ;SIM RTI

        RTS PC

ENDAT:  CLR LPSCSR
        CLR CLCSR
        SUB R0,PNTCNT
        MOV PNTCNT,@PTADR
        JMP DI

PTADR:  0
DBX:    0
DBY:    0
SPTEMP: 0
PNTCNT: 512.
DAT:    0
DATX:   0
DATY:   0

.END
*
```

Program B5 DIGIN1.MAC (cont.)

```
;        **************************
;        *DIGITAL INPUT DATA COLL.*
;        **************************

;2 CAMERA VERSION,CAMERA SELECT VIA INTERUPT
;FOR LPSIN & LPSOUT INTERUPT LINES


;AUTHOR:            W.BRUEGGER
;        MC MASTER UNIV. BIOMED ENG.
;        HAMILTON,ONT


;DATA COLLECT. FROM LPS DIG.INP IN 2 BYTES.
;FORTRAN : CALL DIGIN2(XADDR1,YADDR1,XADDR2,YADDR2,NO.OF PTS.)
;START AND STOP WITH ST1

        .TITLE DIGIN2
        .GLOBL DIGIN2


                .MCALL .REGDEF
        .REGDEF

        OUTVEC=314

DIGIN2: CLR CLCSR
        MOV 177776,SPTEMP
        TST (R5)+
        MOV (R5)+,DBX
        MOV (R5)+,DBY
        MOV (R5)+,DBX2
        MOV (R5)+,DBY2
        MOV @R5,PTADR
        MOV @(R5)+,PNTCNT
        MOV @R5,PTADR2
        MOV @(R5)+,PNTCT2
        CLR @#177546
        MOV #INP,310     ;DIG INP VECT
        MOV #300,312     ;BR6
        MOV #CAM2,OUTVEC;ADDR F CAMERA #2 DATA COLL.
        MOV #240,316     ;BR5 FOR CAM #2
        MOV #ENDAT,304   ;SCHM VECT
        MOV #200,306     ;BR4
        TST CLCSR
        BPL .-4          ;WAIT FOR ST1
        MOV #7,@#177566 ;BELL
        MOV #40000,CLCSR;INT EN
```

```
        MOV DBX,R5          ;ADDR OF X-BUF F INP DAT
        MOV PNTCNT,R0
        MOV PNTCT2,S0
        MOV DBX2,R2         ;ADDR OF X2-BUF F INP DAT
        MOV #LPSCSR,R1
        MOV #LPSINP,R3
        MOV #40100,R4       ;INT EN IN-AND OUTPUT
        MOV R4,LPSCSR

I:      WAIT
        BR I
        BR I
        BR I
INP:    MOV @R3,(R5)+
        DEC R0
        BLE ENDAT
        MOV R4,@R1
        RTI

DI:     CLR CLCSR
        MOV #7,@#177566
        MOV DBX,R3
        MOV DBY,R1
        MOV PNTCNT,R0
DISC:   MOV (R3),DAT
        CLR (R3)
        MOVB DAT,(R3)+
        INC R3
        CLR (R1)
        MOVB DAT+1,(R1)+
        INC R1
        DEC R0
        BPL DISC
        MOV DBX2,R3
        MOV DBY2,R1
        MOV PNTCT2,R0
DISC2:  MOV (R3),DAT
        CLR (R3)
        MOVB DAT,(R3)+
        INC R3
        CLR (R1)
        MOVB DAT+1,(R1)+
        INC R1
        DEC R0
        BPL DISC2
        TST (SP)+
        TST (SP)+
        MOV SPTEMP,177776;SIM RTI

        RTS PC
```

Program B6 DIGIN2.MAC (cont.)

```
CAM2:   MOV @R3,(R2)+     ;BUF F CAM #2
        DEC S0
        BLE ENDAT
        RTI

ENDAT:  CLR LPSCSR
        CLR CLCSR
        SUB R0,PNTCNT
        MOV PNTCNT,@PTADR
        SUB S0,PNTCT2
        MOV PNTCT2,@PTADR2
        JMP DI

PTADR:   0
PTADR2:  0
DBX:     0
DBY:     0
SPTEMP:  0
PNTCNT:  512.
DAT:     0
PNTCT2:  0
DATX:    0
DATY:    0
DBX2:    0.
DBY2:    0
S0:      0

.END
*
```

Program B6 DIGIN2.MAC (cont.)

```
;        SUBROUTINE FRAME
;        ****************

;DETERMINES FRAME BOUNDARY OF THE CCD211 DATA STREAM.

         .TITLE FRAME
         .GLOBL FRAME
         .MCALL .REGDEF,..V2..
         .REGDEF
         ..V2..

FRAME:   TST (R5)+
         MOV @(R5)+,A
         MOV @(R5)+,B
         CLR @(R5)
         BIC C,A
         BIC C,B
         CMP A,B
         BEQ F1
         INC @(R5)+
F1:      RTS PC
A:       0
B:       0
C:       177776
         .END

*
```

Program B7 FRAME.MAC

```
      C      SEPARATION SUBROUTINE FOR UNPACKING X LABELS
      C      ****************************************
      C
             SUBROUTINE SEPAR(IBX,IBY,NP,N1,X,Y,L,LL,K,KK)
             DIMENSION IBX(NP),IBY(NP),X(K,KK),Y(K,KK)
             REAL IXT,IYT
             I=3
             L=1
             IBLEMX=0
             IBLEMY=0
       10    CALL FRAME(IBY(I),IBY(I+1),IFRAME)
             I=I+1
             IF (IFRAME) 10,10,20
      C
      C      SETUP OF 1ST FRAME
      C
       20    II=1
             LFRA=I
      C
       27    DXT=IBX(I)
             DYT=IBY(I)
             IBX(I)=-10000
             IXT=0
             IYT=0
             M=1
       21    I=I+1
             IF((I-N1).GE.0)GOTO 105
             CALL FRAME(IBY(I-1),IBY(I),IFRAME)
             IF (IFRAME .GT.0)GOTO 26
             CALL DETEC(DXT,DYT,IBX(I),IBY(I),ILAB,15)
             IF(ILAB)25,25,21
       25    IXT=IXT+IBX(I)
             IYT=IYT+IBY(I)
             IBX(I)=-10000
             M=M+1
             GOTO 21
      C
       26    IF(M-1)22,22,23
       23    X(1,II)=(DXT+IXT)/M
             Y(1,II)=(DYT+IYT)/M
             II=II+1
             IF(II .GT. LL)GOTO 24
             I=LFRA
      223    I=I+1
             IF((I-N1).GE.0)GOTO 105
```

Program B8 SEPAR.FOR

```
0042          IF(IBX(I).LT.0)GOTO 223
0044          GOTO 27
      C
0045   22     IF(II .LE. LL)I=I+1
0047          GOTO 27
      C
      C       TRACKING FROM 1ST FRAME ON...
      C
0048   24     IE=1
0049          DO 1 J=1,LL
0050          IX=X(1,J)
0051          IY=Y(1,J)
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0052          CALL DISV(IX,IY,1,12,IE)
0053          IE=0
0054    1     CONTINUE
      C
0055   30     L=L+1
0056          IF(L-K)133,133,110
0057   133    II=1
0058          LFRA=I
      C
0059   31     I=LFRA
0060          IXT=0
0061          IYT=0
0062          M=0
0063   32     I=I+1
0064          IF(I-N1)35,35,110
0065   35     CALL FRAME(IBY(I),IBY(I+1),IFRAME)
0066          IF (IFRAME)40,40,140
0067   40     CALL DETEC(X(L-1,II),Y(L-1,II),IBX(I),IBY(I),ILAB,10)
0068          IF (ILAB)42,42,32
0069   42     IXT=IXT+IBX(I)
0070          IYT=IYT+IBY(I)
0071          M=M+1
0072          GOTO 32
      C
0073   140    IF(M)50,100,50
0074   50     X(L,II)=(IXT/M)+.5
0075          Y(L,II)=(IYT/M)+.5
0076   53     II=II+1
0077   51     IF(II-LL)31,31,30
0078   100    IF(L-1)101,101,102
0079   101    X(L,II)=X(L-1,II)
0080          Y(L,II)=Y(L-1,II)
```

Program B8 SEPAR.FOR (cont.)

```
103     IX=X(L,II)
        IY=Y(L,II)
        CALL DISV(IX,IY,1,12,0)
        GOTO 53
102     X(L,II)=X(L-1,II)+(((X(L-1,II)-X(L-10,II))/9.))
        Y(L,II)=Y(L-1,II)+(((Y(L-1,II)-Y(L-10,II))/9.))
        IF((N1-I).LT.100)GOTO 110
        GOTO 103
C
C
C
105     WRITE(7,77)
77      FORMAT(' NO SETUP POSSIBLE!')
110     L=L-2
        RETURN
        END

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C
        SUBROUTINE DETEC(X1,Y1,IX2,IY2,ILAB,IDELTA)
C
        IX1=X1
        IY1=Y1
        IF ((IABS(IX1-IX2))-IDELTA) 10,10,20
10      IF ((IABS(IY1-IY2))-IDELTA) 15,15,20
15      ILAB=0
        RETURN
20      ILAB=1
        RETURN
        END

*
```

Program B8 SEPAR.FOR (cont.)

APPENDIX C

TABLE OF THE THEORETICAL FIELD

IN THE X-Z FIELD

Description

The tables in App. C list the maximum expected error in the X-Z field due to deviations from the true values in X- and Z-direction.

Error in mm over the X-Z field for dX = +1 bit

23.	22.	21.	21.	21.	21.	21.	21.	22.	23.
23.	22.	22.	22.	22.	22.	23.	23.	24.	24.
23.	23.	23.	23.	23.	23.	24.	25.	26.	27.
23.	23.	23.	23.	24.	25.	25.	26.	28.	29.
23.	23.	24.	24.	25.	26.	27.	28.	30.	31.
23.	24.	24.	25.	26.	27.	29.	30.	32.	34.
23.	24.	25.	26.	27.	28.	30.	32.	34.	37.
24.	24.	25.	27.	28.	30.	32.	34.	37.	40.
24.	25.	26.	27.	29.	31.	34.	36.	40.	44.
24.	25.	26.	28.	30.	33.	35.	39.	43.	47.

X-Z FIELD COORDINATES FOR SELECTED PARAMETERS

2256.	2714.	3153.	3575.	3979.	4368.	4742.	5102.	5448.	5783.
2209.	2672.	3121.	3556.	3978.	4388.	4786.	5172.	5548.	5913.
2163.	2630.	3089.	3537.	3977.	4408.	4831.	5245.	5652.	6050.
2119.	2590.	3057.	3519.	3976.	4429.	4876.	5320.	5759.	6193.
2077.	2552.	3026.	3501.	3975.	4449.	4923.	5397.	5870.	6344.
2036.	2514.	2996.	3483.	3974.	4470.	4971.	5476.	5986.	6501.
1997.	2477.	2966.	3465.	3973.	4491.	5019.	5558.	6107.	6667.
1960.	2442.	2937.	3447.	3972.	4512.	5068.	5642.	6232.	6842.
1924.	2407.	2909.	3430.	3971.	4533.	5119.	5728.	6363.	7025.
1889.	2374.	2881.	3413.	3970.	4555.	5170.	5817.	6500.	7219.

STOP --

Table C1 Theroretical error over the X-Z field caused by deviations dX and dZ from the true value in X- and Z-direction, and the corresponding field coordinates for the field covered by the two CCD-cameras (field coverage as per fig. 6.4.).

REFERENCES

Andrews, B. (1976) : "Ph.D. Thesis", (in preparation), Univ. of Strathclyde, Scotland.

Bibermann and Nudelmann (1971) : Photoelectric Imaging Devices, vol. 2, Plenum Press, New York-London.

Bruegger, W. and Milner, M. (1977) : "Computer aided tracking of body motions using a CCD-image-sensor", Medical and Biological Engineering and Computing, (in press).

Bullock, M.I. and Harley, I.A. (1972) : " The measurement of three-dimensional body-movements by the use of photogrammetry", Ergonomics, vol. 15, 3, 309-322.

Cheng, I. (1974) : "Computer-television analyses of biped locomotion", Ph.D. Thesis, Ohio State Univ.

Dinn, D.F., Winter, D.A. and Trenholm, B.G. (1970) : "CINTEL-Computer interface for television", IEEE Trans. on Computers, vol. C-19, 11, 1091-1093.

EMR Schlumberger (1974) : Trade Literature on the "ODD"-optical data-digitizer, EMR Photoelectric, Princeton, N.J.

Grieve, D.W. (1968) : Biomedical Engineering, 3, 119.

Gueth, V., Abbink, F. and Heinrichs, W. (1973) : "Eine Methode zur chronozyklographischen Bewegungsaufzeichnung mit einem Prozessrechner", Int. Z. angew. Physiol., Springer Verlag, 151-161.

Hershler, C. (1977) : "Quantitative electromyographic and goniometric analyses of normal and pathological human gaits", Ph.D. Thesis, Mc Master Univ., Hamilton.

Jarrett, M.O. (1976) : "The television/computer system for human locomotion analysis", Ph.D. Thesis, University of Strathclyde, Scotland.

Kasvand, T. and Milner, M. (1972) : "Pattern recognition applied to measurement of human limb positions during movement", J. of Cybernetics, 2, 1, 66-78.

LPS-11 (1973) : Laboratory Peripheral System User's Guide, Digital Equipment Corporation, Maynard, Mass.

Marey, E.J. (1894) : Le Movement, Masson, Paris.

Milner, M., Dall, D., Mc Connell, V.A., Brennan, P.K. and Hershler, C. (1973) : "Angle-diagrams in the assessment of locomotor function", S. Afr. Med. J., 47, 951-957.

Mitchelson, D.A. (1975) : "Recording of movement without photography", in Grieve et al : Techniques for the analysis of human movement, Lepus, London.

Molen, N.H. and Boon, W. (1972) : "Measurement of momentary velocity in a study of human gait", J. Biomechanics, vol. 5, 273-276.

PDP-11 (1973) : Processor Handbook, Digital Equipment Corporation, Maynard, Mass.

RETICON Co. (1973) : Trade literature on the "RETICON" solid state image-sensor arrays, Mountain View, Calif.

Schottky, W. (1930) : "Ueber den Entstehungsort der Photoelektronen in Kupfer-Kupferoxydul-Photozellen", Phys. Z. Leibzig, vol. 31, Nov, 913-925.

SELCOM, AB (1975) : Trade literature on the "SELSPOT"-system, Mölndal, Sweden.

Séquin, C.H. and Tompsett, M.F. (1975) : "Charge-transfer-devices", Bell Telephone Laboratories, Murray Hill, N.J., Academic Press Inc., New York, N.Y.

Weber, W. and Weber, E. (1836) : Mechanik der menschlichen Gehwerkzeuge, Dietrich, Göttingen.

Winter, D.A., Greenlaw, R.K. and Hobson, D.A. (1972) : "Television-computer analysis of kinematics of human gait", Computers and Biomedical Research, 5, 498-504.

Winter, D.A. and Reimer, G.D. (1972) : "Quantization errors in calculation of volumes, areas and coordinates in medical images", Developments in electronic imaging techniques, Proc. of Society of Photo-Optical Instrumentation Engineers, vol. 32, San Mateo, Calif., Oct., 16-17.

Woltring, H.D. (1975) : "Single and dual-axis lateral photodetectors of rectangular shape", IEEE Trans. on El. Dev., 22, 581-590.

Woltring, H.D. (1977) : "Measurement and control of human movement", Ph.D. Thesis, Univ. of Nijmegen, Netherlands, Peters and Haarsma Press, Nijmegen.