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Title: Hardware Implementation of Color Transforms in the Analog Domain for Wood Surface Analysis.

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This thesis discusses the hardware implementations of certain linear and non-linear color space transforms thought to be useful in the analysis of wood surfaces for defect detection.

The developmental system's color image digitizer contains 5 bits per color while the input signal contains considerably greater resolution. This often degrades the information content of the image when certain color transforms are performed. Performing these transforms at real-time speeds demands extremely fast operating hardware.

In order to avoid loss of information content and obtain real-time operating speeds, the color transforms were implemented using analog circuits.

Linear transforms, as proposed by Forrer (FORR 1987), were implemented using high speed operational amplifier-based circuits. Non-linear transforms such as ratioing or intensity normalization and contrast enhancement were implemented using high-speed analog divider circuits.

The results showed that, for the linear transforms described, significant improvement in image quality was observed. This was supported by analysis of the transformed image histogram. The contrast enhancement circuit has the ability to enhance certain features such as blue stain. All circuits operated at real-time speeds and the resultant images had lower noise content as compared to transformations performed digitally.

Hardware Implementation of Color Transforms in the Analog Domain for Wood Surface Analysis

by

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CHAPTER 1

INTRODUCTION

1.0 The wood products industry is undergoing extensive modernization. As a part of this effort, various high technology areas are being researched for direct and indirect applications. Machine vision or scanning technology is being considered for applications in the wood products industry because it is a non-contact technique easily integrated into existing manufacturing processes. Surface analysis for defect detection using machine vision currently is being researched in this industry, for improvements in plywood quality and production time.

Forrer (FORR 1987), working with a group of researchers at the Forest Research Laboratory, Department of Forest Products, Oregon State University, investigated the analysis of color images of wood using Karhunen-loeve (KL) transformations similar to those performed by Ohta (OHTA 1985). Ohta used KL transformations on natural scenes in order to obtain an optimal color space for image segmentation to separate objects such as houses and trees. The segmentation technique helped reduce the pattern recognition problem for the computer. The KL transform is based on a principle of information theory by which a measure is said to have large discriminant power if its variance is large. Forrer et al. carried out similar KL transforms on images of wood surfaces to increase the usefulness of the color information for defect detection. Examples of defects to be detected were knots, pitch pockets, and blue fungi stain. Forrer's investigations resulted in a color space similar to the one obtained by Ohta. The KL transform indicated that a nearly optimal set is approximated by:

I(1) =	(R+B+G)/3	most important measure
I(2) =	(R-B)/2	second most important measure
I(3) =	(2G-R-B)/4	third most important measure

It was decided to use this color space for the surface analysis of wood, resulting in the need to linearly transform the raw CIE (Commission Internationale d'Eclairage, an international body for standards) red, green, and blue.

Further investigations by the FRL vision group suggested that other non-linear transformations on the red, green, and blue color space may be useful; these are ratioing and contrast enhancement.

Ratioing is a division operation of two signals that can result in useful information. Contrast enhancement results in the amplification of that portion of the signal of greatest interest and in effect stretches the image's contrast.

The linear and non-linear transformations were originally implemented on the host computer. However, this method has several drawbacks, some of which were:

* High-speed, real-time image processing was not possible on the host computer.
* A better color digitizer was necessary. That is, larger bit count per color was essential.

The FRL vision group decided to overcome these difficulties of slow speed and reduced information content by performing these transformations with analog circuits prior to image digitization. This approach provided increased precision of the transformed color signals in real time. The analog approach is also less expensive than a digital hardware implementation.

The hardware was designed for maximum flexibility to permit further research on combinations of the implemented transforms, for example linear transforms may be processed by the non-linear transformations or vice versa. This allows the researcher to process signal/information in a variety of ways.

CHAPTER 2

LITERATURE REVIEW

2.0 The literature review consists of two sections. The first section describes research in the area of machine vision for surface analysis of wood. The second section will describe the implementation of various color transforms and how they are used.

Some of the earliest work was performed by Lakatosh (LAKA 1966). He reviewed several methods for determining and classifying surface defects in wood. In his study he analyzed various samples of wood using ultraviolet light, visible light, gamma radiation and ultrasonic waves. He suggested that color might prove useful in the analysis of wood surface defects. He classified wood surface defects according to their chromatic content. His classification was based on the CIE X,Y,Z color space.

Szymani and McDonald (SZYM 1981) and Szymani (SZYM 1984, 1985) analyzed similar techniques. They concluded that visible light vision systems were optimally suited for surface analysis of wood.

Conners (CONN 1983, 1984) and McMillin (MCMI 1984) described a conceptual automated lumber processing system (ALPS). This system was designed around a gray scale machine vision system and was capable of detecting eight common types of defects found in the southern red oaks. They detected the surface defects by employing texture analysis techniques. Conners (CONN 1985) analyzed maple wood surface by combining a gray scale system with red, blue and green filters. It was shown that the red-blue filter combination performed best on all defects except wood decay. It was not stated if the filters used were standard CIE R, G and B filters.

Forrer (FORR 1987) developed an algorithm which uses color information for detecting defects in Douglas - fir veneer (Pseudotsuga menziesii). Their earlier investigations of color spaces determined that the color space proposed by Ohta (OHTA 1985) was suitable for wood. Their method of defect detection was based on statistical techniques. A fairly high rate of success was obtained in detecting certain surface defects in Douglas - fir.

This section will review implementations of linear and non-linear color transforms both in software or in hardware. A discussion of the current techniques in linear and non-linear transformations should help the reader understand their usefulness in color imagery and image processing.

The topic of color transforms appears in many areas of research, especially in the area of satellite imagery. One of the earliest papers was a conference report by Stockton (STOK 1976). This paper describes the selection of the correct color space for image enhancement. It also suggests hardware implementations of color transforms using either digital or advanced analog signal processing.

Because of relatively powerful computers, the normal practice today is to carry out signal processing digitally. This method offers the advantage of higher noise immunity and ease of data/signal manipulation. A major drawback of any digital signal processing system is the dependance of signal precision on the data bus width. That is, increased signal precision requires an increase in data bus width. Analog signal processing is highly prone to noise but it does not depend on the data bus width for its signal quality. Color image digitizers typically have a low number of bits to quantify each of the three primary colors. Therefore, performing these transformations digitally may cause considerable signal loss and additional expense as compared to the analog implementation .

A paper by King, Kaupp and Waite (KING 1984) describes the importance of color transforms. The paper explores the importance of Intensity, Hue and Saturation (I,H,S) for analyzing Landsat and Seasat satellite color images. It further explains the geometric non-linear relationship between the R,G,B color space and the I,H,S color space. An algorithm is presented for conversion from R,G,B to I,H,S and vice versa. A mapping of the I,H,S triad onto a R,G,B color CRT is also considered.

The concept of mapping the I,H,S triad onto a R,G,B color CRT is used by many color imaging systems involved with satellite imagery. The conversion from R,G,B to I,H,S and vice versa is a non-linear operation which is easier to implement in software. Because this operation requires intensive computation, it is usually implemented with look-up tables in hardware. Sometimes it is easier to implement certain non-linear operations in hardware rather than to use a combination of hardware and software.

Buchanan and Pendergrass (BUCH 1980) questioned the feasibility of the I,H,S model replacing the R,G,B model. They conclude that it would not be possible to do so in every application. Further this paper presents an architecture of a machine which transforms R,G,B color space in to I,H,S color space and vice versa. The idea behind this hardware implementation is to have large look-up tables in silicon. This piece of hardware is patented (U.S. Patent. 4183046) and therefore no significant details were given. The authors state that 64 levels of intensity, 32 levels of hue and 8 levels of saturation are normally sufficient for a color T.V. monitor to display images represented by the I H S transformations.

Robertson and O'Callaghan (ROBE 1988) claim that by using the perceptually uniform color space (UCS) significant improvements in the interpretability of remotely-sensed geoscientific data is obtained. A computational framework encompassing the mapping of data into UCS is presented and practical application of this framework to various types of images is described.

An application note (Max Vision AT - 1) by Datacube, a company involved in image processing hardware, gives an excellent explanation of the concept of contrast enhancement which can be demonstrated by expanding or stretching an intensity histogram. This technique is useful for separating features in images with small intensity ranges.

CHAPTER 3

INTRODUCTION TO COLOR TRANSFORM MATHEMATICS

3.1 INTRODUCTION: This chapter will look into the mathematics of color transforms. A brief discussion will be presented on the KL transform which is the basis for the linear transforms. Further, the non-linear transforms will be analyzed mathematically in order to understand their operation.

3.2 LINEAR TRANSFORMS: In image processing linear transforms and non-linear transforms are used for a variety of tasks, such as image enhancement or image segmentation. Non-linear transforms are useful but are generally compute intensive and their behavior is difficult to predict.

The KL transform is difficult to perform at real-time speeds. An image which has undergone KL transformations is generally very good for segmentation, that is, objects can be easily segmented with further processing. The linear transforms are a set of color features which approximate the typical results of the KL transform on wood images. The linear transforms are obtained from the KL transforms as follows:

Let S be a complete image and let A be the covariance matrix of the distributions of R (red), G (green), and B (blue) in S. Let $\lambda 1$, $\lambda 2$ and $\lambda 3$ be the eigenvalues of A and $\lambda 1 > \lambda 2 > \lambda 3$. Let $Wi = \{ WRi\ WGi\ WBi \}$ for i = 1, 2 and 3 be the eigenvectors of A corresponding to λi, respectively. The color features X1, X2, X3 are defined as:

$$Xi = WRi*R + WGi*G + WBi*B$$
$$\text{for } \{ \| Wi \| = 1,\ i = 1,2 \text{ and } 3\}$$

X1, X2 and X3 are generally uncorrelated, and X1 is the best feature in the sense that it has the largest variance (the value is $\lambda 1$). X2 is the best among the features orthogonal to X1. This process of calculation of X1, X2, and X3 for the entire image is the KL transform.

Experimentally obtained eigenvectors of A for a whole image of wood or natural scene indicated that W1 is approximately (1/3, 1/3, 1/3), W2 is approximately (1/2, 0, -1/2) and W3 is approximately (-1/4, 1/2, -1/4). This gives the required color features or linear transforms as :

$$(I)1 = (R + B + G)/3$$
$$(I)2 = (R - B)/ 2$$
$$(I)3 = (2G - R - B)/4$$

3.3 NON - LINEAR TRANSFORMS: The non-linear transforms are not exactly non-linar, they are so called because they are not strictly additive or subtractive. The non-linear transforms considered in this thesis are of two types: contrast enhancement and ratio. Both these transforms are based on the concept of division.

Contrast enhancement works on the concept of stretching or extending an image's intensity histogram. This is obtained mathematically by dividing an image's histogram by a constant. This same effect is observed when the incoming signal is divided by a known constant voltage Vi. Mathematically this could be represented as

$$Y_{out} = Y_{input} / Vi \qquad Vi = 10 \text{ mv to } 0.7 \text{ V}$$

The ratio is the same mathematically as the contrast enhancement, but instead of Vi being a constant the denominator is another time-varying signal. One application of the ratio uses the intensity as the denominator while the numerator is a color dependant signal, resulting in an image free of intensity variation. This image should now contain color-dependant features.

CHAPTER 4

THE IMAGING SYSTEM

4.0 INTRODUCTION: Oregon State University Forest Research Laboratory's image processing system is described in the following pages. The following sections should help the reader to fully understand the existing machine vision system, its disadvantages and why analog processing was chosen as a solution to them.

4.2 SYSTEM DETAILS: The image of the wood surface is obtained by a JVC color camera. It is a orthicon tube type camera of studio quality. A typical response curve of this type of camera is depicted in Figure 4.0 . The camera operates through a camera control unit which is also made by JVC. The camera control unit provides balancing between cameras and output to the monitor. If the operator switches between cameras, the camera control unit balances changes such as brightness and color levels. The unit provides two types of outputs. These outputs are :

1. composite color video output
2. R,G,B video outputs.

The composite color video output is a RS - 170 type and provides composite color video signals into a 75 ohm load. The R,G,B video outputs are also RS-170 compatible and provide the red (R), green (G) and blue (B) information on three separate channels. Along with these three channels there is a fourth signal channel which provides the Synchronization (sync) pulses.

The color image digitizer is the other important component utilized in this system. It is a AT&T TARGA 16 color digitizer/image capture board. The board plugs into a bus slot on an IBM PC-AT computer. The digitizer can accept composite or R,G,B video. The source is software selectable via the keyboard of the IBM PC-AT. The digitizer captures images in one camera frame interval (1/30 of a second). Internally it uses three channels, one each for the red, green and blue signals to independently digitize each channel's information with 5 bits of resolution or 32 levels of intensity. An individual pixel's information is contained in a two byte word with the most significant bit indicating whether output to the monitor should be from the camera or the digitizer. The remaining 15 bits contain the color information with each primary represented in 5 bits. This results in a total of 32768 possible colors for display. A complete connection diagram of this hardware is illustrated in Figure 4.1 .

The TARGA card can be controlled by user written programs with keyboard entered commands. The IBM PC-AT used has a megabyte of onboard device memory (DRAM type).

Software needed to control the digitizer is provided in a software package written by the FRL vision group called VMENU. VMENU has extensive libraries for digital image processing such as filtering, thresholding and edge detection.

4.3 SYSTEM DRAWBACKS:

Several characteristics of the existing hardware limit system performance as follows:

1.Signal resolution:

The camera provides information content per color equivalent to 9 bits, whereas the digitizer produces 5 bits per color (primary color).

2. Round-off error:

Round-off errors occur during digitization of the image.

3. Processing Time:

Lack of real time operating speeds.

4.4 IMPROVEMENTS: ANALOG PROCESSING: In this section a discussion of how to reduce existing system limitations will be considered. Analog processing was selected to minimize these limitations for this application because of the following:

1. Signal resolution:

The camera's analog output has a resolution equivalent to 9 bits whereas the digitizer has only 5 bits per color. Therefore implementing the transforms before the image capture should yield better resolution. Analog circuits are quite well suited for this application since an analog circuit having the required bandwidth and dynamic range is quite simple in design.

2.Round-off error:

Digitizers have a tendency to round off values. That is, if an input signal is present which has a value between two adjacent discrete digital levels, the digitizer outputs a value closest to the actual value. Analog circuits have the least rounding off effects. Theoretically, for an off-set and noise-free analog circuit, it should be possible to have exact and accurate results.

3. Processing time:

It is quite well known that analog circuits operate at real time speeds. In the case of digital processing, a certain amount of time is lost in conversion from analog to digital and vice versa. This conversion time can be reduced by using very fast but expensive hardware. Performing the transformations digitally again involves moving bits in either circuits or in software to perform digital addition or subtraction, which is time consuming. Analog chips to perform these transformations have become available recently at relatively low cost.

4.5 PROBLEMS ASSOCIATED WITH ANALOG CIRCUITS:

Analog processing also has certain difficulties, such as:

1. Off-set adjustment and drift with temperature.
2. Extensive calibration.
3. Modification difficulty to reprogram the processing algorithm. Should another algorithm be used, it is generally very difficult to make the same circuit function for the new algorithm.

It will be pointed out in the remaining chapters how problems associated with these analog circuits were minimized.

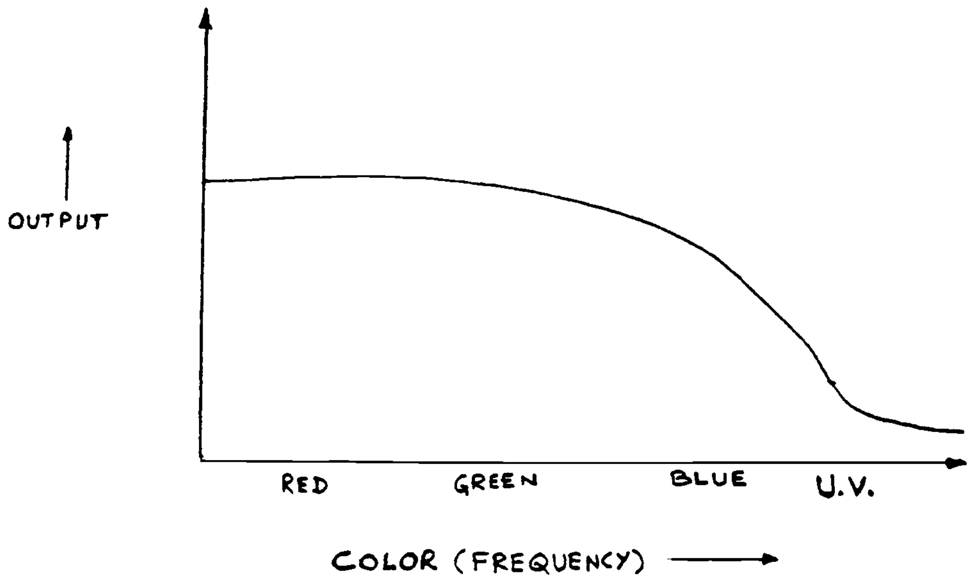


Figure 4.0 Response curve of color camera.

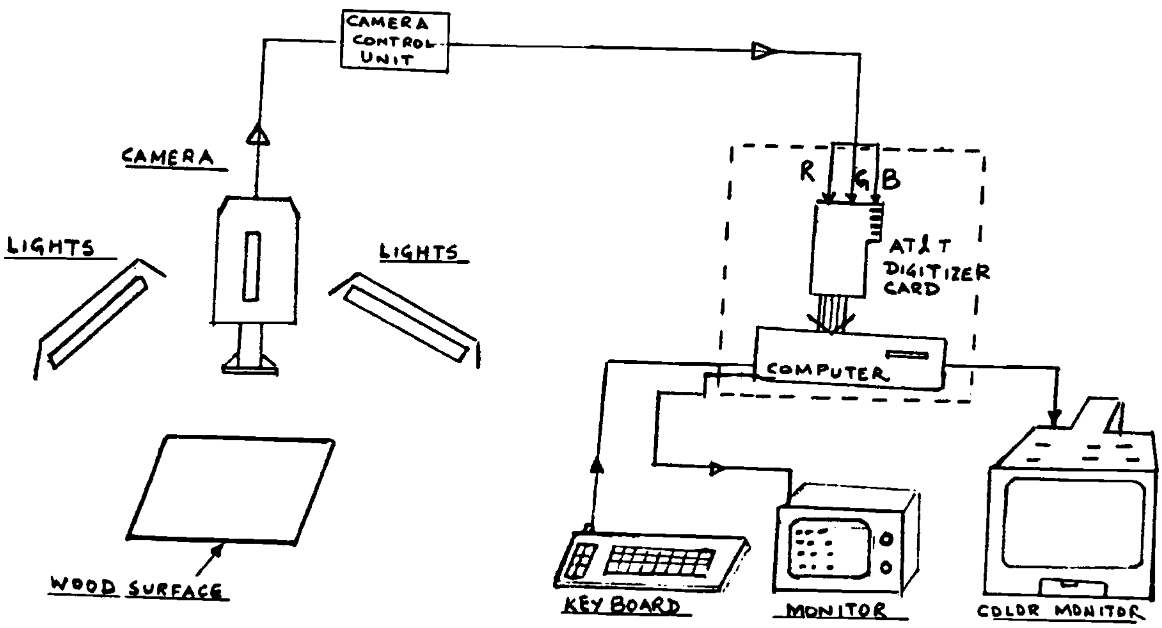


Figure 4.1. Component connection diagram of the vision system.

CHAPTER 5

HARDWARE IMPLEMENTATION

5.1 INTRODUCTION: This chapter discusses the hardware implementation of the color transforms. The discussion describes the operation and design of the circuits as well as component selection and layout techniques.

5.2 LINEAR TRANSFORM IMPLEMENTATION: The linear transforms receive red, green, and blue signals from the camera and output a signal which is a linear combination of them. The linear transforms implemented are of four types and each is implemented with an independent circuit.

Three of the linear transforms implemented are the ones suggested by Forrer (FORR 1987). A fourth linear transform is also implemented that can approximate the other three transforms.

The transforms in general had to receive red, green, and blue information signals which are RS-170 compatible and output the required signal which is also RS-170 compatible. The RS-170 standard assumes a impedance of 75 ohms and a signal of 0.7 volts peak to peak. The RS-170 is an internationally accepted video standard.

The transforms are:

$$(I)1 = K (R + B + G)$$

$$(I)2 = K (R - B)$$

$$(I)3 = (KG - R - B)$$

$$(I)4 = K_1 (K_2 (R - B) + K_3(R + B) + G)$$

The K's in these equations represent independent variables which can be varied from around 0.20 to about 2.0 .

As can been seen from the equations, the transforms are relatively simple to implement in hardware using analog circuits. Analog circuits required to perform a large number of mathematical operations can be designed using operational amplifiers or OP-AMP. The circuits designed for these transforms are illustrated in the appendix Figures A.1 to A.4 . The design considerations were greatly influenced by the high frequency of video signals. Typical design considerations were:

1. Operating speed of the OP-AMP, i.e. cutoff frequency and slew rate.
2. Distortion and noise
3. Circuit layout
4. Compatibility with the existing imaging system.

Following is a discussion of how the considerations were approached in the design development.

The operating speed required the selection of an operational amplifier capable of handling high frequencies. Video signals associated with the existing system have a typical bandwidth of 5 Mhz. This establishes a lower limit for the highest frequency the operational amplifier should be capable of processing. An adequate margin of safety was thought to be a bandwidth of 15 Mhz. A variety of operational amplifiers are available which can operate at 15 Mhz. Another important factor placed on the selection of the operational amplifier was a gain of at least two at 15 Mhz. These two criteria together require an operational amplifier with a unity gain bandwidth of 30 Mhz.

The video signals available from the red, green, and blue channels also contain a synchronization pulse. The synchronization, or sync, pulse is given directly by the camera control unit to the digitizer. This component is required for the color signals because the sync pulse assures that there will be nothing displayed during the sync pulse transition. The sync pulse is a fast, negative pulse and has a very short rise and fall time. Due to the presence of this pulse, the operational amplifiers used had to be of a high slew rate type, since this would insure that the color channels are inactive during the sync pulse. After experimentally observing the waveforms, it was determined that a minimum slew rate of 50 volts/microsecond was essential. A higher slew rate would insure improved performance.

The third criterion placed on the operational amplifier was that of low distortion. The operational amplifiers available in the video grade generally do not have very low distortion and noise (as compared to other low frequency operational amplifiers), since they have been designed with only bandwidth as the primary design factor. Low distortion is needed since higher distortion would mean deviation from the required transform which would complicate analysis. Noise is another factor which must be considered, because any noise introduced by the analog circuitry would only distort the image and complicate analysis of the image. As the camera had a resolution of 9 bits, it meant the lowest possible signal which would be significant was 0.7volts/2**9 or approximately 1.4 millivolts. Therefore good design rules dictated a maximum acceptable noise level of less then 0.14 millivolts.

An operational amplifier, EL2020 by Elantec, met these requirements. This device is a pin to pin replacement for the industry standard 741 operational amplifier. Because this device is of the current feedback type, it has good noise immunity. A major advantage of this operational amplifier is that it requires no frequency compensation for gains below unity. Most of the earlier video grade operational amplifiers required extensive compensation when operated with gains of less than three. This operational amplifier provided easy offset adjustment, which resulted in a simplified design and layout. The circuits were built using carbon composition resistors. This type of resistor was used to avoid high frequency inductive effects associated with metal film or other film type resistors.

The fourth criterion placed on the design was the layout. Layout is important since high frequency analog signals are involved. The system was designed on a glass-epoxy wire wrap board. Due to the high frequency of video signals, wire wrapping could not be used. This meant the wiring of this circuit required special attention. All the rules of good layout were observed, such as short interconnecting leads, smallest possible wire path, and inputs and outputs being placed on the opposite sides of the board to avoid oscillations.

The fifth criterion of system compatibility was met by configuring the inputs and outputs to be RS-170 compatible.

5.3 NON-LINEAR TRANSFORM IMPLEMENTATION : The FRL vision group had decided from earlier research that implementing certain non-linear transforms would be useful. The non-linear transforms implemented in hardware were:

1. Ratioing
2. Contrast enhancement.

These two non-linear transforms are very closely related to each other mathematically. They are non-linear because their mathematics do not involve simple operators such as addition and subtraction.

5.3.1 RATIOING:

Ratioing is the division of a signal by another signal. Division is difficult to implement digitally since it requires large look up tables (either in chip form or some other type of memory) or computing power. The hardware used for implementing this ratioing circuit was also analog. The circuit had the input/output relation as:

$$Y(out) = \text{signal } 1/ \text{ signal } 2$$

where signal 1 and signal 2 are any two signals. These signals can be any of the primary color signals or the linear transformed signals. The hardware implementation of this ratioing circuit required similar construction constraints as with the linear transforms, such as:

1. Component selection
2. Layout.

The component selection in this case was simplified by a device made available in late 1985. This device, manufactured by Analog Devices, is the AD 539 integrated circuit: a wide band dual channel linear multiplier/ divider. The device features a low distortion analog multiplier having two identical signal channels (Y1 and Y2), with a common X input providing linear control of gain. Excellent a.c. characteristics up to video frequencies and a 3 dB bandwidth of over 60 Mhz are provided. This device is intended primarily for applications demanding high speed. Internal laser trimmed parameters and bandgap voltage reference provide ease of circuit design and accurate scaling.

Although this device is intended to operate as a stand-alone high-speed multiplier, it can be modified to work as a divider. Conversion from a multiplier to a divider circuit is possible because the operations are reciprocals. This is accomplished by using an inverting amplifier in which the output has the inverse characteristics of the element present in the negative feedback.

Based on this concept and an application circuit using this device, a high-speed analog divider was designed with a bandwidth of 15 Mhz.

Layout was critical for this circuit and constraints similar to those applicable in the linear transforms also apply.

The circuit diagram of this high-speed divider is illustrated in the appendix Figure A.5 . As can be seen from the circuit diagram there are two separate sections.

The first section is designed around the AD 539 multiplier/divider I.C. and the two operational amplifiers (NE 5539). The NE 5539 are inverting amplifiers used to convert the multiplier into a divider. The NE 5539 are very high speed operational amplifiers with a unity gain bandwidth in excess of 50 Mhz. The NE 5539 operational amplifiers were chosen in this case instead of the Elantec EL 2020, because the NE 5539 are conventional operational amplifiers whereas the EL 2020 demands a minimum resistance in the negative feedback path of approximately 700 ohms. This makes the EL 2020 unsuitable because the AD 539 acts like a dynamic signal-dependant resistor.

The AD 539 has two channels associated with it. Only one of the channels is utilized because testing showed that in this application there was no significant improvement in using the two channel approach. The first operational amplifier (NE 5539) acts as an inverting amplifier, and the second NE 5539 operational amplifier provides inversion and offset control.

This circuit was designed according to the RS-170 standard which made it fully compatible with the existing equipment and system.

5.3.2 CONTRAST ENHANCEMENT:

The concept of contrast stretching is an accepted method for enhancing an image. Enhancement in this case means that certain features in the image which are seen by the user of the digital version in greater detail.

The color digitizer uses three color components, namely the red, green and blue. Each of these three color channels can be considered to be independent intensity channels providing information for the color guns in the CRT display.

A histogram is a statistical analysis tool which provides information on the relative population of discrete pixel values in an image. Stated another way, it is a graph whose Y coordinate is number of pixels and whose X coordinate is pixel intensity value. It is an important tool to help in understanding the distribution of intensity values in an image.

An image taken from a low light environment will have many dark gray and black pixels but very few light gray and full white pixels. A histogram of this image is rather narrow. The image can be enhanced by "stretching" or increasing its contrast. This is accomplished by mapping a narrow band of gray level values to a wider band of gray level values. This mapping is done by dividing the histogram by a value determined after an analysis of the raw image's histogram. A typical contrast-enhanced image's histogram (digital processing) is illustrated in Figure 5.0 . As can be seen from this histogram, the information content has remained constant because only the separation of small intensity variations has occured.

The idea of implementing this contrast enhancement technique in the analog domain has several advantages, such as: real-time processing speeds, lower round-off error, 9 bit resolution as input (rather than 5 bit after digitization) and lower cost. This produces an image which contains more information relevant to the user as well as to the computer. The architecture of the system for performing contrast enhancement is shown in Figure 5.1 .

The architecture of this system operates as follows. The signal to be enhanced is the input to this circuit. This signal can either be routed to the divider or can go directly to the digitizer. This is under computer control. If the signal is fed to the divider, then it is divided by a reference voltage which is either generated by a digital input from the computer or by the user's input via a thumbwheel switch. This ratioing essentially produces the histogram stretching.

Providing a switching logic circuit allows the computer to analyze the raw data in one frame and then provide a digital reference voltage value to the computer interface for use by the divider as the denominator for contrast enhancement of the next frame. The computer now inputs the contrast stretched/ enhanced image. The user has the ability to override this automatic computer control. The user can input reference values for stretching the histogram via a thumbwheel switch after disabling the computer's parallel port.

The circuit which performs this division of the histogram is a modified divider circuit. A circuit performing contrast stretching is as shown in appendix Figure's A.6 and A.7 . This circuit is an extension of the divider or ratioing circuit based around the AD539 linear multiplier/divider chip. The circuit has four sections as follows:

1. Linear divider
2. Programmable voltage reference circuit
3. Signal switching circuit
4. Computer interface

The functions of these four sections are described in the following paragraphs.

The linear divider circuit is based around the AD 539 and has been configured in this case as a divider. The circuit is the same as the ratioing circuit.

The programmable voltage reference circuit was designed to accept a digital value and output a voltage proportional to the digital input and a standard voltage reference.

The circuit which translates a digital input into a analog voltage is a digital to analog converter chip (DAC 0806). This chip uses a temperature-compensated 2.5 volt reference diode. The DAC chip works on the R-2R ladder principle and hence outputs a current which is proportional to the digital input. The current to voltage conversion is performed by a operational amplifier (EL 2020) configured as an inverting amplifier. This stage also provides for offset adjustment. Another inverting stage (LM 307) again inverts the signal.

The switching circuit uses open collector gates and small electromagnetic relays. The gates were used to design the switching logic and drive the relays. The relays actually carry video or reference voltages. Relays were chosen to carry the video signals rather than solid state switches because solid state switches have limited high frequency response and distort the signal they carry. Open collector gates (7407) were chosen because of their ability to pull up to 30 volts. The relays were designed to operate with 24 volts DC.

The computer interface is provided by a parallel port. The port was designed so that a parallel printer port of a IBM PC computer could interface with this circuit. The interface was designed using an 8 bit latch (74LS373). The data from the computer is latched by using other control signals provided by the computer. The complete switching logic is also under computer control via the computer interface.

5.4 THE SYSTEM AS A WHOLE: All these circuits were individually tested and later housed in a 19 inch industry-standard rack-mount box. The box contains all the components including power supplies. Thus this design provides a complete stand-alone system. All inputs and outputs are provided on the front panel for easy access. This provides added flexibility for routing the video signals through various combinations of the linear and non-linear transformations.

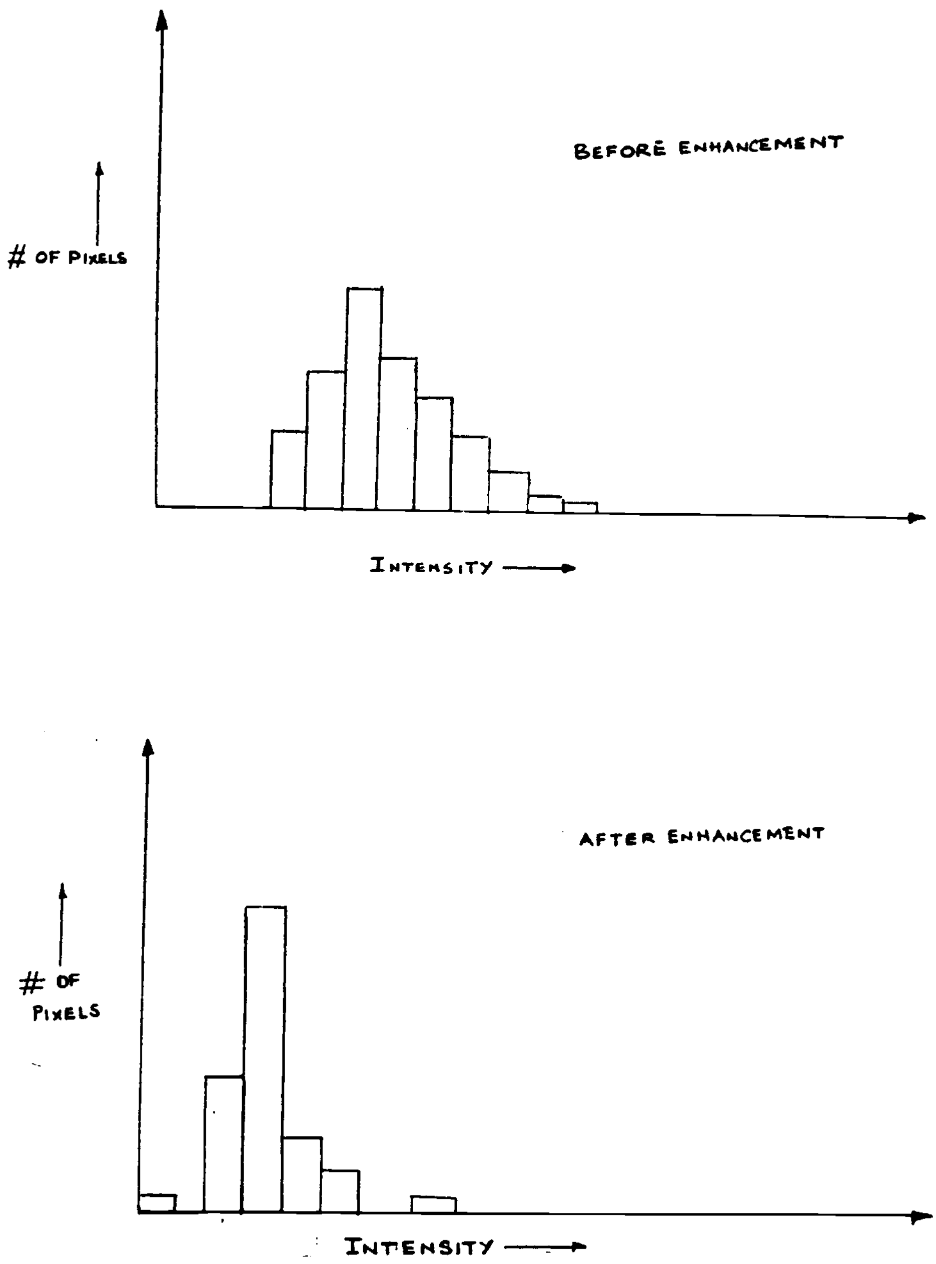


Figure 5.0. Histogram stretching, conceptual digital version.

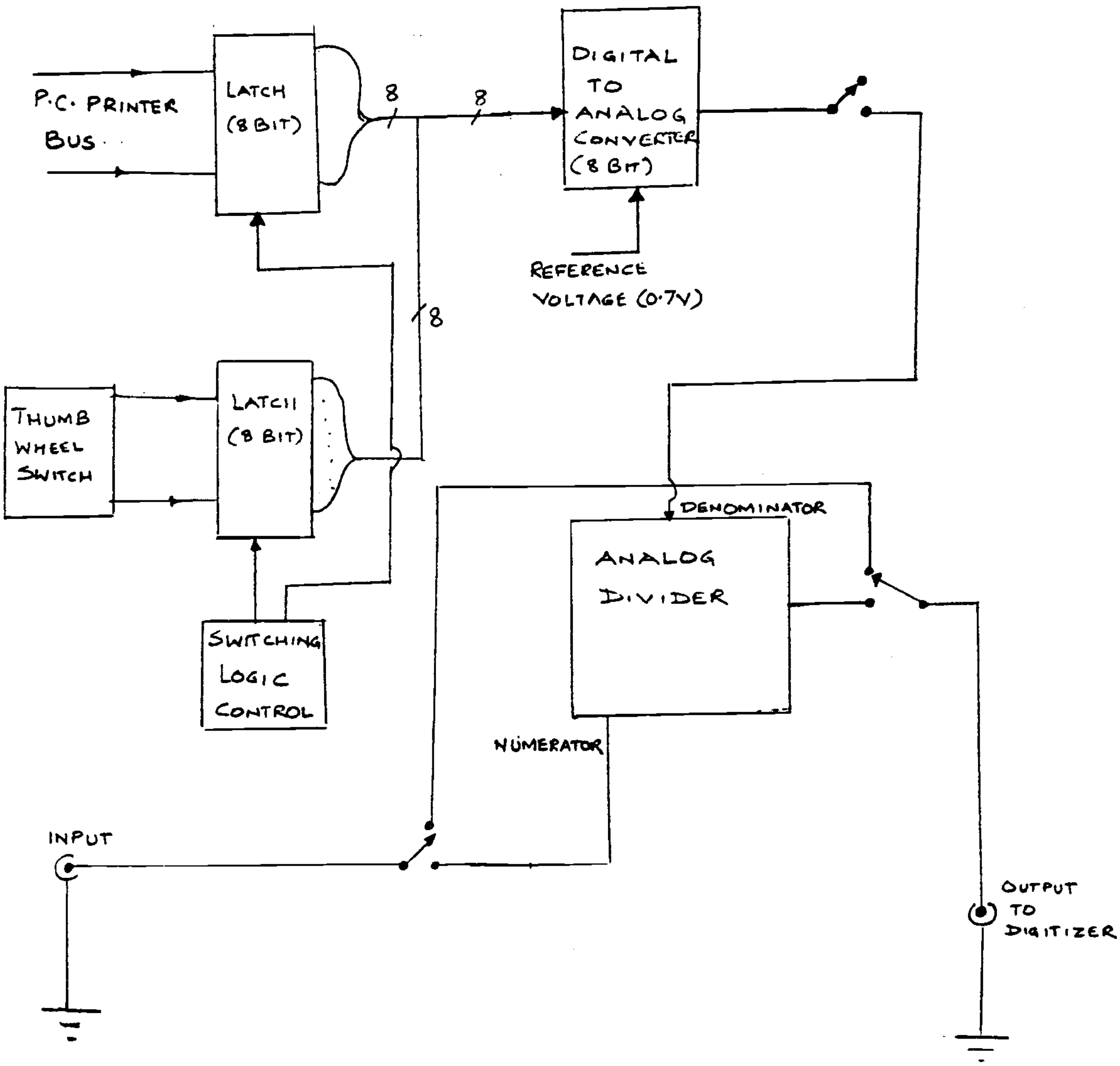


Figure 5.1. Architecture of contrast enhancement in the analog domain.

CHAPTER 6

RESULTS

6.0 INTRODUCTION: This chapter lists a series of tests performed on the designed hardware. These tests were conducted to acquire proof that the hardware was performing correctly. The test procedure will be described first and then the test results.

6.1 TESTING THE LINEAR TRANSFORM HARDWARE:

Image quality test: Images from a single wood surface were constructed using both the digital and analog transforms. Subjective assessment of these images found the analog version images to be clearer (Figure 6.0).

Noise test: The analog transforms are subjected to a single analog to digital conversion (A/D), in contrast to the digital implementation which involves one conversion for each color signal used and therefore should exhibit less A/D conversion error or digital noise. This premise was tested by constructing images of a uniform, saturated orange surface and comparing histograms of both transform methods. The analog histograms consistently exhibited fewer intensity levels than the digital ones (Figure 6.1) and are a measure of the greater variation due to the compounded A/D conversion errors. This explains the increased clarity of the analog transform images in Figure 6.0 .

A similar test was carried out on a wood surface image. The histograms obtained in this case are shown in Figure 6.2. The histograms have I(1) mapped into the red color channel, I(2) mapped into the green color channel and I(3) mapped into the blue color channel. This test indicates that the histograms are almost the same. This indicates that the hardware performs the required transforms. To further test the accuracy of the transforms obtained from the hardware, pixel analysis indicated that the values obtained from the analog and digital versions were within +/- 1 gray scale difference.

Speed test: This test was performed to determine if the hardware version of the linear transforms processed at real-time speeds. This test was performed by subjecting the analog and digital versions of the transforms to an image with a sharp edge in it. Transitions of pixel values were noted across the edge. The digital and analog versions had two pixels associated with the sharp transition edge. This indicates that there is no significant time delay associated with the analog hardware. The only processing time taken by the hardware is the propagation time delay of the operational amplifiers which is negligible when compared to the digitizer's sampling speed. Further, it was possible to perform all the linear transforms in a parallel processing fashion, which again increased processing speed when compared to the digital or software version. The digital or software version took around 3 seconds to perform all the transforms.

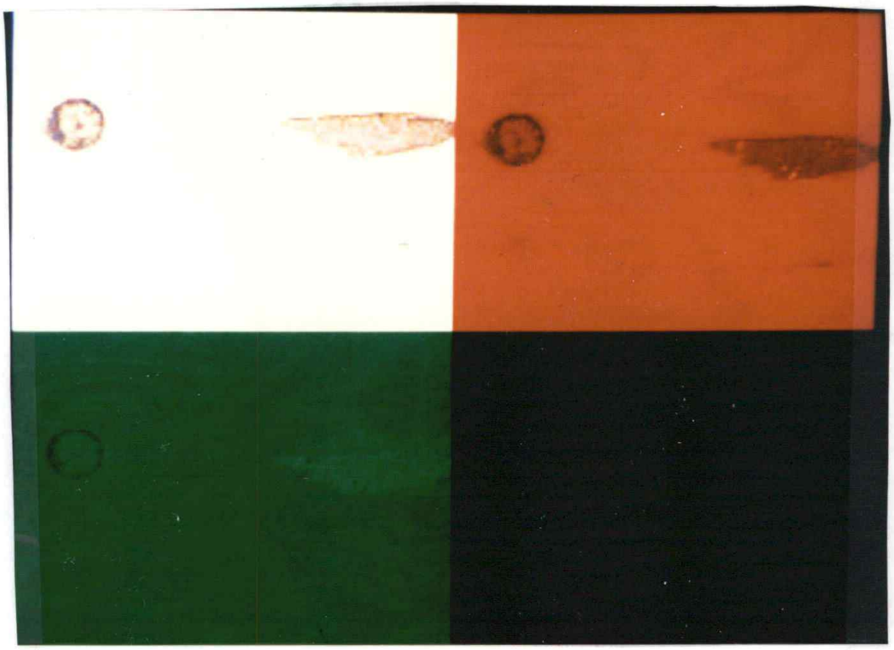
6.2 TESTING THE NON-LINEAR TRANSFORM HARDWARE:

Contrast enhancement: The only test performed subjected the contrast enhancement hardware to an image of wood surface with blue stain fungi. This circuit has good ability to enhance this particular feature. Figure 6.3 shows the raw image, the image transformed by the linear transform I(2), and the enhanced image. Figure 6.4 shows the histogram of this image before and after contrast enhancement. The figures clearly indicate the circuit's ability to stretch histograms.

Ratioing: The tests performed on the ratioing circuit indicated that it performed the poorest as compared to the other circuits. The ratioing circuit was designed for intensity normalization. Tests were carried out on this circuit by giving the numerator and denominator signals from the color and intensity channels (linear transforms I(1) and I(2)) respectively). Pixel by pixel analysis was carried out to ascertain if the circuit was performing its mathematical operation (division). The pixel analysis indicated that the circuit did not accept signals lower than 50 millivolts. The circuit otherwise performed at real-time speeds and had the maximum noise content when the ratio approached unity (numerator to denominator).

When the tests were carried out, the value of unity corresponded to a gray scale value of 25 (5 bit digitizer).

A



B

Figure 6.0. Image quality of linear transforms.

(A) analog (B) digital

Red: I(2), Green: I(1), Blue: I(3)

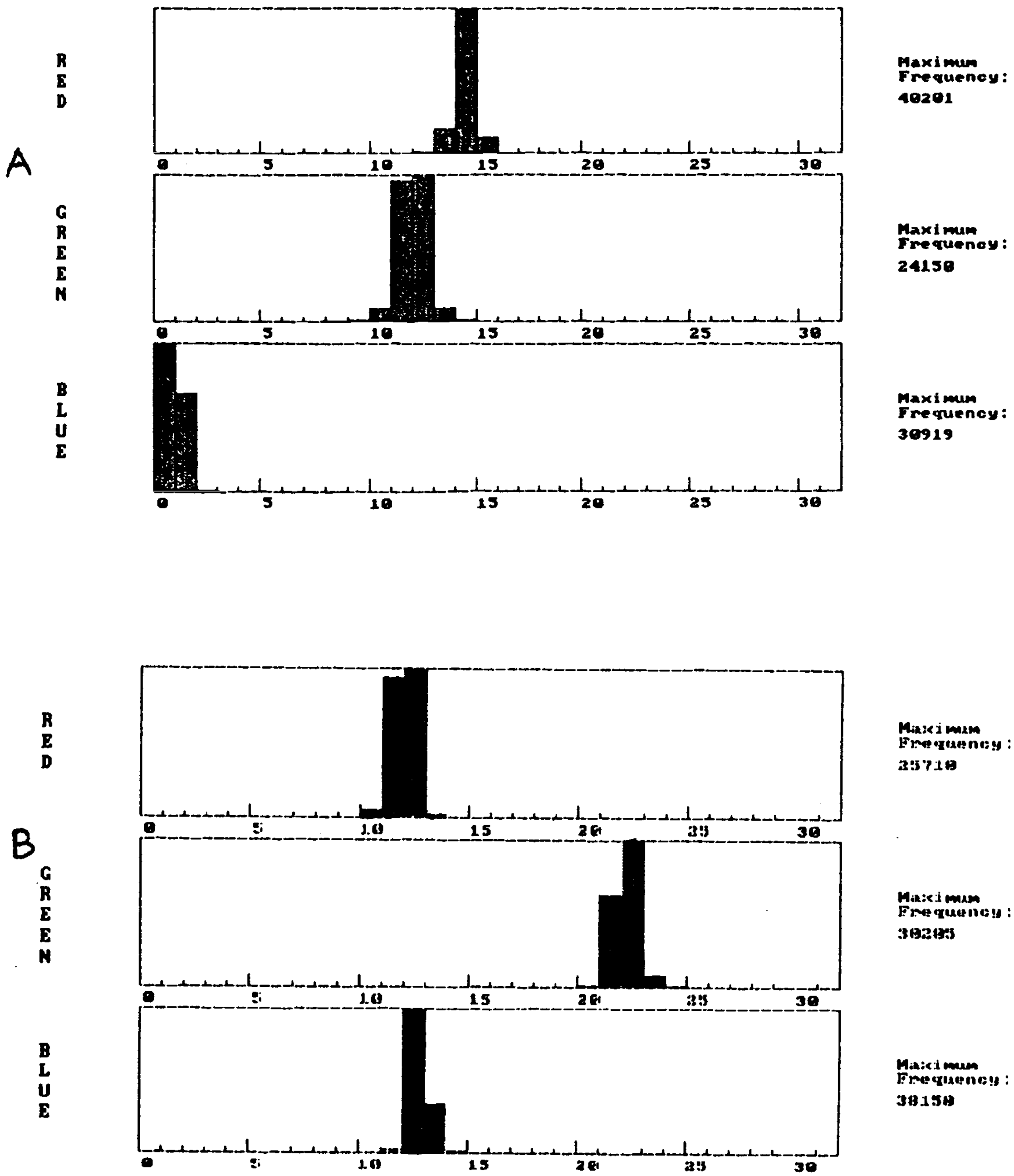


Figure 6.1. Histograms of saturated orange surface.

(A) analog (B) digital

Red: I(2), Green: I(1), Blue: I(3)

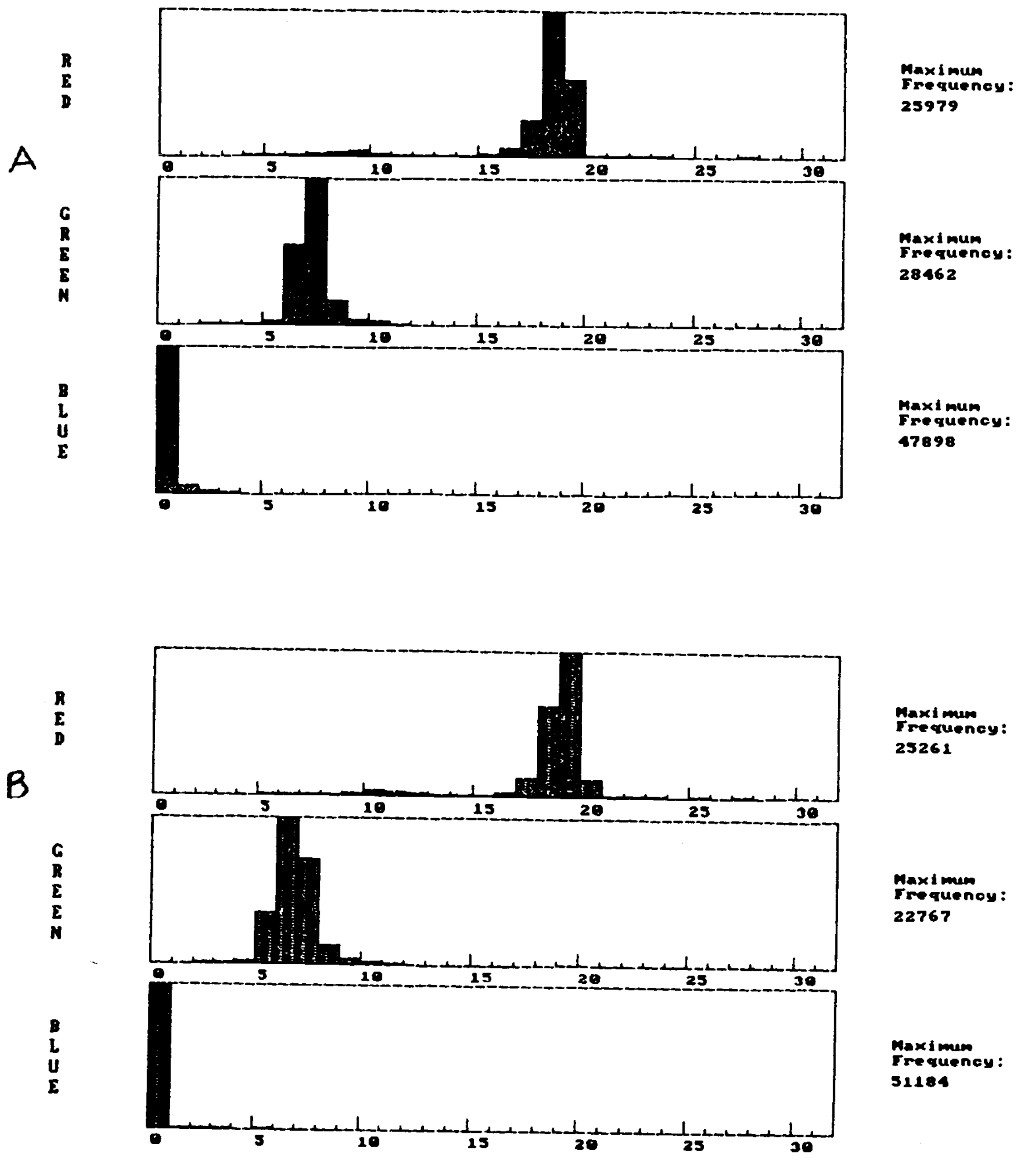


Figure 6.2. Histograms of wood surface.

(A) analog (B) digital

Red: I(2), green: I(1), Blue: I(3)

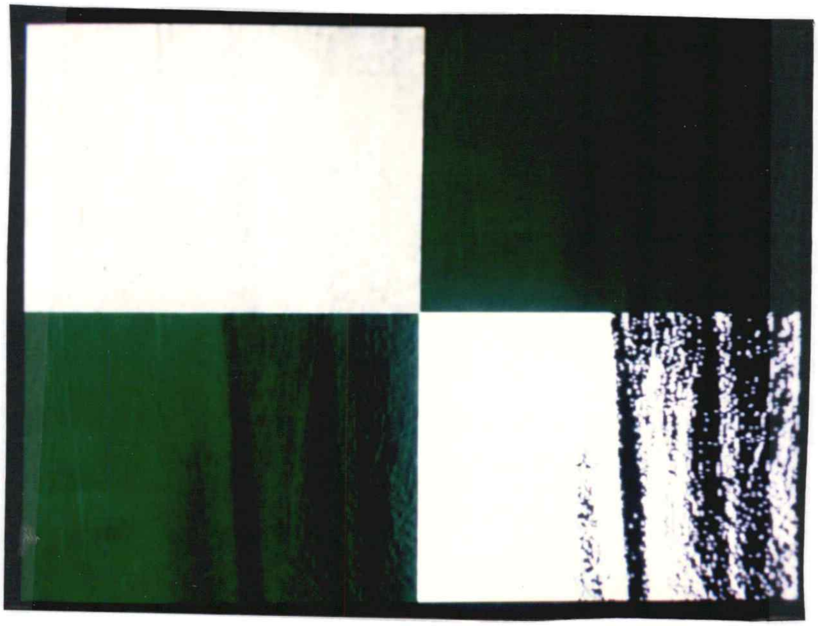


Figure 6.3. Contrast enhancement.

Top left: Actual image (raw R, G, B).

Top right: Image transformed by linear transform I(2).

Bottom left: contrast enhanced image.

Bottom right: Thresholded image showing blue stain.

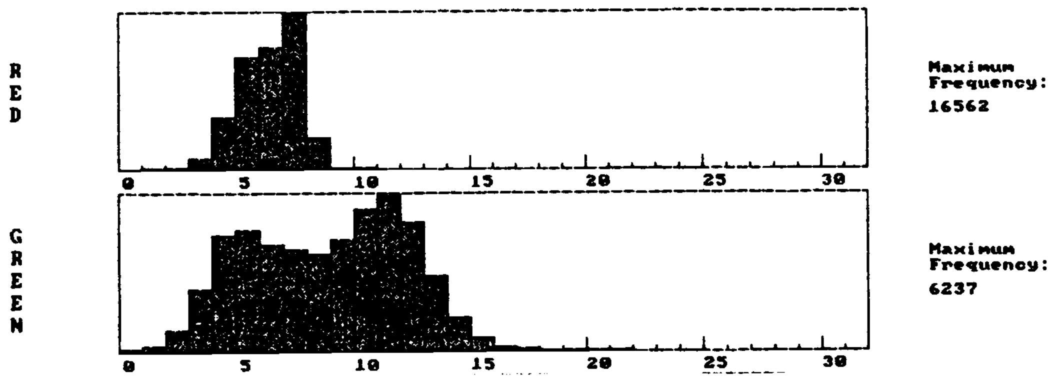


Figure 6.4. Red: Histogram of linearly transformed image prior to contrast enhancement. (linear transform I(2) = (R - B))

Green: Same image's histogram as red but after contrast enhancement. (see Figure 6.3.)

CHAPTER 7

CONCLUSIONS AND DISCUSSION

The results obtained indicate that the analog processing method proved quite effective in this application especially in terms of speed and cost. Certain points to note are:

The hardware designed in this application is analog circuit based and requires frequent calibration check.

The analog linear transforms cut-off values which are less than zero, if values which are less than zero or negative are to be observed then a off-set has to be provided.

The results seem to indicate that linear transforms have better noise characteristics. That is noise generated in linear transforms is very low.

Non - linear transform circuits are unstable when compared to linear transform circuits. This instability is in terms of repeatability.

These facts are quite well supported by the literature available on analog circuits which perform such operations and was not unexpected. One method possible to eliminate frequent calibration checks is to have a circuit which periodically performs calibration checks and performs corrections.

Further developments possible using such analog circuits is possible if high accuracy and high speed devices which perform mathematical operations such as square root, cube etc. are made available.

One immediate possibility is implementing the Intensity, hue, and saturation transform in the analog domain. This method would give real time operating speeds and reduce hardware cost.

CHAPTER 8

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APPENDIX

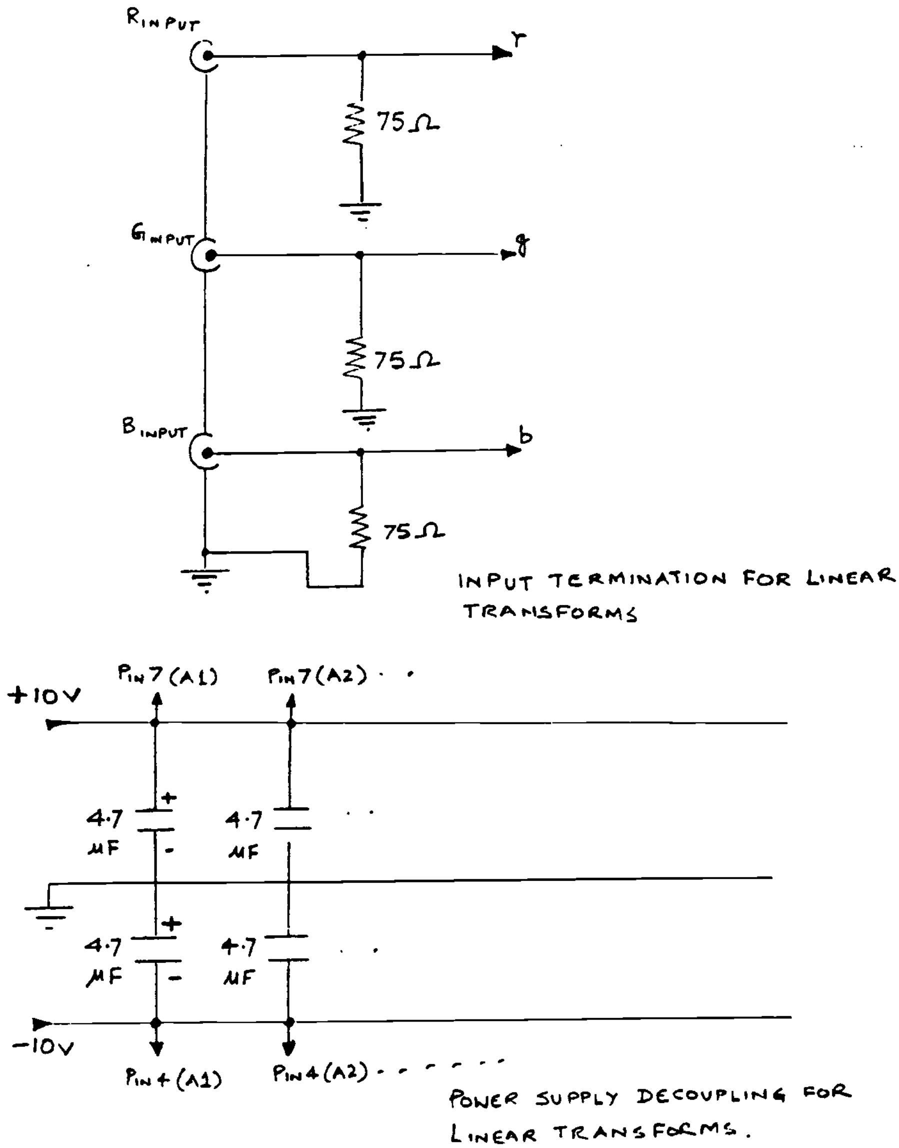
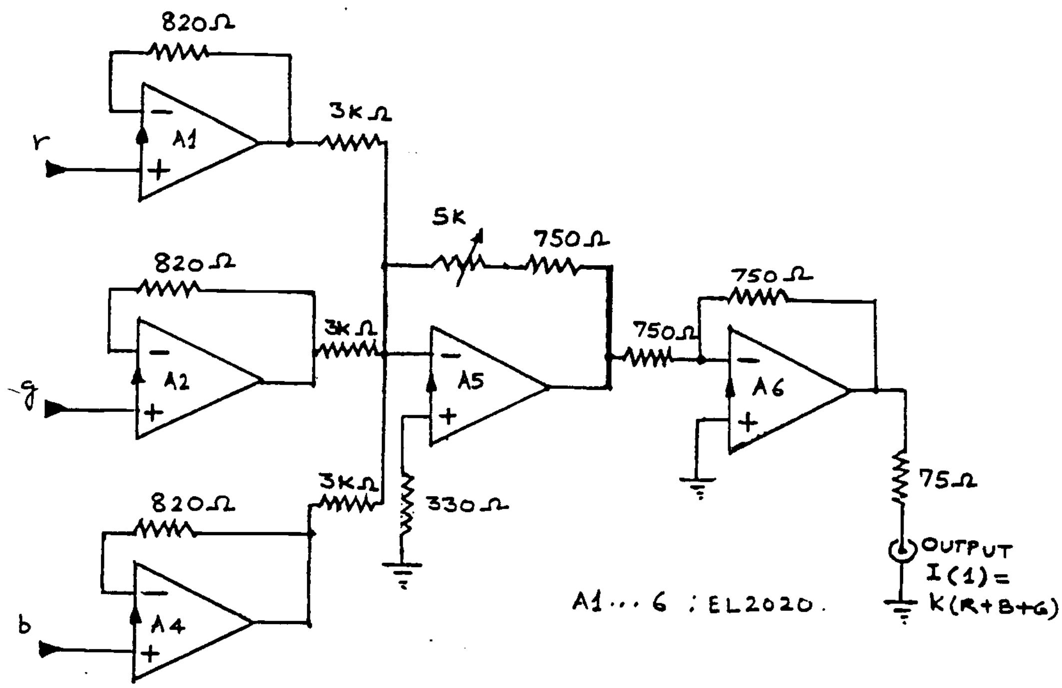


Figure A.1 linear transform circuit diagram.



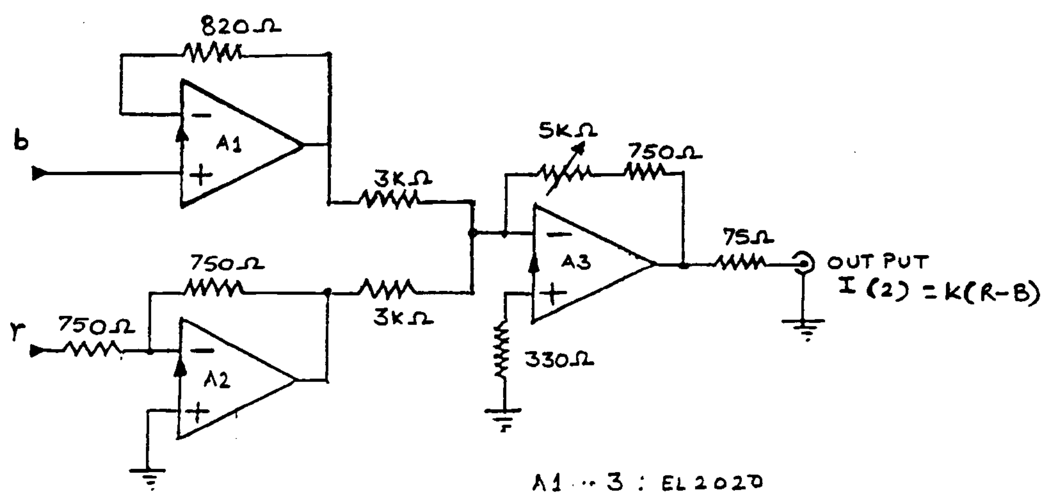


Figure A.2 linear transform circuit diagram.

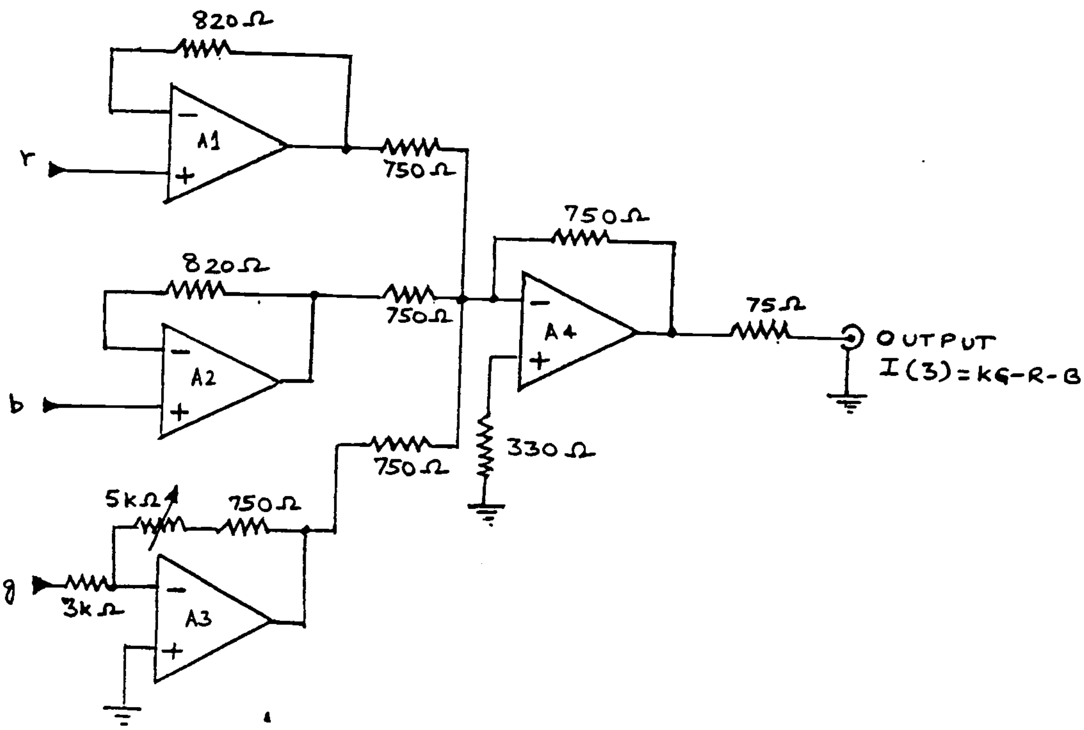


Figure A.3 linear transform circuit diagram.

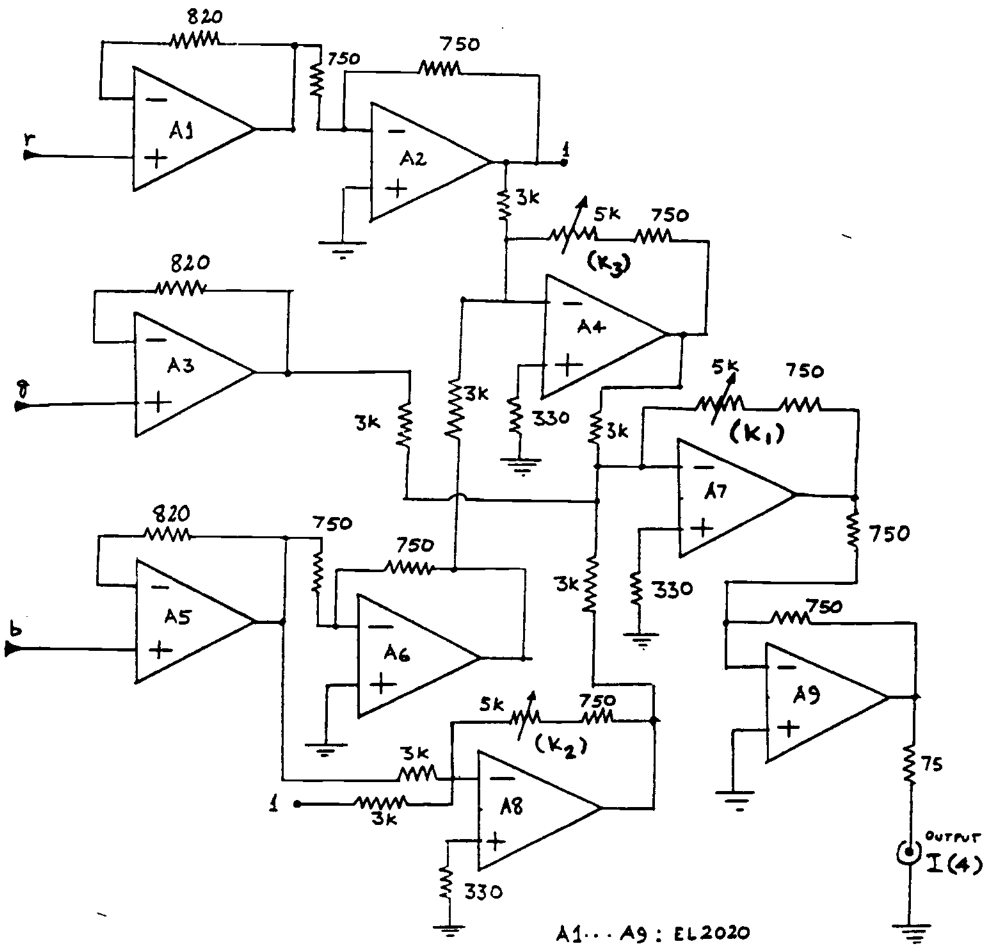


Figure A.4 linear transform circuit diagram.

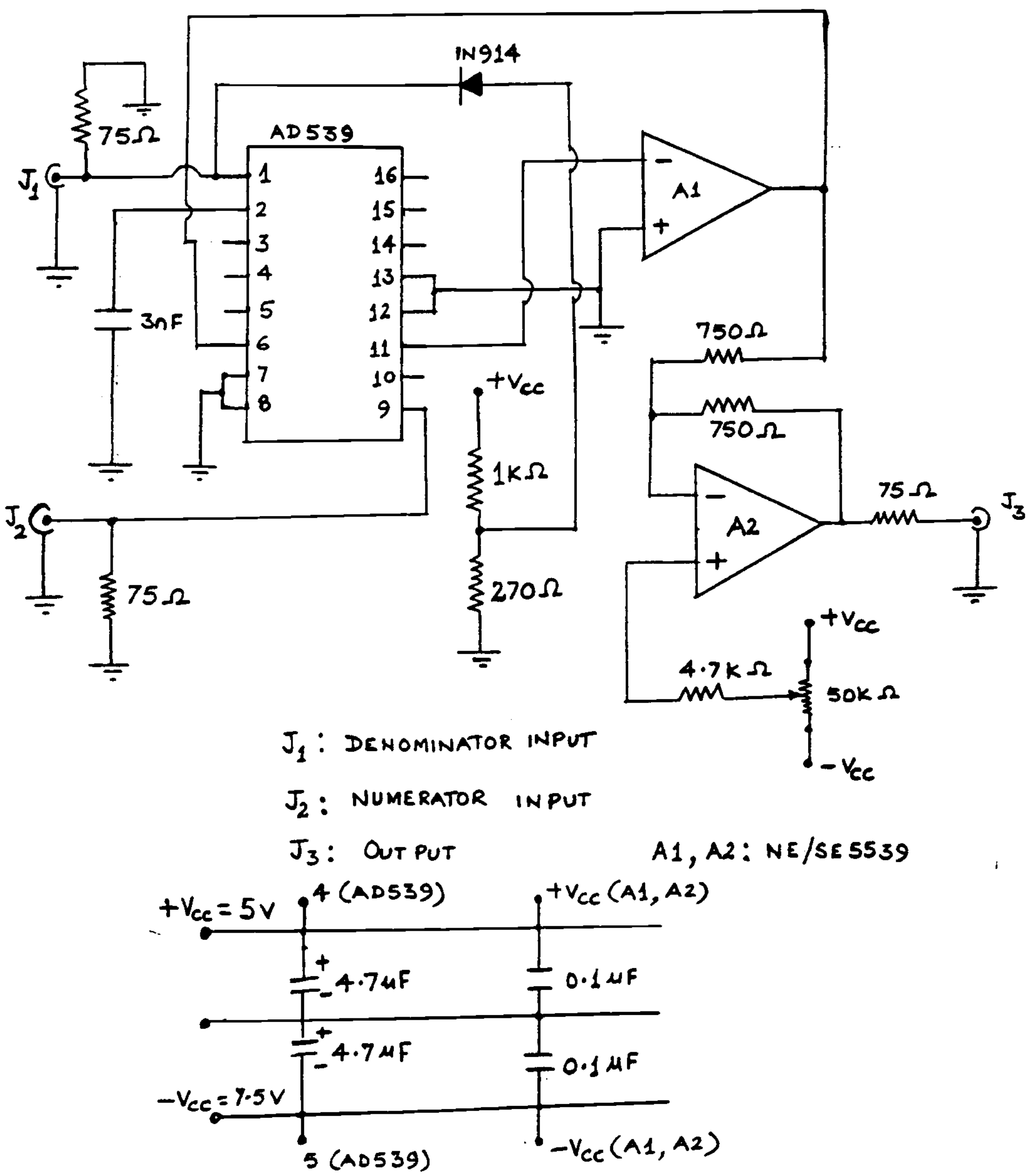


Figure A.5 Analog divider circuit diagram.

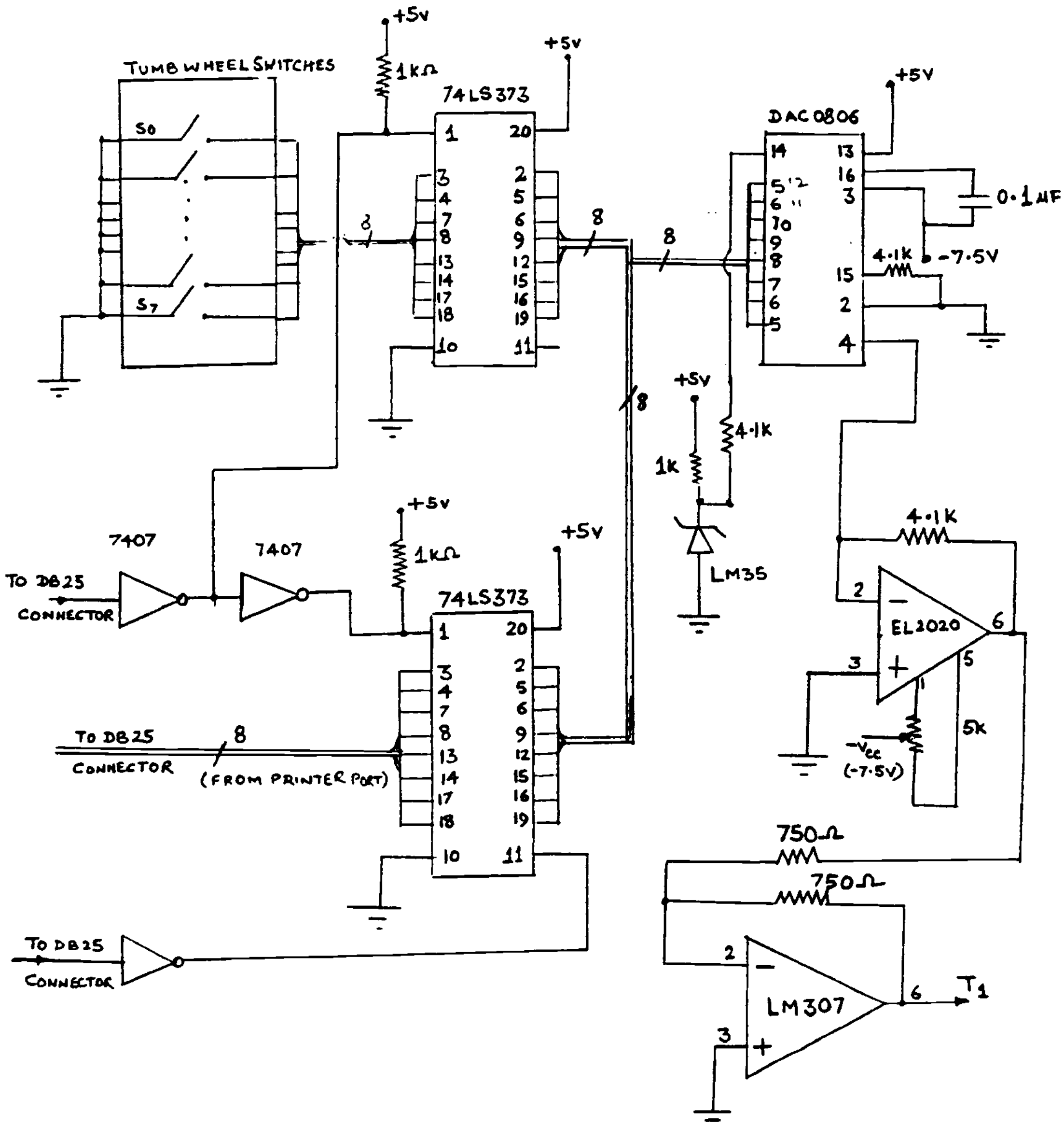


Figure A.6 Contrast enhancement circuit diagram.
(continued on next page)

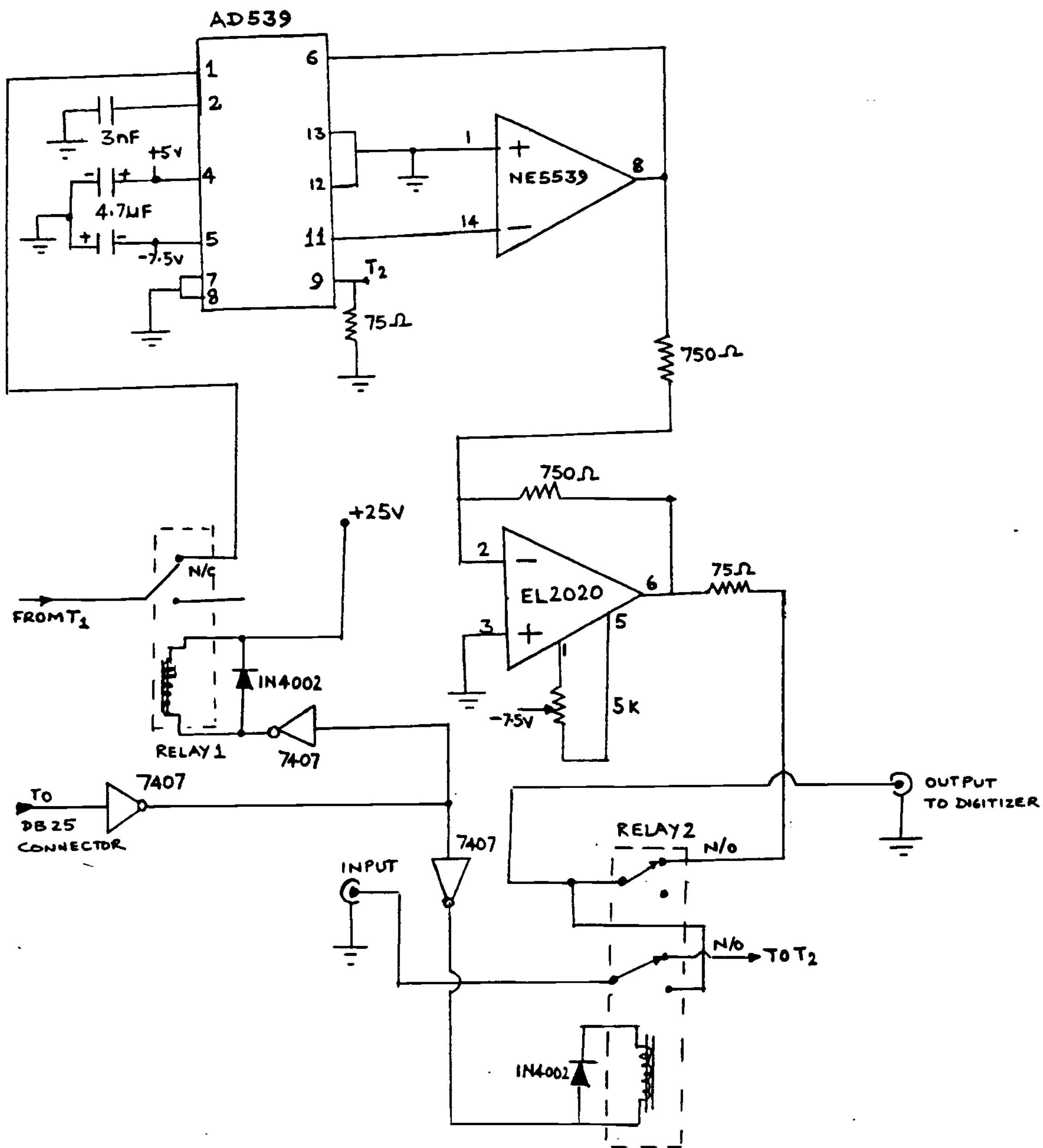


Figure A.7 Contrast enhancement circuit diagram.
(continued from Figure 3.0)