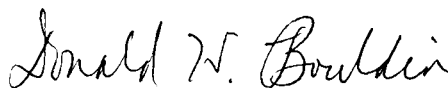


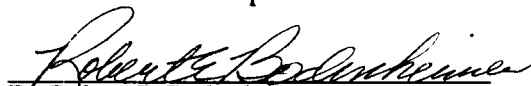
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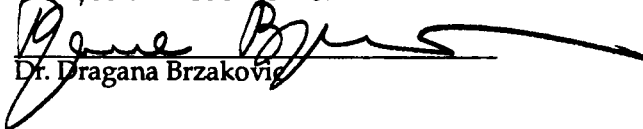


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THE DEVELOPMENT AND IMPLEMENTATION OF A MACHINE VISION SYSTEM FOR
MEASURING PERFORATION REGISTRATION OF POSTAGE STAMPS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Shaun Scott Gleason
May 1992

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ABSTRACT

An on-press machine vision system was developed and implemented that measures the perforation-to-image registration of postage stamps to 0.001-in. accuracy through the use of specialized image processing algorithms and high-speed hardware. The system development can be divided into two separate stages: (1) algorithm development and (2) hardware implementation.

During the development of this perforation registration system (PRS) several different measurement techniques were evaluated to solve the general problem of locating an object in a digital image to subpixel accuracies. The approach presented uses separate techniques to locate the stamp image and the position of the perforation borders. All of the investigated measurement techniques are presented, and the algorithms used in the final PRS are described in detail. The position of the stamp image is found by fitting a three-dimensional paraboloid to a normalized correlation surface to locate the stamp image to a 1/8-pixel accuracy. A separate algorithm used to locate the perforation borders to $\sim 1/16$ of a pixel is based on a least-squares fit of a line through the centers of the horizontal and vertical perforation borders. A unique image acquisition system is presented that is implemented by using front and back illumination by strobe lamps that freeze the motion of the stamps passing by a charge-injection device camera at a rate of 400 ft/min. The registration algorithms are implemented in a combination of specialized image processing hardware and a general-purpose vector accelerator that allow measurements to be made at a rate of 7 Hz. All of this hardware is under the control of a supervisory host computer.

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Chapter 1

Introduction

The Bureau of Engraving and Printing

Background

The Bureau of Engraving and Printing (BEP) is the official printer of U.S. Government securities, of which 93% are Federal Reserve Notes and U.S. postage stamps. Annual production numbers for these security documents are around 40 billion, which include 32 billion postage stamps according to BEP. The BEP is different from many government agencies in that it receives no annual business operation appropriations. It is privately funded by sales of security documents. This requires that BEP run its operation in a manner similar to that of a private business by constantly improving quality and producing products as efficiently as possible.

BEP is the sole printer of legal Federal Reserve Notes, but it still must keep the quality high for reasons such as counterfeit deterrence and building confidence of U.S. citizens in their money supply. However, BEP is not the sole producer of U.S. postage stamps. The U.S. Postal Service also purchases stamps from American Bank Note Company, United States Bank Note Company, KCS Industries, Inc. and several other commercial printers that produce stamps. Prior to 1894, stamp production was done by private industry under government contract (Funk and Wagnall 1979). Over the last few years BEP has seen their contribution to the U.S. Postal Service annual stamp supply fall from above 90% mainly because of an increased market share for commercial printers. BEP would like to increase production speed and improve quality to be able to continue to support its operations through stamp sales to the U.S. Postal Service.

One other motivation for improved quality is the drive for philatelic-quality stamps. Several million stamp collectors buy stamps from the U.S. Postal Service and keep them as collectibles. This represents pure profit for the Postal Service because stamps purchased by collectors never enter the mail-stream. Hence, the Postal Service sets extremely high standards on the stamps issued in hopes that collectors will purchase them. One of the key factors in a philatelic-quality stamp is the perforation-to-image registration, or how well the perforations borders are aligned with the stamp images. A philatelic-quality stamp has a perforation-to-image registration that is

within 0.007 in. of the designed position. For a stamp to be acceptable for use by the general public for mailing, this registration has to be within ~ 0.014 in. of the specified position.

Stamp Production

The stamp printing process will not be described in detail, but some background is necessary to understand some of the problems discussed later. Stamp production is a complex process which involves several different types of printing such as intaglio and offset printing. Multiple colors for stamp images are laid down by separate rollers in the printing press, which introduces the possibility of color misregistration where all of the colors are not overlapped in the desired position. After all of the ink is transferred to the stamp paper, the stamps are first run through an oven to dry the ink and then around refrigerated rollers to cool the paper down before it is collected onto one large spool. These temperature variations can cause significant stretching and/or shrinkage of the stamp paper, depending on the initial moisture content.

A typical finished roll (or web) of printed stamps can be 20,000 ft long, consisting of as many as 10,000 continuous sheets of stamps. The width of the roll depends on the size of the particular stamp being printed. One sheet typically has four panes of 100 stamps each and is ~ 2 ft² as shown in Figure 1.1.

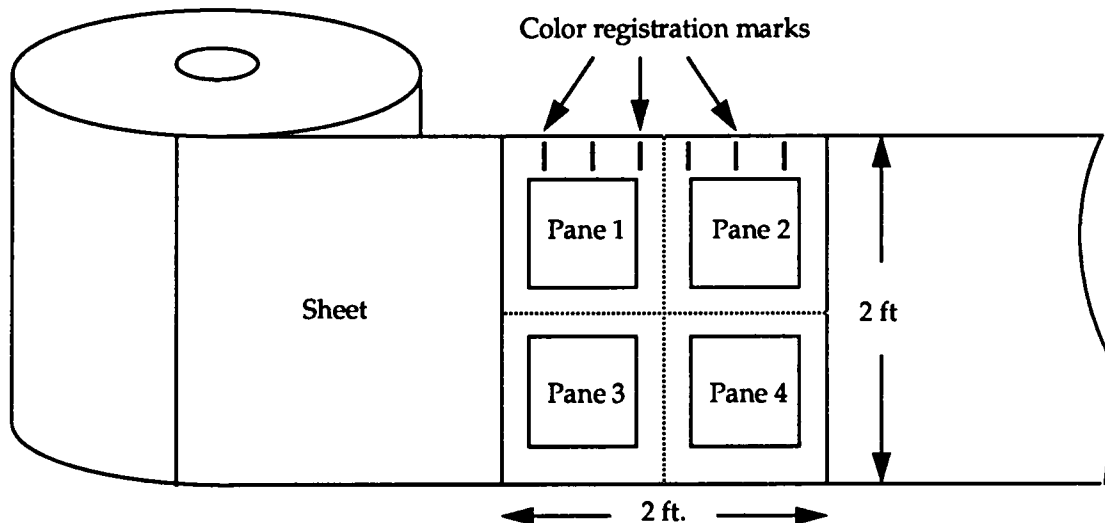


Figure 1.1. Sheet of stamps within a typical printed roll.

Notice the color registration marks that are printed along the edge of the sheet, which are used later in the process. This finished roll is then transferred to a separate press called a *perforator/sheeter* where the stamps are perforated, cut into separate sheets, and stacked. A simplified diagram of a perforator press is given in Figure 1.2.

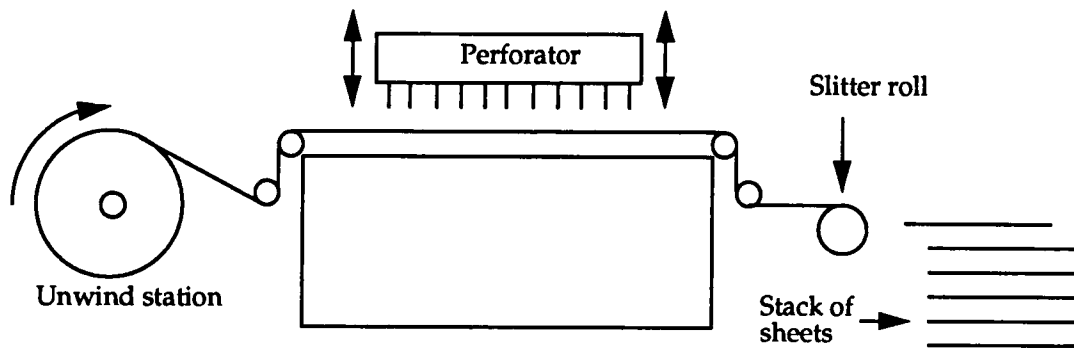


Figure 1.2. Perforator/sheeter press.

The roll is unwound and fed into the perforator section of the machine. The perforator is a large bed of nails, or dyes, which is raised and lowered in synchronization with the stamp motion. Each time the bed of nails falls, one-half of a sheet (two panes) is perforated. The motion of stamp material into and out of the perforator is continuous. Accumulators at the input and output of the machine are used to stop the motion of material inside the perforator for a split second while the nails perforate the stamps. The synchronization of the perforator to the moving stamp web is accomplished by placing a fiber-optic mark sensor over the edge of the stamp paper where color registration marks are printed. By triggering on the output signal of the mark sensor when it detects color registration marks, the system controls the position of the perforator in the direction of web travel. A similar technique is used to control the lateral position of the perforator with respect to the stamp material. Stamps can be perforated at a sustained rate of 400 ft/min.

The Perforation Registration Problem

In the process of stamp printing and perforating, several problems could cause misalignment of the perforator, or bed of nails, with the borders in between the stamps. Statistics show that the problem of perforation-to-image misregistration is the number one reason for spoilage at BEP. The

major cause of misalignment of the perforations with the image is stamp web stretching and shrinkage caused by a combination of the initial moisture content of the paper and the heating and cooling process it goes through after printing. The pattern of dyes in the perforator must be created by placing individual nails in rows and columns at a spacing based on the master drawings of the stamp format being perforated. The position of the dyes cannot be dynamically adjusted while stamps are running through the machine. If the printed pattern of stamps changes size significantly, it is impossible to perforate the stamps correctly. The current system controls the relative position of the paper to the perforator by sensing the color registration marks printed along the side of the stamp web. This may allow stamps very close to the registration marks to be perforated accurately, but stamps on the opposite side of the web can be so far out of registration that the perforations cut through the middle of the stamp image. Perforation-to-image misregistration also occurs when the current registration mark being used as a trigger for the perforator/sheeter happens to be slightly out of alignment with the other colors. Because the perforator is controlled by the position of one single color mark, one color controls the overall fit of the perforation pattern to the stamp images.

Another problem with the current system is that no historical statistics have ever been recorded concerning perforation-to-image registration. The problem has been only spot-checked. No way exists to analyze possible correlations between historical perforation problems and certain printing processes, specific types of stamp paper, one particular shift of operators, etc. A historical base of information could allow the most frequent causes to be found and corrected.

PRS Requirements

The following system requirements for an on-line perforation registration system (PRS) were generated on the basis of the problems with the process described above.

- Measure the perforation-to-image registration to 0.001-in. accuracy.
- Use part of the stamp image itself as a reference point (not a color registration mark).
- Make the measurement on the moving stamp web on an existing press.
- Produce two measurements per sheet at the maximum operating speed of the perforator (400 ft/min).
- Log the registration data for historical purposes.

- Provide the ability to make the measurement on any stamp format (existing or planned).
- Create a suitable operator interface for PRS setup and useful display of registration information.

Registration Approach

A variety of stamp formats and issues must be handled by the PRS. The stamps with well-defined borders can be centered by making sure the distances from the four sides of the image to the perforation boundaries are equal. Other formats do not have a specific border, and the centering of the image within its perforation borders is a subjective process. Figure 1.3 shows these two different situations.

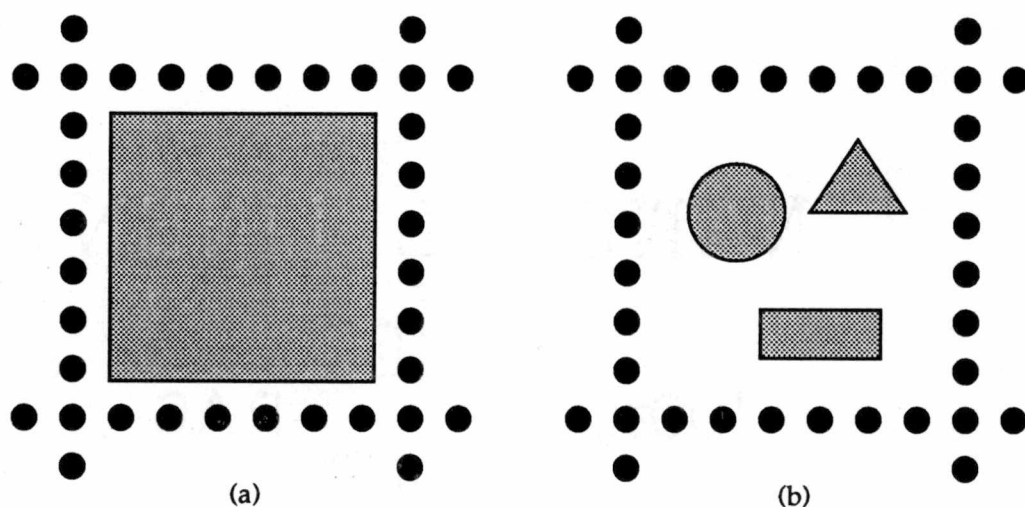


Figure 1.3. Objectively and subjectively centered stamps.

The stamp in (a) can be centered objectively, but (b) must be centered subjectively.

Because optimal stamp image position is sometimes subjective and can vary across different formats, the PRS had to be a reference-based system. Regardless of the technique used for registration measurement, the results had to be compared to the results of the same operations on a subjectively chosen reference image because a computer does not have the capability to make a subjective measurement. This section describes the approaches and corresponding algorithms currently being used to extract the perforation-to-image registration measurement. The process can be divided into four steps:

- image location,
- perforation border location,
- relative distance measurements,
- comparison to a known reference stamp.

The first step is the most challenging because of the irregularity of image features between different stamp issues. The technique used here had to be general enough to handle almost any stamp image, yet accurate enough to attain 0.001-in. accuracy. Several algorithms are presented along with some experimental results. The algorithm implemented in the final PRS is based on a least-squares fit of a three-dimensional paraboloid to the normalized correlation surface generated by correlating the test stamp image with a given reference image. The development and theory behind this algorithm will be presented.

In contrast to the unpredictable stamp images, the perforation borders are very regular in shape and relative position. The methods used to locate these borders takes advantage of their regularity to achieve high accuracies. This algorithm, which is based on a least-squares fit of a line through the perforation centroids along each border, will be discussed in detail.

Once the relative locations on the image and perforations are found in both the reference and test stamps, horizontal and vertical distances can be compared. The difference in these values is recorded in a database and displayed to the press operator in real time.

Hardware Implementation

Another challenging aspect of the PRS requirements is the speed requirements of making two measurements per sheet on a stamp web traveling at 400 ft/min. Given a typical sheet of stamps y 2 ft long, this translates into ~150 ms per measurement. The hardware used to achieve this goal employs three separate processors. The first processor is in the host computer and is used mainly for supervisory control and data management. The second processor is a reduced instruction set computer (RISC) processor in a vector accelerator module that executes specialized image processing functions. The third processor, a Motorola 68000, is part of a stamp synchronization device that allows the speed and timing of the PRS operations and image acquisitions be tied to the stamp web motion.

One group of hardware is designed for and dedicated to image processing applications. These

modules along with the acquisition system consisting of a charge-injection device (CID) camera, front and back illuminating strobe lamps, a video digitizer, and a fiber-optic mark sensor will be presented.

Chapter 2

Image Feature Registration

This chapter discusses various techniques for locating features in a digital image. An assumption is made here that the stamp images have already been acquired with a camera, digitized, and stored in memory. Image acquisition methods for the final PRS will be discussed in Chapter 3. Because the stamp images are unpredictable across different stamp issues, the technique chosen had to be general enough to handle a variety of image features. The perforations, on the other hand, are very predictable, and a very specific technique that takes advantage of their regularity was employed. Both of the algorithms used in the final system are presented, and some of the other algorithms that were tested during development, but did not meet the PRS requirements, are also presented because they could be useful alternatives under different circumstances.

One approach to locating the position of a feature in an image is through the use of a centroid technique. As will be discussed in this chapter, an advantage to using the centroid technique is that it can be used as a global technique and, therefore, will not be as sensitive to small local flaws or variations in the image. A second image processing approach to locate a unique image feature of the stamp is that of template matching. Template matching calculations between two images tell the degree to which the two features match each other. Two different template-matching algorithms are presented in this chapter.

For this image processing application, accuracy beyond the best integer pixel registration was desired, and an algorithm that interpolates to a fraction of a pixel was implemented. This type of algorithm accomplishes what is called *subpixel registration*. Several subpixel registration techniques that perform to varying accuracies and at different speeds will be discussed in this chapter.

Centroid Technique

Image Location

One promising global alternative for finding accurate subpixel shifts that was tested is the centroid technique. In this method, the center of mass of a reference digital image is calculated by first choosing an origin anywhere on the image. Then the sum of all the pixel gray-scale values multiplied by their horizontal (x) distances from the origin is calculated. This sum is called the *cen-*

tral moment, m_{10} , of the image and is used to find the x coordinate of the centroid (Rosenfeld and Kak 1982). To find the y coordinate, one must calculate the central moment, m_{01} . These central moments can be expressed as

$$m_{10} = \sum_x \sum_y (x - x_0) z(x, y) \quad (2.1)$$

$$m_{01} = \sum_x \sum_y (y - y_0) z(x, y) \quad (2.2)$$

where x_0 and y_0 are the pixel coordinates of the chosen origin. The centroid (x_c, y_c) of a digital image is found by dividing the first central moments by the simple summation of all of the pixel grey-scale values, m_{00} .

$$x_c = \frac{m_{10}}{m_{00}} \quad (2.3)$$

$$y_c = \frac{m_{01}}{m_{00}} \quad (2.4)$$

The value of the centroid is already given in subpixel form due to the nature of the calculation. If the centroid for the same feature in the test and reference images could be found accurately, the difference between the locations of the two centroids would be the subpixel shift needed to register the two features. A problem with the technique is that the area one wishes to find the centroid of must be thresholded from the background. For example, to find the centroid of the perforation, a mask must be created that allows the image of the perforations to come through while setting the rest of the image to zero (black). Any background pixel that has a value other than zero will cause the centroid to shift, so all of the extraneous information other than the specific area of interest must be nulled out. This can be accomplished at the perforations by using a backlight apparatus that will saturate the camera sensor where light passes through the perforation holes. This part of the acquisition system will be illustrated in the next chapter. The saturated pixel values can be thresholded because they have a gray-scale values higher than those of the rest of the pixels in the image. Finding the centroid of the stamp image presents a more difficult problem. Because the registration technique used must be robust enough for all different stamp formats and images, a way to consistently threshold the stamp image itself from the background had to be developed. A weighting function was implemented that accomplishes this task. The function is

$$I(x, y) = \frac{[i(x, y) - i_b]^2}{255} \quad (2.5)$$

where $i(x, y)$ is the intensity of the original image at the pixel (x, y) , i_b is the dominant background intensity of the image, and $I(x, y)$ is the intensity of the weighted image. The average background intensity is found by computing the mode of a histogram along a row or column of pixels in the image background. One can see that when a pixel intensity is near the average background intensity, it will be forced to zero in the new image by Equation (2.5). The pixel values which are far away in intensity from the average background value will be highlighted in the new image.

Figure 2.1 shows the 20th Universal Postal Congress stamp with line AB in the background area of the image.



Figure 2.1. Stamp image with column AB in background area.

The histogram in Figure 2.2 was found by considering all the pixels along line AB. The peak at i_b indicates the dominant background intensity used in Equation (2.5) to null the background.

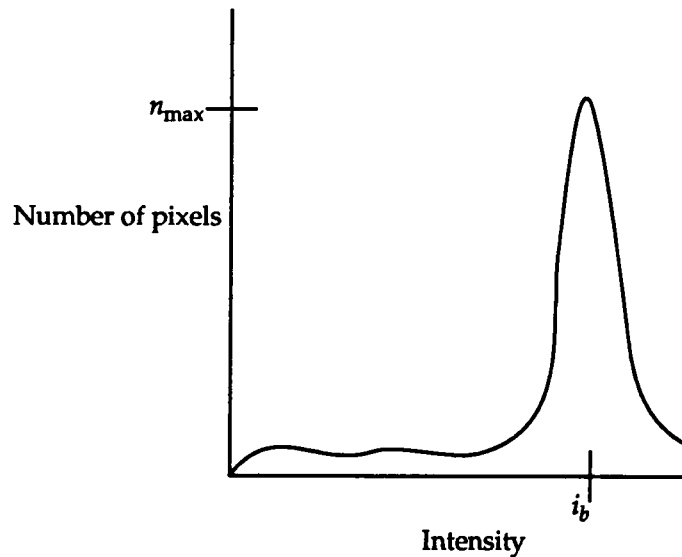
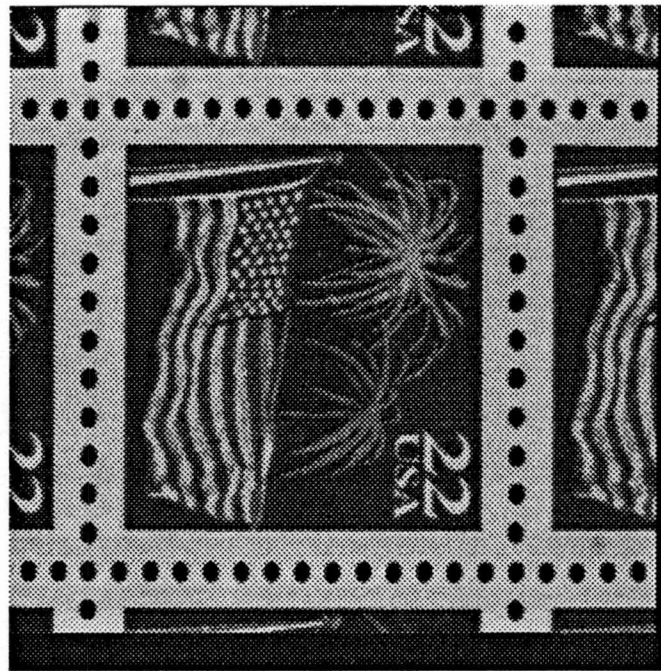


Figure 2.2. Histogram along one column of the image background.

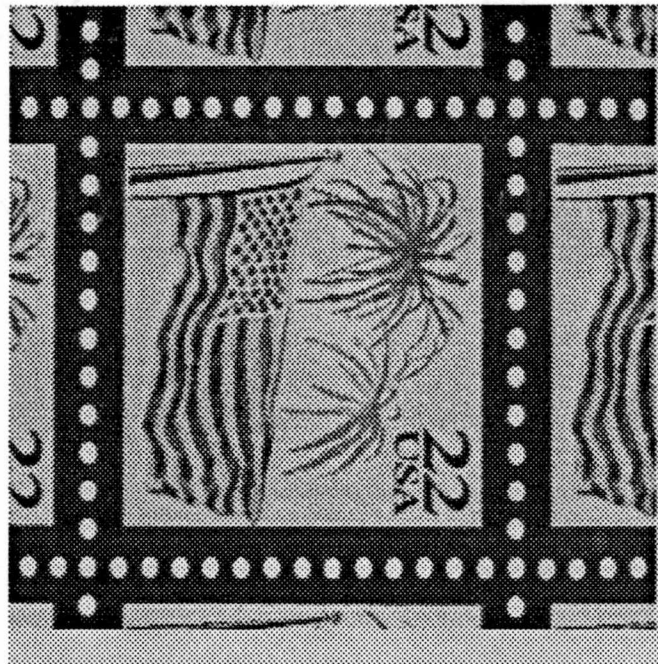
The images shown in Figure 2.3 show a before and after image of the Flag with Fireworks stamp using the weighting function in Equation (2.5). The perforations were also masked out of this image to produce a stamp image floating on a black background. Physical shifts of the image will then be equal to shifts in the centroid because the effects caused by background information shifting in and out of the field of view are eliminated. Also, the perforations will have to be masked out of the image to keep them from corrupting the centroid value.

Perforation Border Location

The centroid technique was also implemented to locate the position of the perforation border. A global method that uses the whole border was implemented to try to better approximate how the human eye would to measure the registration. A human would consider all of the perforations along one border in trying to determine the distance from the image to the perforation. The first step in the process is to locate the centroid (center of mass) of each individual perforation hole on the stamp image. Next, these centroids are grouped into horizontal and vertical borders on the basis of their relative (x, y) positions. The final step is to calculate the least-squares, best-fit line through all of the centroids of the perforations in one border.



(a)



(b)

Figure 2.3. Flag with Fireworks stamp images before and after weighting function.

The image in (a) is the original and (b) is after the weighting function is applied to the original. The image in (b) has zero background values.

Let the equation of the line of interest be of the form $y = mx + b$ and the centers of mass of the perforation holes along one border be $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$, where n is the number of perforation in one border. To completely describe the line, the values of the slope m and the y -intercept b must be found. Because more perforations are along one border (~ 20) than there are unknowns in the line equation (only two), this is an overdetermined system. To allow contribution of all of the centroids to the final line position, a least-squares technique was employed. Least squares (or linear regression) is based on the minimization of the error between the position of line $y = mx + b$ and the position of the perforation centroids that it is trying to approximate (Hurley 1987).

By creating the difference function, taking the derivative of that difference function, and setting it equal to zero, the expressions for m and b can be found to be

$$m = \frac{n \sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2} \quad (2.6)$$

and

$$b = \frac{\sum_{i=1}^n y_i \sum_{i=1}^n x_i^2 - \sum_{i=1}^n x_i \sum_{i=1}^n x_i y_i}{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2} \quad (2.7)$$

The line is used as the reference for the perforation border location as shown in Figure 2.4. All registration measurements are made as the perpendicular distance from some reference point in the image to the perforation line. This technique allows all of the holes along a border to contribute to the actual border position and also is immune to problems associated with interstitial spacing problems within the perforation border, which will be described in the next section.

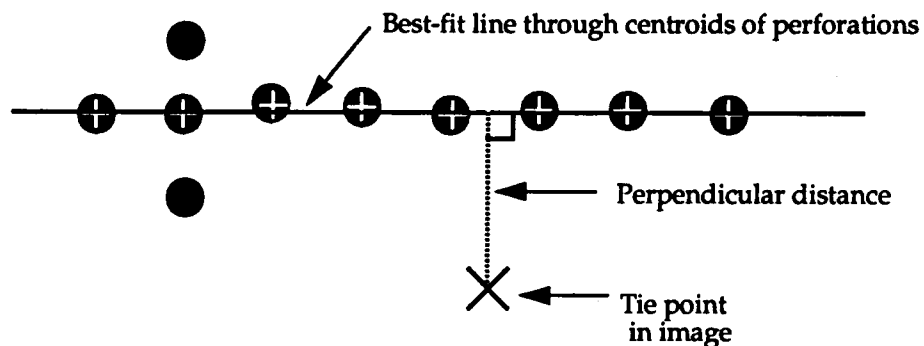


Figure 2.4. Least-squares fit to perforation border.

Template Matching Technique

A second technique tested during the PRS development is that of template matching. Consider a reference template of image data $R(x, y)$, and a test image search window $T(i, j)$ as shown in Figure 2.5.

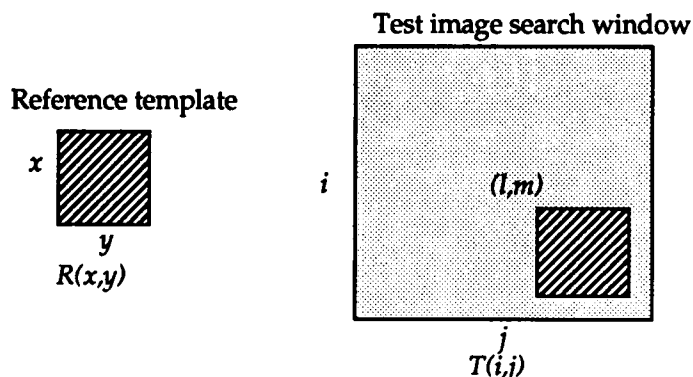


Figure 2.5. Template-matching concept.

One way to locate the feature of interest in $T(i, j)$ is to load the template $R(x, y)$ with the image data that represent the feature of interest. Then place $R(x, y)$ at every possible location on $T(i, j)$ and calculate the correlation, or degree of similarity, between the two. Depending on the type of correlation used, a maximum or a minimum correlation value will occur when the template lies directly on top of the matching feature of interest. The type of correlation can be as simple as a pixel-by-

pixel subtraction of the reference and test templates. An ideal match in this case would be zero.

The first step in the process of registering two similar images is to find the best whole pixel (or integer pixel) match. One way to accomplish this is to move a small window or feature of the reference image over the test image one pixel at a time and calculate the simple correlation between the two windows. The correlation will be a maximum when the reference window lies directly on top of its match in the search window. The size of the reference window should be as small as possible for maximum computation speed, but at the same time enough detail must exist in the window to uniquely identify that specific part of the image. The accuracy to which this method locates the feature is dependent on the pixel size of the acquisition system. The typical pixel size of an acquired stamp image in the PRS is between 3 and 4 mils, so the accuracy is limited to that range.

SSDA Fast-Correlation

The first algorithm implemented in the PRS is called a *sequential similarity detection algorithm* (SSDA) and is an efficient way to do a coarse search for similar features (Barnea and Silverman 1972). The main idea behind the algorithm is that when two image patches are registered perfectly in the spatial domain, the difference between the two will be due only to noise in the acquisition system and printing variations. This fact is used to create an error threshold curve $E_t(n)$, which serves as an error limit. Accumulated error functions are generated by subtracting corresponding pixels in reference and test templates in a random order as shown in the equation

$$E(n) = \sum_{\text{rand}(x)} \sum_{\text{rand}(y)} |R(x, y) - T(i + x, j + y)| . \quad (2.8)$$

$E(n)$ is the accumulated error function after n subtractions have taken place, $R(x, y)$ is the reference intensity at pixel (x, y) , and $T(i + x, j + y)$ is the corresponding test intensity in the search area where (i, j) is the position of the upper left corner of the reference window within the search area as shown in Figure 2.5. When the error threshold E crosses E_t , the algorithm stops and moves the reference template R with respect to the search area (increments i and j) and repeats the subtraction process. E_t is chosen unique to the situation such that the error at the registration pixel will follow (but stay just below) the curve. It is based on the fact that the noise is uncorrelated and random and can be represented by the function

$$E_i(n) = \frac{1}{\lambda} e^{-n\lambda} \quad (2.9)$$

where λ is the mean of the image noise and n is the number of points being considered (Papoulis 1984).

Only a few points of misregistered image patches need to be subtracted before the accumulated error between the images shoots above the threshold. Figure 2.6 illustrates the accumulated error versus the number of points correlated for a misregistered and a registered image. The nine accumulated error function curves in the graph were generated by moving the test template to the eight pixel locations surrounding the best match and then placing R directly on its match within T at the point $i = l$ and $j = m$. Notice that the error function generated at the registration point stays a significant distance below the rest of the functions. About 55 subtractions were considered before the registered error function crossed the threshold compared to about 25 or fewer points for the eight surrounding points.

Figure 2.7 is a 3-dimensional plot where the bottom plane is the (x, y) position of the reference template R within the test template T , where a correlation is being calculated. The vertical axis represents the number of points considered by the SSDA. The spike in the center of the surface occurred at the registration point where the two images matched the best. The smaller peaks represent the other nonregistered points.

The shape of the threshold function in Figure 2.6 was modeled on the basis of approximations of the noise in the system, λ , and changed several times to try for optimal results from the algorithm. The variety of different image features (any existing or potential stamp format) prevented the algorithm from returning the optimal match location every time. For this reason a second algorithm was investigated.

Normalized Correlation

Normalized correlation is a much more robust template-matching algorithm than the simple subtraction technique. It works well even in the presence of lighting variations and small local flaws around the feature of interest.

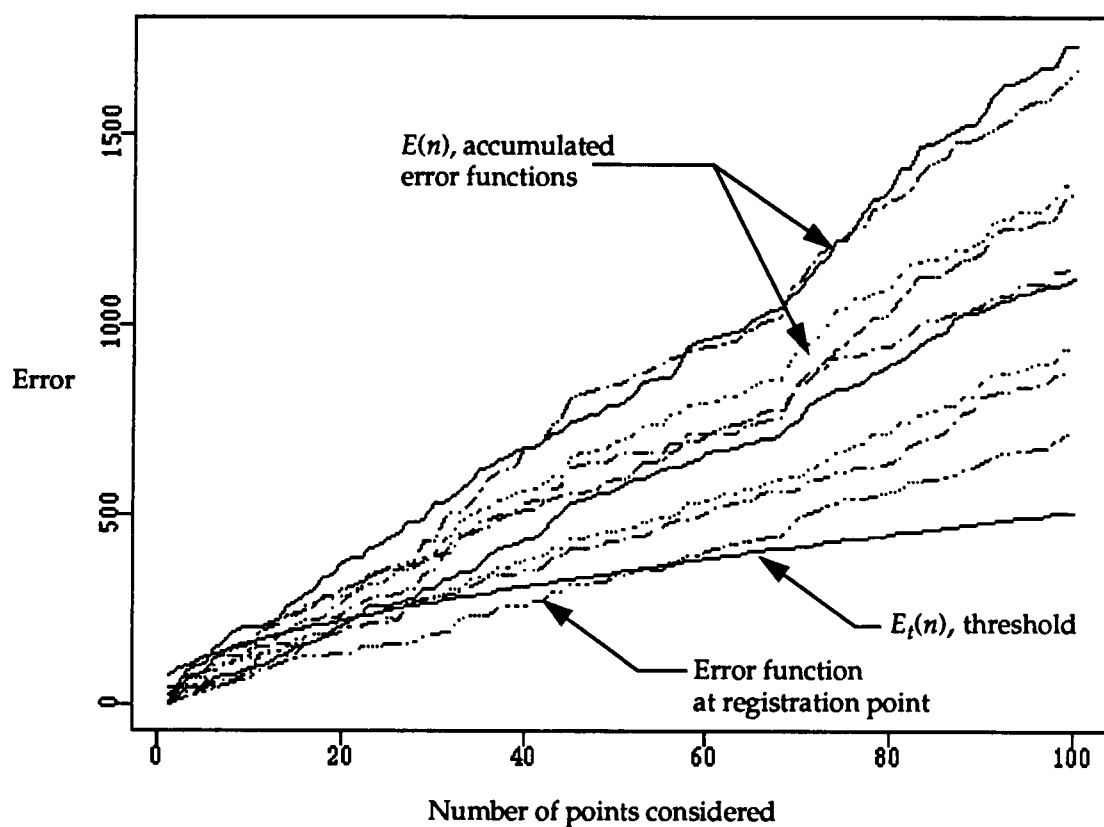


Figure 2.6. Sequential similarity detection algorithm error functions.

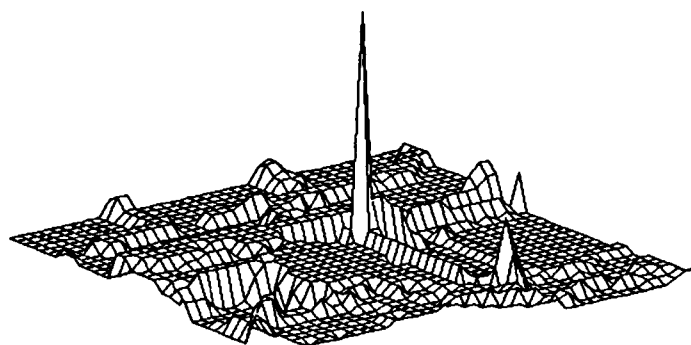


Figure 2.7. Number of points considered for correlation algorithm.

The square of the normalized correlation c between $R(x, y)$ and $T(i, j)$ (from Figure 2.5) for some position (l, m) in T where $l \leq i - x$ and $m \leq j - y$ is given by

$$c^2(l, m) = \frac{\left[\sum_x \sum_y R(x, y) T(l+x, m+y) \right]^2}{\sum_x \sum_y [R(x, y)]^2 \sum_x \sum_y [T(l+x, m+y)]^2} \quad (2.10)$$

In this application of Equation (2.10), the substitution $z(l, m) = c^2(l, m)$ was made to provide a larger falloff in the correlation value. The normalized correlation Equation (2.10) will produce a value ranging from 0 to 1 with 1 meaning a perfect match and 0 meaning no correlation at all (Gonzales and Wintz 1987). Remember that Equation (2.10) shows the normalized correlation operation for a single position of the reference template with respect to the search window. The reference template can be placed in $(i-x)(j-y)$ different positions. For example if the reference template was a 40 by 40 window and the search area was a 70 by 70 window, Equation (2.10) would have to be evaluated 900 times to generate the full surface.

To find the best match between the two features to the nearest pixel, the maximum normalized correlation value for the whole window must be found. Because evaluating Equation (2.10) at $(i-x)(j-y)$ different points can be very expensive in terms of computation time, it was decided to first implement a coarse search of the area by evaluating the normalized correlation at every other pixel location. Once the location of the best match was narrowed down to a smaller area, the normalized correlation was calculated at every pixel location to pinpoint the feature of interest to the nearest pixel. Figure 2.8 shows an example normalized correlation surface.

Perforation Border Location

The template-matching procedure was also tested for effectiveness in locating the perforation border. The crossing of two perforation borders at the corner of the stamp was used as the reference template for comparison because it is a unique feature of the border as shown in Figure 2.9. When this method was tested on several different stamps, problems began to appear because of irregularities in the perforation hole spacing. The irregular spacing is a result of two problems that manifest themselves during the perforation process.

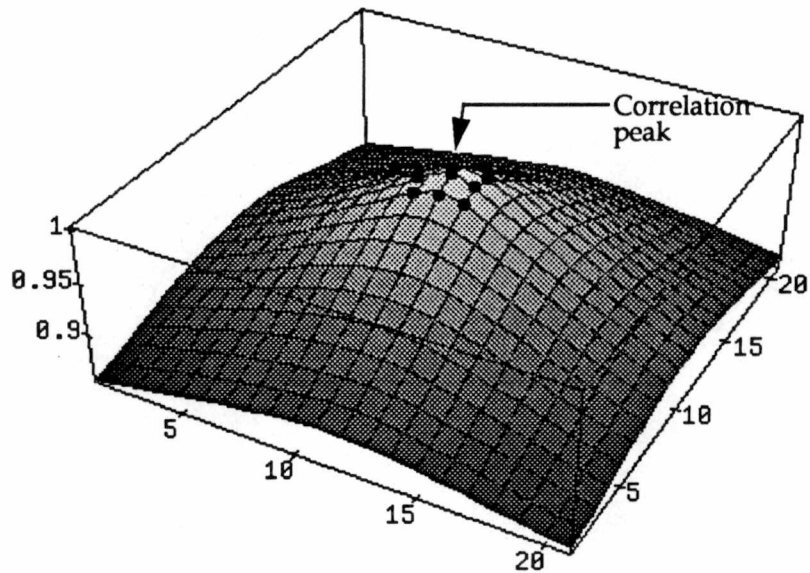


Figure 2.8. Correlation surface with peak and eight surrounding points marked.

One source is misalignment of the dyes on the perforator press, and the second is due to some stretching and deformation of the paper as the dyes cut through the stamp web. The distance between successive holes along a border vary by distances as large as 0.003 in. Figure 2.9 gives an exaggerated illustration of the problem where at the intersection of two boundaries the spacing variations are large enough to cause a registration error because of a feature mismatch, not an overall position shift.

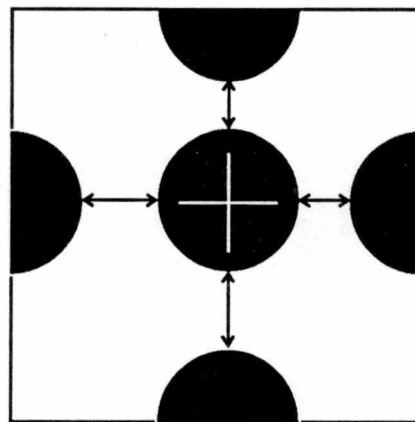


Figure 2.9. Perforation interstitial distance variation.

Subpixel Interpolation

To achieve better than integer pixel accuracy, some type of subpixel algorithm must be implemented. Several are presented here that can be very effective under certain circumstances.

Lagrange Polynomial Fit

An algorithm was written that fits a second-order Lagrange polynomial to the correlation data surface shown in Figure 2.8 (Burden and Faires 1989). After one polynomial was fitted in the x direction and another in the y direction, it was believed that the mathematically calculated maxima of the curves could be used as an approximation of the subpixel shifts needed to find the registration point. Figure 2.10 shows an example of a polynomial fit along a cross section of the correlation surface.

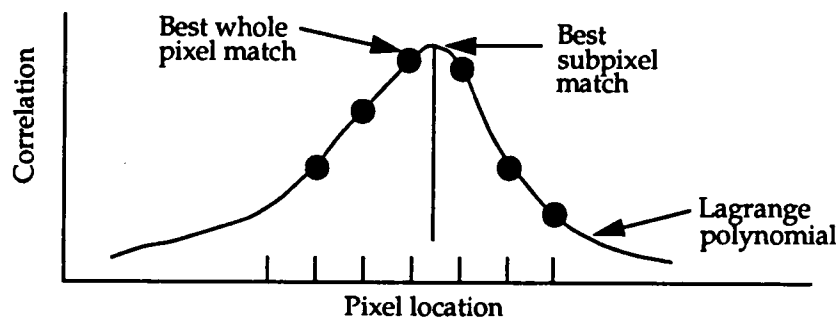


Figure 2.10. Lagrange polynomial fit to correlation surface.

It was discovered, however, that there was not enough variation in the correlation values at the integer pixels surrounding the whole pixel peak. This caused the maxima of the polynomials to always lie at the center of the integer pixel match previously found. Even when there was a significant subpixel shift between two stamp images, this method did not find it. In an application where a steep correlation peak exists, this could be a simple way to find the subpixel shift.

Subsampling

This problem led to the application of another subpixel algorithm called *subsampling*. The procedure in subsampling is to find the best whole pixel match, then zoom in on a small window surrounding the whole pixel registration point. If one zooms in on a digital image by a factor of two,

one then sees the same window of the image represented by twice as many pixels as illustrated in Figure 2.11.

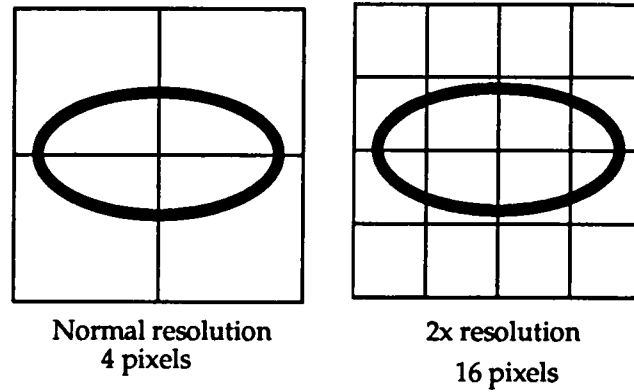


Figure 2.11. Subsampling illustration.

The part of the image that was previously represented by four pixels is now represented by sixteen. The values for the new pixels located in between the originals can be found by using bilinear interpolation, which essentially finds a new pixel value based on a weighted average of the surrounding pixels. The new value for a pixel point (x', y') which lies somewhere between integer pixels of an image can be found as follows (Ballard and Brown 1982). Let x and y be the integer parts of x' and y' . This allows one to say that (x', y') is surrounded by four other integer pixel locations

$$\begin{array}{cc} (x, y+1) & (x+1, y+1) \\ & (x', y') \\ (x, y) & (x+1, y) \end{array}$$

If the fractional parts of x' and y' are f_x and f_y then the new gray level given to the point (x', y') is

$$(1-f_x)(1-f_y)z(x, y) + (1-f_x)f_yz(x, y+1) + f_x(1-f_y)z(x+1, y) + f_xf_yz(x+1, y+1) \quad (2.11)$$

Once this zoomed image was successfully produced, the correlation algorithm was applied again to find the correlation peak to within 1/2 of a pixel. Given a perfect bilinear interpolation

algorithm, an image zoomed by a factor of n and then registered based on the new whole-pixel values could theoretically give registration accuracy to $1/n$ of a pixel. This process worked well down to $1/4$ of a pixel, but when the image was zoomed eight times to achieve the needed accuracy of 0.001 in., too much information was lost in the bilinear interpolation approximations. The zoomed image no longer could uniquely identify a specific location. The correlation surface became so flat that the maximum was no longer a unique and meaningful point. The algorithm produced errors in the registration values beyond the acceptable limits. This process works much better on binary images where the gray-scale transitions are from 255 to 0 or 0 to 255. A binary image window can be zoomed many times and still contain unique information. A group at the University of South Carolina claims accuracies of $1/50$ of a pixel on binary images of speckle patterns (Tran and Huhns 1986).

Paraboloid Surface Fit

This section of the paper develops another subpixel technique for the general-case problem of locating a unique feature in a digital image (Gleason et al. 1990). The application of the technique to three different cases of image features will be discussed. The first and simplest case considers an object that is symmetric with respect to the x and y axes and lies on a zero background. The second and third cases examine the effects of nonsymmetric image features and nonzero backgrounds such as those found in most stamp images. The assumption is made in developing the algorithm that the template containing the feature of interest is square to simplify the math, but this procedure can be generalized to any size rectangle.

General case reference and search areas

Consider a square template R of size n that is given by

$$R = \begin{bmatrix} r_{0,0} & r_{0,1} & \cdots & r_{0,n-1} \\ r_{1,0} & r_{1,1} & & \cdots \\ \cdots & & \cdots & \cdots \\ r_{n-1,0} & \cdots & \cdots & r_{n-1,n-1} \end{bmatrix}. \quad (2.12)$$

Now the search for R will be made in a square search window T of size m where $m > n$ and is given by

$$T = \begin{bmatrix} t_{0,0} & \dots & \dots & \dots & t_{0,m-1} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & t_{i-1,j-1} & \dots & t_{i-1,j+n} & \dots \\ \dots & \dots & \dots & R & \dots & \dots & \dots \\ \dots & t_{i+n,j-1} & \dots & t_{i+n,j+n} & \dots \\ \dots & \dots & \dots & \dots & \dots \\ t_{m-1,0} & \dots & \dots & \dots & t_{m-1,m-1} \end{bmatrix}. \quad (2.13)$$

It is important to notice at this point that the object R lies somewhere within the region of T as shown in Equation (2.13). If R is placed directly on top of its match in T , the correlation would have a value of 1 because the image features are identical by definition. Then, to generate the other eight surrounding points, R is translated one pixel in all eight directions (left, right, up, down, and diagonally) from its current position and the normalized correlation is found according to Equation (2.10). For example, if R were slid up one pixel from its original position, the normalized correlation $z_{1,0}$ would be given as

$$z_{1,0} = \frac{\left(\sum_{\alpha=0}^{n-1} (r_{0,\alpha}) (t_{i-1,j+\alpha}) + \sum_{\alpha=0}^{n-1} (r_{1,\alpha}) (r_{0,\alpha}) + \dots + \sum_{\alpha=0}^{n-1} (r_{n-1,\alpha}) (r_{n-2,\alpha}) \right)^2}{S_R^2 \left(S_T^2 + \sum_{\alpha=0}^{n-1} (t_{i-1,j+\alpha})^2 - \sum_{\alpha=0}^{n-1} (r_{n-1,\alpha})^2 \right)} \quad (2.14)$$

where the subscripts of z represent the x and y direction of template movement and

$$S_R^2 = \sum_{x=0}^{n-1} \sum_{y=0}^{n-1} r_{xy}^2 \quad (2.15)$$

$$S_T^2 = \sum_{x=i}^{i+n-1} \sum_{y=j}^{j+n-1} t_{xy}^2 \quad (2.16)$$

The numerator of Equation (2.14) is simply the dot product between R and the region of T that lies directly underneath it. The denominator consists of the dot product of R against itself multiplied by the dot product of the test region covered by R against itself. The second term in the denominator of Equation (2.14) is found by taking the test region dot product S_T^2 and adding the new row of T covered as a result of sliding the template up one pixel and then subtracting out the row at the bottom of the template that was uncovered (see Figure 2.12). It is also helpful to note

that $S_R^2 = S_T^2$ in this case because T contains the identical feature R .

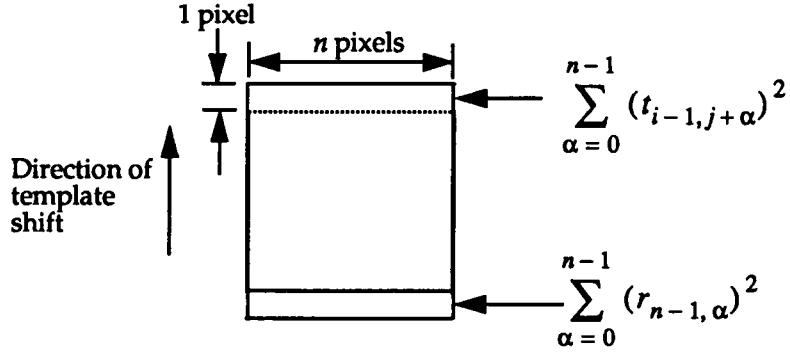


Figure 2.12. Calculating the $z_{1,0}$ correlation term.

It is evident that if R was moved down one pixel from its original position the resulting correlation value $z_{-1,0}$ would be

$$z_{-1,0} = \frac{\left(\sum_{\alpha=0}^{n-1} (r_{0,\alpha}) (r_{1,\alpha}) + \sum_{\alpha=0}^{n-1} (r_{1,\alpha}) (r_{2,\alpha}) + \dots + \sum_{\alpha=0}^{n-1} (r_{n-1,\alpha}) (t_{i+n,j+\alpha}) \right)^2}{S_R^2 \left(S_T^2 + \sum_{\alpha=0}^{n-1} (t_{i+n,j+\alpha})^2 - \sum_{\alpha=0}^{n-1} (r_{0,\alpha})^2 \right)} \quad (2.17)$$

The general case Equations (2.14) and (2.17) are used to illustrate the theory behind the subpixel surface fit.

Symmetric reference feature on a zero background

Consider the case where the reference template given in Equation (2.14) is symmetric with respect to the x and y axes. That is,

$$r_{x,i} = r_{n-1-x,i} \quad (2.18)$$

and

$$r_{i,y} = r_{i,n-1-y} \quad (2.19)$$

In other words, the left half of the reference is a mirror image of the right, and the top is a mirror

image of the bottom. Examples of this type of image feature would be a square, circle, or rectangle of uniform intensity.

Also in this case, assume that the background of T is all zero. It can then be shown that $z_{1,0}$ is exactly equal to $z_{-1,0}$ by looking at Equations (2.14) and (2.17). Notice that the terms in the numerator of each equation that contain any t entries will go to zero because of the zero background. This makes the numerators of Equations (2.14) and (2.17) equal. Also notice that the terms in the denominator involving t fall out. Finally, the terms in each denominator that subtract a row of the reference template are equal because of the symmetry of the reference template. The top row $r_{0,a}$ is the same as the last row $r_{n-1,a}$ as illustrated in Equation (2.18). This leaves

$$z_{1,0} = z_{-1,0} = \frac{\left(\sum_{\alpha=0}^{n-1} (r_{0,\alpha}) (r_{1,\alpha}) + \sum_{\alpha=0}^{n-1} (r_{1,\alpha}) (r_{2,\alpha}) + \dots + \sum_{\alpha=0}^{n-1} (r_{n-2,\alpha}) (r_{n-1,\alpha}) \right)^2}{S_R^2 \left(S_R^2 - \sum_{\alpha=0}^{n-1} r_{0,\alpha}^2 \right)} \quad (2.20)$$

Note that r_0 in the denominator can be replaced by r_{n-1} . Because of the x and y axes symmetry, it can be shown that in general

$$z_{i,j} = z_{-i-j} \quad (2.21)$$

which says that all of the normalized correlation pairs on opposite sides of the peak must be equal to each other for the case of a symmetric feature on a zero background considered here.

Nonsymmetric reference on zero background

This section shows that the type of reference template can be expanded to include features that are not symmetric, and the paraboloid surface fit will still be very accurate under certain conditions.

Consider the case where T has a zero background, but the reference template is any general feature. The only difference between this case and the previous one is that Equations (2.18) and (2.19) no longer hold true. In this case, $z_{1,0}$ and $z_{-1,0}$ are not equal because the subtracted terms in the denominators of Equations (2.14) and (2.17) are not the same. That is,

$$\sum_{x=0}^{n-1} (r_{0,x})^2 \neq \sum_{x=0}^{n-1} (r_{n-1,x})^2 \quad (2.22)$$

Notice that even though these terms are no longer equal, their value, which is the dot product of one row (n pixel intensities) in the template, would in most cases be very small compared to the $ST2$ term, which consists of the dot products of the remaining $n - 1$ rows summed together. So if the reference template is sufficiently large, $z_{1,0}$ will be approximately equal to $z_{1,0}$. Most of the testing done with the algorithm has been with n greater than or equal to 20 pixels. The analysis just described can be applied to all of the eight points surrounding the peak. The difference between $z_{-1,-1}$ and $z_{1,1}$ will vary slightly more because moving R in a diagonal direction introduces a new row as well as a new column to be subtracted from terms in the denominators of the equations. But in the final analysis, the extra row and column of data have a negligible effect on the total value of the correlation. An example of a correlation data set is given in Figure 2.13.

Including nonzero background effects

This section uses the same approach as the last section to show that nonzero background in T will have a small effect on the symmetry of the correlation surface if the reference template is large enough.

As the nonsymmetric template R is moved over a template T with a nonzero background, the denominator effects introduced in the last section still apply, but new terms are introduced in the numerator of the correlation equation because the reference template moves onto some nonzero background as it is translated one pixel in each direction. The terms involving the background that were previously dropped in Equations (2.14) and (2.17) must now be included.

The contributions of these extra rows and columns to the final result are minimal compared to the dot product of the remaining $n - 1$ rows and columns. As R moves further away from the best match (the correlation peak), more and more rows and columns are introduced to add to the difference in slope on opposite sides of the correlation peak. But since this algorithm requires only that the reference be moved one pixel in each direction around the peak, it is accurate to model opposite points as being equal.

Figure 2.13 shows an excerpt from a normalized correlation data file that shows the peak of

the surface (having a value of 1) and several other values around the maximum. These data were taken by correlating a nonsymmetric reference feature against a test search area with nonzero background. These data verify that for this particular case the approximations given previously hold true. The correlation values on opposite sides of the peak vary only in the fourth significant digit even with the nonsymmetric feature and nonzero background.

0.951022	0.959333	0.964479	0.967207	0.964564	0.958956	0.950671
0.959285	0.969520	0.976865	0.980503	0.976653	0.969197	0.959110
0.965005	0.977052	0.987385	0.993011	0.987366	0.976713	0.964791
0.966576	0.979440	0.991529	1.000000	0.991275	0.978717	0.966024
0.964989	0.977040	0.987364	0.993366	0.986756	0.975710	0.963091
0.959590	0.969570	0.976406	0.980073	0.976460	0.968355	0.958349
0.951502	0.959323	0.964331	0.967243	0.965018	0.959177	0.950923

Figure 2.13. Example of normalized correlation data.

Modeling a Surface to Fit the Data

The model of the surface that fits the set of normalized correlation data points is now considered. In a one-dimensional case it can be shown that if there exists some maximum point $z_{0,0}$ and points on either side of $z_{0,0}$ that are of equal value and are equidistant from $z_{0,0}$, then the smallest degree curve that will pass through the three points and have a mathematical maximum at $z_{0,0}$ is a parabola of second degree (Lancaster and Salkauskas 1973) (see Figure 2.14).

It follows that one-dimensional parabolas can be fitted through the maximum correlation value of the surface in Figure 2.14 and any two other points on opposite sides of the peak. The only difference between all of the parabolas is their widths due to different surface gradients depending on the correlation pair $(z_{i,j}, z_{-i,-j})$ being considered.

This behavior can be modeled in three dimensions by a paraboloid of one sheet that has the general equation

$$z(x, y) = ax^2 + by^2 + cxy + dx + ey + f. \quad (2.23)$$

This surface can be visualized by taking a one-dimensional parabola and rotating it about its axis of symmetry while allowing the width to vary such that it forms a three-dimensional paraboloid with an elliptic base as shown in Figure 2.14.

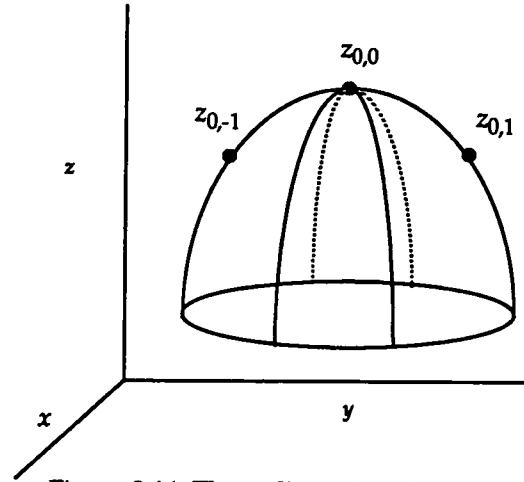


Figure 2.14. Three-dimensional paraboloid.

The solution for the coefficients of the paraboloid can be found by solving the system of equations

$$\mathbf{Ax} = \mathbf{b} \quad (2.24)$$

where

$$\mathbf{A} = \begin{bmatrix} x_0^2 & y_0^2 & x_0 y_0 & x_0 & y_0 & 1 \\ x_1^2 & y_1^2 & x_1 y_1 & x_1 & y_1 & 1 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ x_8^2 & y_8^2 & x_8 y_8 & x_8 & y_8 & 1 \end{bmatrix} \quad (2.25)$$

$$\mathbf{x} = \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \end{bmatrix} \quad (2.26)$$

and

$$\mathbf{b} = \begin{bmatrix} z_0 \\ z_1 \\ \dots \\ z_8 \end{bmatrix} \quad (2.27)$$

The correlation data points in $\mathbf{b}$ have been redefined from $z_{0,0}$, $z_{0,1}$, $z_{1,0}$, etc., to z_0 through z_8 to be consistent with the $\mathbf{A}$ matrix format. Because there are only six unknown values in the coefficient matrix $\mathbf{x}$ and nine correlation data points are supplied by the correlation maximum and the eight surrounding neighbors as given in $\mathbf{b}$, the system of equations is overdetermined. Because $\mathbf{A}$ is a rectangular matrix and cannot be inverted in the normal fashion to solve for $\mathbf{x}$, a least-squares regression must be used. This approach has an advantage in that all nine points can contribute to the position and shape of the resulting paraboloid.

Application of a pseudoinverse method (Stewart 1973) can be applied to the system. The first step is to multiply both sides of Equation (2.24) by $\mathbf{A}^T$, the transpose of $\mathbf{A}$:

$$\mathbf{A}^T \mathbf{A} \mathbf{x} = \mathbf{A}^T \mathbf{b} . \quad (2.28)$$

Gaussian elimination could be applied to Equation (2.28), or because $\mathbf{A}^T \mathbf{A}$ is a square matrix, it can be inverted by a numerical algorithm to solve for $\mathbf{x}$ as shown in Equation (2.29) (Press et al. 1988):

$$\mathbf{x} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b} . \quad (2.29)$$

Once the coefficients of the surface are known, the maximum of the paraboloid can be found by taking the gradient of $z(x, y)$ in Equation (2.23) with respect to x and y and setting them equal to zero as follows:

$$\frac{\delta z}{\delta x} = 2ax + cy + d = 0 \quad (2.30)$$

$$\frac{\delta z}{\delta y} = 2by + cx + e = 0 . \quad (2.31)$$

The values for x and y at the peak can be solved for directly as

$$x = \frac{(2db - ce)}{(c^2 - 4ab)} \quad (2.32)$$

and

$$y = \frac{(2ae - dc)}{(c^2 - 4ab)} . \quad (2.33)$$

Note that this is a closed-form solution for the maximum. No iterative steps are involved, and the execution time is therefore deterministic.

The application of the algorithm can be summarized as follows:

1. Determine the best integer pixel match between the reference template and the feature of interest in the search window.
2. Find the normalized correlation at the peak and eight surrounding points ($z_0, \dots, z_8$) by using Equation (2.10).
3. Set up the matrices for the system as shown in Equations (2.24) through (2.27) using the correlation data points and their associated (x, y) positions.
4. Solve for the coefficients of the paraboloid, $a, b, \dots, f$ by using a numerical method on Equation (2.28).
5. Use the coefficients and Equations (2.32) and (2.33) to calculate the position of the surface maximum.
6. Add this subpixel value to the integer pixel location found in step 1 to precisely locate the feature.

The accuracy of this algorithm is compared to the centroid technique in the next section.

Comparison of Centroid vs Template-Matching Techniques

Experimental Setup

Some experiments were carried out in the early stages of the development to test the validity of the centroid method and the template-matching-with-subpixel-interpolation method. The equipment used to acquire images for these tests is not the equipment used in the final PRS. The camera used for the image acquisition was a charge-coupled device (CCD) area sensor camera with a resolution of 512 by 512 pixels. The largest area of stamp web that had to fit into the camera's field of view was approximately 2.0 in. wide and 1.54 in. high. This led to an accuracy of 3.9 mil/pixel in the horizontal (x) direction and 3.0 mil/pixel in the vertical (y) direction. To safely reach the desired accuracy of 0.001 in./pixel, 1/8-pixel accuracy was required. Fluorescent tubes operating at a frequency of 50 kHz were used for illumination. A fluorescent lamp controller was used to drive the lamps at this high frequency and also to regulate the light level at a constant intensity through feedback from a phototransistor. The reason for the operating frequency higher than the normal 60 Hz was to be sure that the camera integrated over many periods of the light cycle when an image was acquired. At 60 Hz, it was questionable whether the intensity was constant from acquisition to acquisition because the integration time of the camera (33 ms) was on the order of one light cycle (16.7 ms). Any variances in the light cycle brightness could cause varying intensities in acquired images. By integrating over many periods, small changes were averaged out. The images were digitized to 256 levels of gray.

The stamps were placed on a 2-axis, micrometer controlled translation stage and moved in 0.001-in. increments. Also, the whole apparatus was attached to a high-resolution rotation stage as shown in Figure 2.15.

Experimental Results

The simple paraboloid algorithm and the centroid technique were tested extensively by using translated stamp images. The testing was conducted as follows. A stamp was placed beneath the high-resolution CCD camera on a translation stage, and a snapshot was taken and stored as a reference.

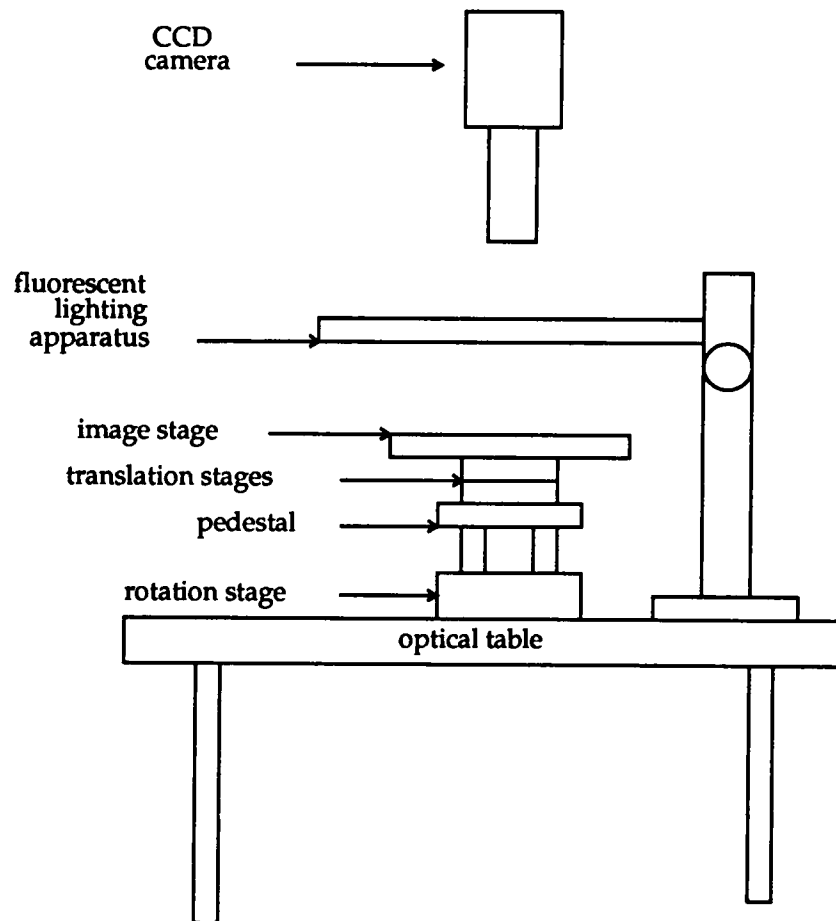


Figure 2.15. Experimental setup.

Using the micrometer-controlled translation stages, the stamp image was moved in 0.001 in. increments in both the horizontal and the vertical directions. Several images were acquired and stored. The simple paraboloid technique and the centroid method were used to find the shift of the image as well as the distance between the image and the perforation after each translation.

Shown in Table 2.1 are several trials of the experiment with the stamp translated by different amounts. The first column gives the actual shift of the image with respect to the reference in both the horizontal and the vertical directions. The second column gives the shift calculated for the image feature by the paraboloid algorithm. The third column shows the error in the distance measurement from shot to shot.

Table 2.1. Experimental results: correlation method.

Actual shift x (10^{-3} in.)	Actual shift y (10^{-3} in.)	Calculated shift x (10^{-3} in.)	Calculated shift y (10^{-3} in.)	Error in x (10^{-3} in.)	Error in y (10^{-3} in.)
1.0	0.0	0.9	0.0	0.1	0.0
2.0	0.0	1.9	0.0	0.1	0.0
3.0	0.0	2.8	0.0	0.2	0.0
0.0	1.0	0.0	0.9	0.0	0.1
0.0	2.0	0.0	2.0	0.0	0.0
0.0	3.0	0.1	3.0	0.1	0.0
5.0	5.0	4.9	5.0	0.1	0.0

Centroid Technique

Table 2.2 shows the same test results found by using the centroid technique.

Table 2.2. Experimental results: centroid method.

Actual shift x (10^{-3} in.)	Actual shift y (10^{-3} in.)	Calculated shift x (10^{-3} in.)	Calculated shift y (10^{-3} in.)	Error x (10^{-3} in.)	Error y (10^{-3} in.)
1.0	0.0	0.8	0.0	0.2	0.0
2.0	0.0	2.0	0.3	0.0	0.3
3.0	0.0	2.9	0.1	0.1	0.1
4.0	0.0	3.8	0.1	0.2	0.1
0.0	1.0	0.0	1.1	0.0	0.1
0.0	2.0	0.0	1.9	0.0	0.1
0.0	3.0	0.1	2.9	0.1	0.1
0.0	4.0	0.0	3.8	0.0	0.2
2.0	2.0	1.8	2.2	0.2	0.2
4.0	4.0	3.7	3.9	0.3	0.1

The results in both are well within the 0.001-in. accuracy desired, but the centroid technique is consistently less accurate.

Template-Matching Technique

After the previous experiment showed that the template-matching technique outperformed the centroid method, more extensive testing was conducted on the subpixel registration algorithm to better quantify the accuracy and repeatability (Gleason et al. 1990). The first step in this second experimental procedure was to acquire a reference image for use in the measurement process. After this image was stored in memory, a unique feature was selected as the reference template for correlation purposes. The position of the reference feature was defined as the origin of a cartesian coordinate system. The translation stages were used to shift the stamp in 0.001-in. increments in x , y , and combinations of both. Five hundred sixty images were acquired at 10 different locations. At each new position, the subpixel cross correlation algorithm was used to estimate the amount of shift from the starting position. The calculated shift was compared to the actual shift as measured by the micrometer. This experiment was designed to determine both the accuracy and the standard error by precisely positioning the printed sheet and by acquiring many images at each location. The results of this experiment are shown in Figure 2.16.

In this plot, the axes represent the fraction of a pixel that the sheet was shifted in the x and y directions. The circles are centered at the ten positions where data were acquired, and their radius represents 1/16 of a pixel. The squares are centered at the mean position calculated by using the subpixel correlation, and their width and height correspond to one standard error in the x and y directions respectively.

As can be seen from Figure 2.16, the mean calculated location was within 1/16 of a pixel at each actual position. Another important conclusion is that the magnitude of the standard error was on average less than 1/32 of a pixel. Results from this experiment proved that the algorithm was sufficient for the needs of the application.

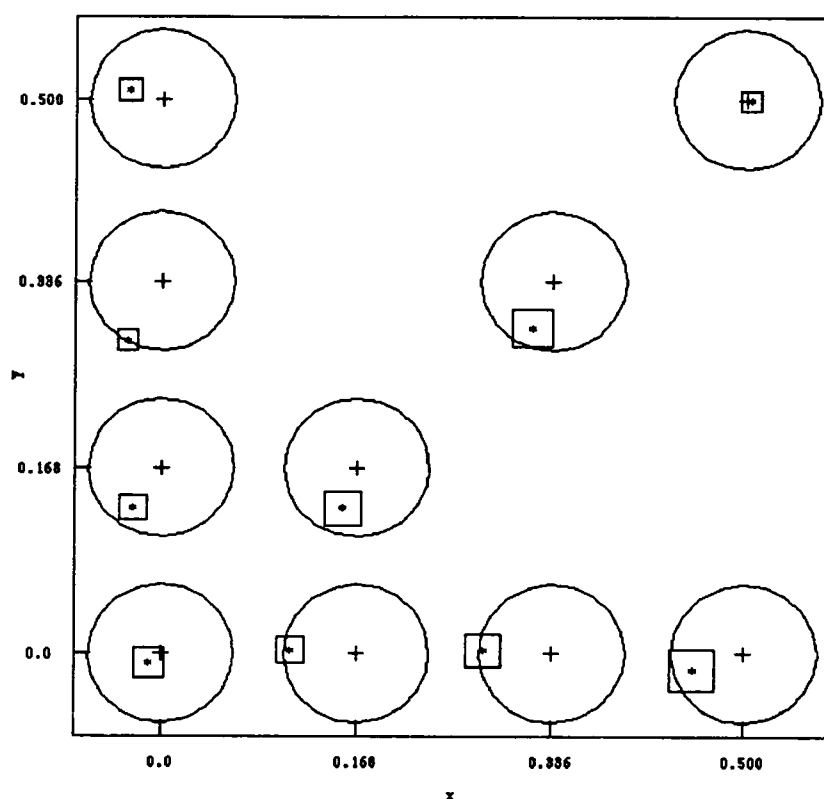


Figure 2.16. Paraboloid subpixel algorithm accuracy.

Plot of calculated translations of a printed graphic image, circles centered at ideal location with a radius of one-sixteenth pixel and squares centered at mean of calculated location with width and height representing one standard deviation in x and y respectively.

Performance in Presence of External Disturbances

Printing Variations

The results shown in Tables 2.1 and 2.2 and Figure 2.16 were found by acquiring images of the same stamp translated different distances, and, therefore, the experiment did not show how printing variations from stamp to stamp would affect the measurement accuracy. Data showing measurements made on several different stamps from the same sheet were acquired. The first column in Table 2.3 indicates the number of the particular stamp on the sheet. The second column gives results found by the simple paraboloid method. The third column shows the physical measurement of the distance from a point in the image to the edge of the perforation corner made with a

microscope. Finally, the absolute value of the error is shown in the last column. As one can see from the results, only one stamp (5) had an error greater than 0.0005 in.

Table 2.3. Paraboloid algorithm performance in presence of printing variations.

Stamp	Paraboloid Registration (10^{-3} in.)	Actual Distance (10^{-3} in.)	Error (10^{-3} in.)
Reference	0.1	95.5	0.1
1	-0.2	96	0.3
2	0.3	95	0.2
3	-0.7	96	0.2
4	-0.7	96.5	0.3
5	-0.9	97	0.6
6	-2.5	98	0.0
7	0.8	95	0.3
8	1.9	94	0.4
9	-0.3	95.5	0.3
10	-0.1	95.5	0.1
11	0.3	95.5	0.3
12	-0.1	95.5	0.1
13	-0.3	96	0.2
14	-1.7	97.5	0.3

Although the measurements made in Table 2.3 are on different stamps, one cannot assume that such accurate results will be obtained when stamps from different sheets and webs are tested. The fact that the reference and all of the test stamps used in Table 2.3 are on the same sheet eliminates some other variables that could make the measurement more difficult. Two important variables and their effects that must be considered are color misregistration and rotation.

Color Misregistration

The simple paraboloid technique has tested the best overall in all of the registration experi-

ments. The main advantage of this technique is its high accuracy, but, as in any physical system, high-accuracy measurements are sensitive to any type of disturbance or variation. Color misregistration is common in the printed stamps that will be inspected by this system, and the local correlation technique is sensitive to the color shifts. Color misregistration causes the correlation peak amplitude to shrink as well as shift in unpredictable directions. The degree of these errors depends totally on the size and content of the window on the stamp image being inspected and the degree of color alignment error. A partial solution to the problem would be to enlarge the reference window and consider a larger part of the image. This would reduce the overall effect through averaging, but it is very costly in terms of execution time of the code that must implement the algorithm. The cost of doing a normalized correlation rises quickly as the size of the window is increased. Another global method that takes less time would be useful.

Rotation

The main rotation problem anticipated is rotation of the whole stamp (perforations and image together) because of small web misalignment as it passes under the camera. Another scenario that should be considered is image rotation within the perforation borders. This type of image shift would cause problems in finding an accurate (x, y) registration measurement.

The first problem involving rotation of the whole stamp can be addressed by performing a translation and rotation of the coordinate system to match the rotated image. The first step is to measure the angles (θ_{tst} and θ_{ref}) of a line passing through the center of all of the perforations on one border in the test and reference images. The rotation angle, α , can then be calculated as the difference between θ_{tst} and θ_{ref} . By translating the origin of the coordinate system to be at the center of the upper-left corner, the problem is converted to a simple one of rotating a coordinate system about its origin by the angle α . The equations to convert from a point (x, y) to a point (x', y') in a rotated coordinate system by angle α can be found by

$$x' = (x - x_0) \cos \alpha + (y - y_0) \sin \alpha + x_0 \quad (2.34)$$

$$y' = (y - y_0) \cos \alpha + (x - x_0) \sin \alpha + y_0 \quad (2.35)$$

where (x_0, y_0) is the chosen origin of the coordinate system (Gonzales and Wintz 1987).

Rotation also has an effect on the correlation values between two images. If the rotation gets

large enough, a strong correlation peak can be lost. Table 2.4 shows the effect of rotation on correlation values for a uniform intensity feature of a square on a constant background. The correlation peak remains very high for these small rotation angles. A square correlates well with small degrees of rotation because most of the intensities will still overlap. In a window where there is a lot of fine detail, the correlation value falls off quicker, but the peak is still strong for reasonable rotations. Also, as the angle of rotation increases, the correlation value falls off more rapidly. The rotation of the stamp images on the press will not be any higher than 1.0 degree.

Table 2.4. Correlation vs rotation.

Rotation angle (deg)	Correlation
0.0	0.9999
1.0	0.9994
2.0	0.9987
3.0	0.9976
4.0	0.9974
5.0	0.9972
6.0	0.9950

Algorithm Selection

On the basis of the theory and experimental data presented in this chapter, it was decided to implement the template-matching algorithm with subpixel interpolation to find the location of the image feature. A combination of the centroid technique and the least-square fit of a line through the perforation centroids was chosen as the algorithm to be implemented in the final PRS. An example of a measurement on the Pteranodon stamp with the various dimensions indicated is shown in Figure 2.17. These distance measurements are compared to the same measurements in the reference image to determine the final registration values. Chapter 3 discusses how the images are acquired for processing.

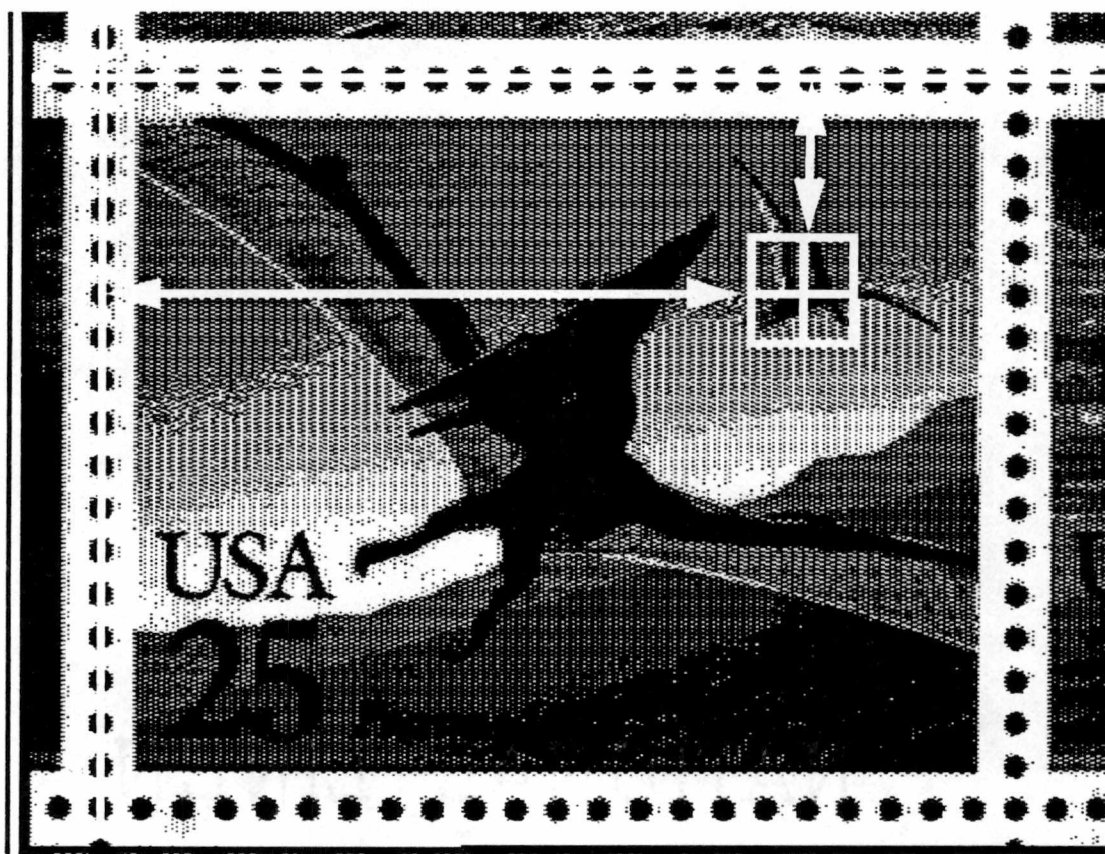


Figure 2.17. Example registration measurement.

Chapter 3

Image-Acquisition System

Although the image-acquisition system in a machine vision application is one of the most important parts of the architecture, it is many times overlooked. The acquisition pieces consist of an illumination system, an optical focusing system, some type of photodetector that converts photons into electrical signals, and an analog-to-digital converter that converts the electrical signals into digital numbers for storage on a computer. Many designers of image processing systems focus on the processing power of the computers and accelerators that will do the number crunching before they consider the optimal configuration of the lighting arrangement that can potentially do some powerful processing at essentially the speed of light. This chapter will describe the PRS acquisition system components and give background as to how each component contributes to reaching the final goal of the perforation-to-image registration measurement.

Machine Vision Camera

Cameras with solid state sensors are very common and are now generally less expensive than the older vidicon tube cameras they are replacing. Two common type of solid state sensors are charge-coupled devices (CCDs) and charge-injection devices (CIDs). The camera selection for the PRS was made on the basis of background research done on these two type of sensors. All solid state sensors operate on the basis that a photon striking a photoconductive material such as silicon will generate electron-hole pairs. The electrons can travel within the silicon some distance before they recombine with a hole. A photosite on a solid state sensor is an electric field that captures and collects the traveling charges. The amount of light that strikes a photosite is proportional to the collected charge at that location (Batchelor et al. 1985).

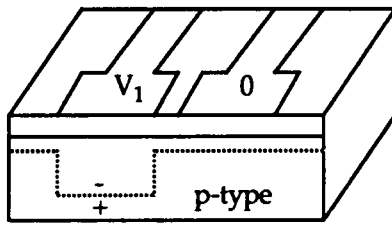
Charge-Coupled Devices

The two types of photosites used in CCD sensors are metal-oxide semiconductor (MOS) capacitors or photodiodes. In the CCD these photosites are used as charge collectors. A MOS capacitor photosite is created by placing an electrode above some p-type silicon and applying a negative voltage to generate an electric field that will collect charge. This electric field is sometimes called a *potential well* for illustrative purposes. The MOS capacitor starts out in a depleted

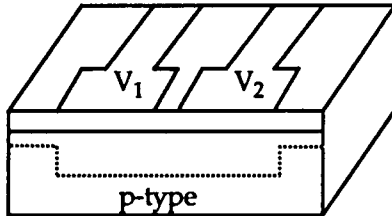
mode, then builds up charge as the photons generate electron-hole pairs in the silicon. The charge is not read at each individual site after the integration period but is transferred row by row to a shift register which similarly transfers the charge in each column to an output amplifier where the charge is converted into a video signal. The charge transfer mechanism is similar to that used in bucket-brigade devices (BBDs) where charge is moved through a series of capacitors. In a two-phase CCD each photosite is made up of two MOS capacitors. The electrode on one of the MOS capacitors is biased at a potential V during photon integration as shown in Figure 3.1(a). Once the charge is integrated, transfer is accomplished by turning the adjacent MOS electrode on to the device potential V . This causes the charge to spread uniformly between the two adjacent potential wells as seen in Figure 3.1(b). All of the charge is then transferred from the first to the second site by turning off the voltage on the first electrode [Figure 3.1(c)]. By pulsing the electrode voltage, the light-induced charge can be transferred down a line of pixels into a shift register and subsequently read out (Ravich 1987).

A disadvantage of using MOS capacitors as photon collection devices is the polysilicon electrodes on the surface of the CCD. These tend to absorb some of the light (especially in the ultraviolet) and change the overall spectral response of the sensor. A major improvement that is taking place in CCD technology is the increased use of photodiodes as the photon-collecting sites instead of MOS capacitors. This configuration has the advantages of fewer electrodes to impair the spectral response of the photodiode and the lower readout noise of the CCD shift register. These devices are sometimes called *charge-coupled photodiode devices* (CCPDs).

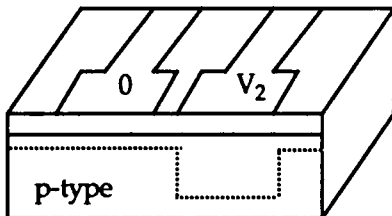
Multi pinned phase (MPP) mode of operation is being employed in large format area array CCDs to reduce the dark current (Woody 1991). During integration and readout, the electrodes are held at a negative potential to create an inverted layer of p-type material at the silicon-oxide interface. By reducing the number of available carriers, the surface dark current can be significantly reduced.



(a) During charge collection only one electrode is turned on.



(b) After charge collection the second electrode is turned on to begin charge transfer.



(c) Shifting of the charge is completed by removing the voltage from the first electrode.

Figure 3.1. Two-phase charge-coupled device charge transfer.

Another technique is being used to improve the quantum efficiency (ratio of incident photons to generated electrons) of the CCD imager. Typically, the CCD is illuminated from the top where all of the gate structure and polysilicon electrodes are located. These obstructions reduce the quantum efficiency, thereby lowering the sensitivity. Furthermore, the change in quantum efficiency is wavelength dependent, causing a nodal (wavy) spectral response. The problem is most significant in the ultraviolet, or blue region of the spectrum because polysilicon absorbs a portion of the ultraviolet light before it reaches the silicon. A technique being used by some CCD manufacturers is backside illumination. Illumination from the backside avoids the gate structures, but for photons to penetrate to the desired depth, the substrate must be thinned down to a few microns. Until recently, the thinning process was not practical, but advances in semiconductor manufacturing have greatly improved the process.

One major complaint about CCD performance in the past has been their susceptibility to blooming or spilling of excess charge into neighboring pixels when a large number of photons are

incident on a single or small number of pixels. Many of the newer devices are adding antiblooming circuitry. A diode is added at each pixel site that connects the potential well of that pixel to the substrate through a control gate. The potential on this gate is set lower than the potential of the barrier between pixels so that excess charge will "run off" through the diode rather than into the neighboring pixel.

Charge-Injection Devices

The CID solid state sensors also use a MOS capacitor to collect photon-generated charge. In this type of sensor the charge at each site is read by injecting the charge into the substrate and monitoring the generated current. Each photosite in a CID consists of two adjacent MOS capacitors which integrate the incoming light as shown in Figure 3.2 (a). During readout, one electrode is pulsed to a higher potential, causing its portion of the charge to shift over to the adjacent potential well. The second MOS electrode is then pulsed, which injects all of the charge into the substrate as shown in Figure 3.2(b).

Instead of injecting the charge into the substrate, another method of readout is sometimes implemented by reapplying a negative voltage to the first MOS capacitor. This causes all of the charge to shift back to the first potential well. Measuring the current generated during this charge transfer creates the video signal. This type of video signal extraction is called *nondestructive readout* (NDRO) because the charge is still present and can be read again. It tends to be less noisy than reading current caused by charge injected into the substrate. An epitaxial layer is fabricated underneath the photosensing sites to collect the injected charge and prevent image lag and blooming (Tseng et al. 1985). The CID structure is more flexible than the CCD because the charge transfer mechanism does not require pixel-to-pixel shifting of charge. This allows easier implementation of capabilities like adjustable integration times, variable scanning rates, and asynchronous triggering.

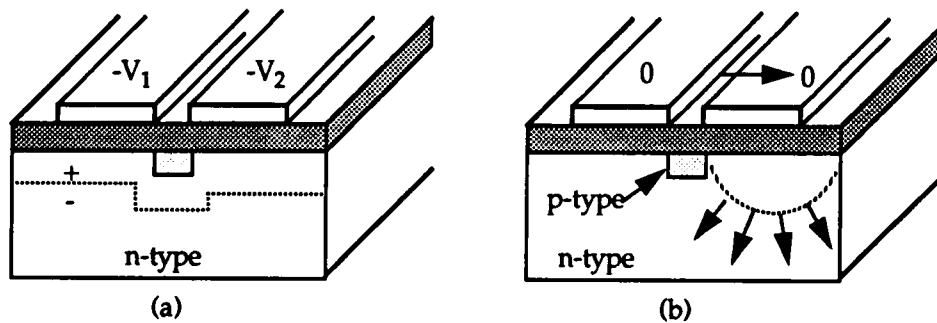


Figure 3.2. Charge-injection device charge collection (a) and subsequent transfer and injection (b).

Advantages and Disadvantages of CCD and CID Sensors

To make an intelligent selection of a camera, the merits of each had to be compared with those of the other. Presented here are some of the general strengths and weaknesses of each sensor type.

CCD Advantages

- The CCD readout mechanism is a low-noise process suitable for low-light-level imaging.
- Quality CCDs have dynamic ranges as high as 10^5 under adequate lighting conditions.
- Solid state sensors have unlimited lifetimes.
- CCDs currently have the highest output data rates (35 MHz max) of any solid-state sensor.

CCD Disadvantages

- The dark current amplitude and nonuniformity in a CCD sensor are higher than those in a CID.
- A problem unique to CCDs (especially large format) is charge transfer inefficiency (electrons left behind in the shifting of charge from row to row).
- The polysilicon electrodes on the light-gathering surface of front-illuminated CCDs attenuate the spectral response in the blue region.
- Blooming is a problem that occurs when excess charge from one photosite spills over into surrounding pixels.
- Because of the systematic addressing requirements, photosite geometries are inflexible. SSPDs and CIDs have individually addressable elements that can be laid out in any shape.

CID Advantages

- CIDs have lower dark current than CCDs.

- The full well capacity (total number of electrons one pixel can store) of the CID is larger than that of the CCD.
- The NDRO capabilities are useful in some applications
- The dynamic range is comparable to CCDs (up to 10^5).
- Because of the readout design of CIDs, they are addressable.
- Subframe scanning to achieve higher frame rates is easily implemented in the CID because of its flexible design.
- An epitaxial layer is fabricated underneath the photosensors, which absorbs the injected charge to reduce blooming and image lag.
- CIDs have individually addressable elements that can be laid out in any geometry for specialized sensor shape requirements.

CID Disadvantages

- Noise due to clocking of data and output capacitance of CIDs is high compared to CCDs.
- The CID shares a problem with the CCD in that polysilicon electrodes are more absorptive in the blue region.
- Photon absorption by the epitaxial layer causes the CID to be less light sensitive.

On the basis of the comparison presented, a CID camera was chosen for the PRS application. The output of the CID camera is in a progressive, noninterlaced format. Also, the CID sensor on the camera has a square-pixel configuration which makes the geometry of the measurement relatively simple compared to most 4:3 aspect ratio, RS170-type cameras, which have rectangular pixels.

Optics

The choice of a lens for the PRS was based on the requirements for magnification, object distance, and depth of field. By using the thin lens model shown in Figure 3.3 a specification for the focal length of the lens, f , can be calculated (Jatko 1990).

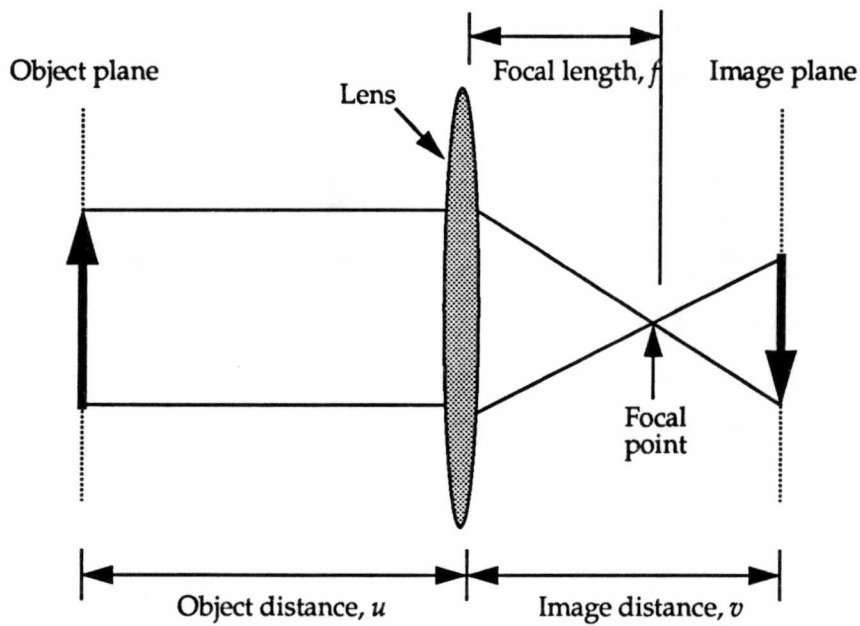


Figure 3.3. The thin-lens model.

The magnification, or reduction, m , is the ratio of the size of the image on the camera sensor to the actual size of the physical object. By using similar triangles, the magnification can be found from the ratio of the image distance v to the object distance u as shown in Equation (3.1):

$$m = \frac{v}{u}. \quad (3.1)$$

The square CID sensor used has an 11-mm diagonal, and the average diagonal of the stamps being imaged is about 35.5 mm. This leads to a magnification of 0.31.

The focal length of the lens can be found by using Equation (3.2). The difficulty with this equation is that the image distance v is sometimes difficult to measure because it is the distance from the lens to the surface of the CID sensor inside the camera:

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}. \quad (3.2)$$

By substituting Equation (3.1) into Equation (3.2), a simpler equation for calculating the focal length can be found:

$$f = \frac{mu}{m+1} \quad (3.3)$$

An object distance of approximately 9 in. was required to prevent the image from being obscured by the strobed illumination. Substituting a magnification of 0.31 and an object distance of 9 in. (228.6 mm) into Equation (3.3) gives a desired focal length of 54 mm.

The depth of field of an optical system is the distance along the optical axis of the lens through which the object can be moved and still remain in focus at the sensor surface, or image plane. Figure 3.4 illustrates this concept (Jatko 1990).

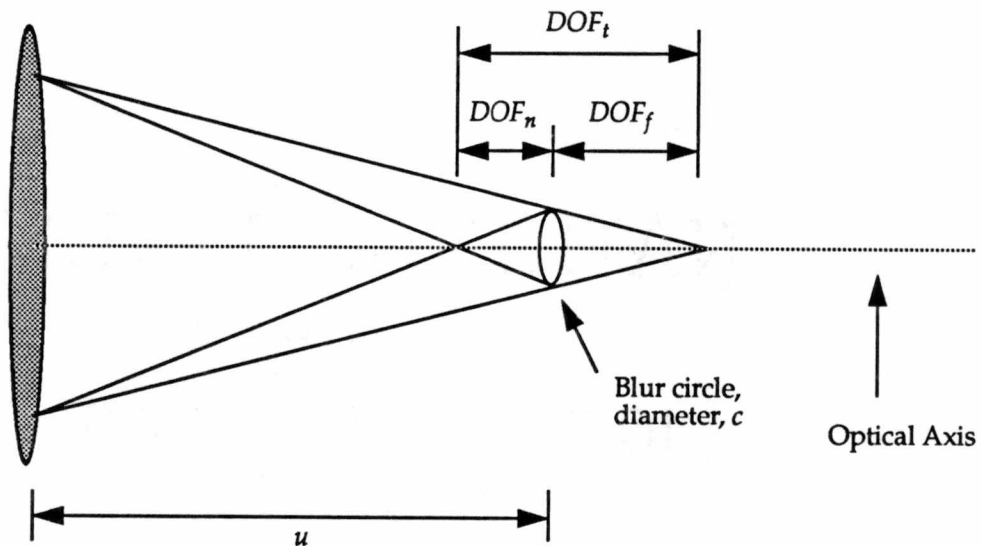


Figure 3.4. Depth of field (DOF) of an optical system.

Because the stamp web will be moving past the sensor at 400 ft/min in an area of the press with significant vibration caused by the large perforator, it was important that the depth of field be large enough to compensate for any flutter. The blur circle shown in Figure 3.4 represents an area of uncertainty in the image formation. In the case of a solid state sensor with square photoreceptors, any part of the object that is small enough to be imaged onto a single pixel has a degree of uncertainty associated with it because the whole area is averaged and is represented by a single intensity value. In the case of the PRS, the blur circle diameter c can be approximated as the center-

to-center pixel distance (or pixel pitch) ρ divided by the magnification m :

$$c = \frac{\rho}{m} . \quad (3.4)$$

The near depth of field (DOF_n) and the far depth of field (DOF_f) are given by

$$DOF_n = \frac{cu}{a+c} \quad (3.5)$$

$$DOF_f = \frac{cu}{a-c} \quad (3.6)$$

where a is the aperture of the lens. In the PRS optical system with $a = 5$ mm and $r = 15$ mm, the DOF_n and DOF_f were calculated as 2.19 and 2.23 mm respectively. This gives a total depth of field, DOF_t , of 4.42 mm. A backing plate was designed to support the stamp web near the image acquisition area on the perforator/sheeter for stabilization. A macro lens with a focal length of 55 mm especially designed for close-up photography was used as the lens for the PRS.

Illumination

Linear Strobe Lamps

Most strobe light systems have a typical flash duration anywhere from 10 to 20 μ s. Consider a web moving at 400 ft/min, which is the maximum speed of the perforator/sheeter press where the perforations are punched. This corresponds to 80 in./s. A flash duration of 10 μ s translates to 0.0008 in. of stamp motion in the acquired image. This motion is very close to the accuracy that the system is trying to achieve (0.001 in.), so it was decided to find a strobe with a flash duration on the order of 1 μ s. The strobe lights chosen for the PRS are linear strobe lamps designed for wide web illumination applications. These lamps are specifically made for the printing industry. The xenon bulbs are 20 in. long and are designed to illuminate across a 24-in. section of web material from a distance of approximately 12 in. They have a nominal flash duration of 10 μ s which seems to indicate a potential for image blurring at 400-ft/min web speeds. However, the actual duration of the flash pulse at the peak intensity is much narrower than 10 μ s and freezes the motion of the stamp image well within the required 0.001-in. accuracy.

Two strobe units were used to illuminate the stamp as illustrated in Figure 3.5. The stamp image surface is illuminated by one linear strobe light with a 45-degree incidence angle. The

stamp is also illuminated from behind by another strobe unit. The purpose of backlighting is to enhance the intensity of the perforations in the acquired image. The light passing through the perforations is bright enough to saturate the camera, which makes it much easier for the image processing hardware to locate all of the perforations. A piece of mylar film was placed over the filament to scatter the light coming through. This ensures that specular effects caused by direct transmission of the photons from the strobe lamp striking the camera sensor will not occur.

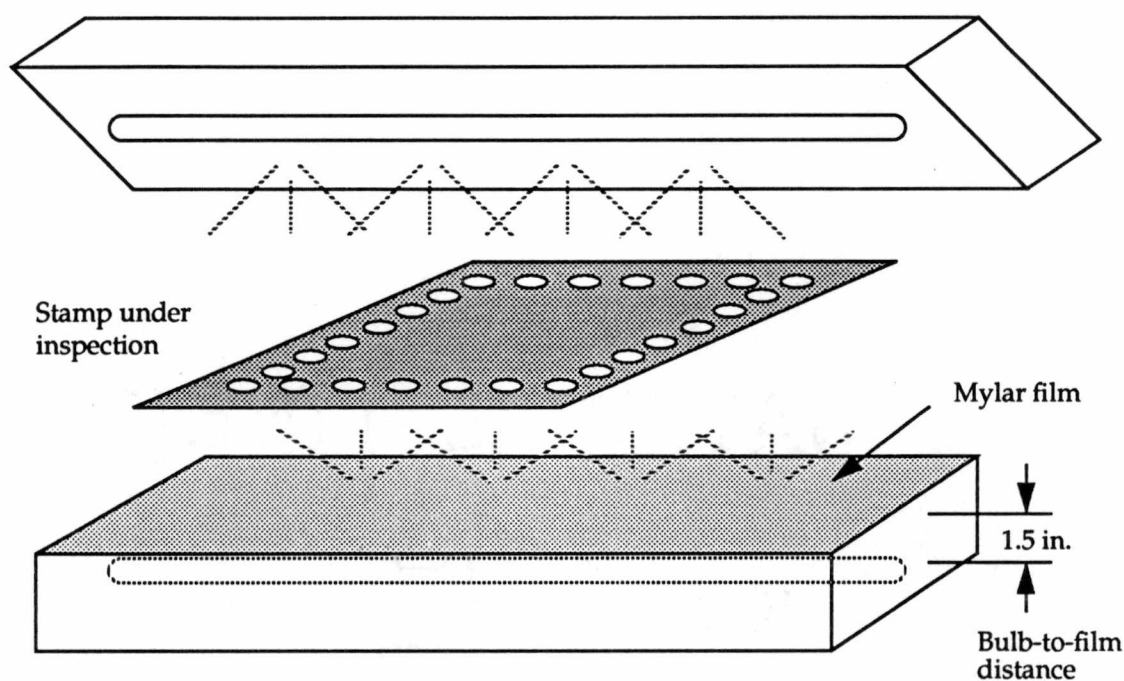


Figure 3.5. Illumination configuration.

Attenuating Neutral Density Filter

There are two sources of variance in the level of illumination from one image acquisition to another. The first source is the 5% variance in the flash intensity of the xenon bulbs in the strobe lamps. The other factor is the intensity profile of the light coming through the mylar filter on the bottom strobe. The strobe lamps provide a fairly uniform illumination field when used as a reflective light source positioned at least 12 in. from the object surface. In the case of the rear-illuminating strobe lamp, the camera was sensing the transmitted light from the lamp at the mylar filter.

Because the filter was within 1.5 in. of the bulb (Figure 3.5), the intensity falloff towards the end of the bulb became significant as shown in Figure 3.6.

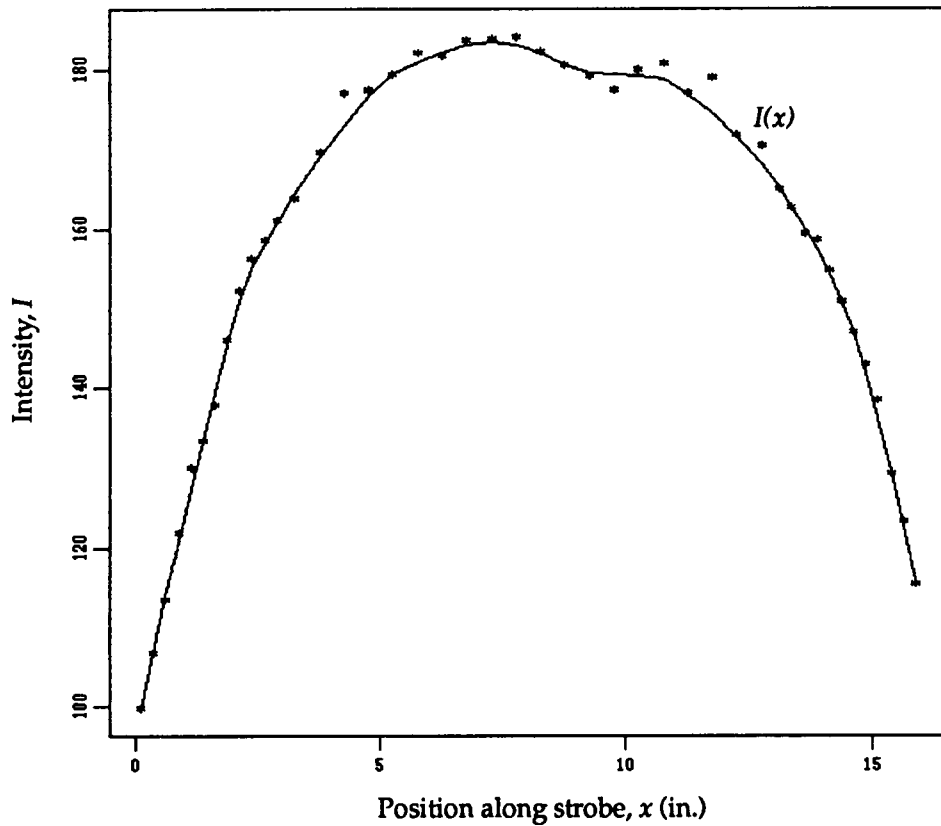


Figure 3.6. Intensity profile of strobe lamp.

An attenuation function was created that had the effect of suppressing the intensity of the lamp in the center to bring it down closer to the intensity at the lamp ends. The equation for the attenuation function $A(x)$ can be written as

$$A(x) = 1 - \frac{I_{\min}}{I(x)} \quad (3.7)$$

where $I_{\min}$ is the minimum intensity in the field of view, and $I(x)$ is the intensity at some point x along the strobe lamp. The result of evaluating $A(x)$ based on the intensity profile $I(x)$ shown in Figure 3.6 is given in Figure 3.7.

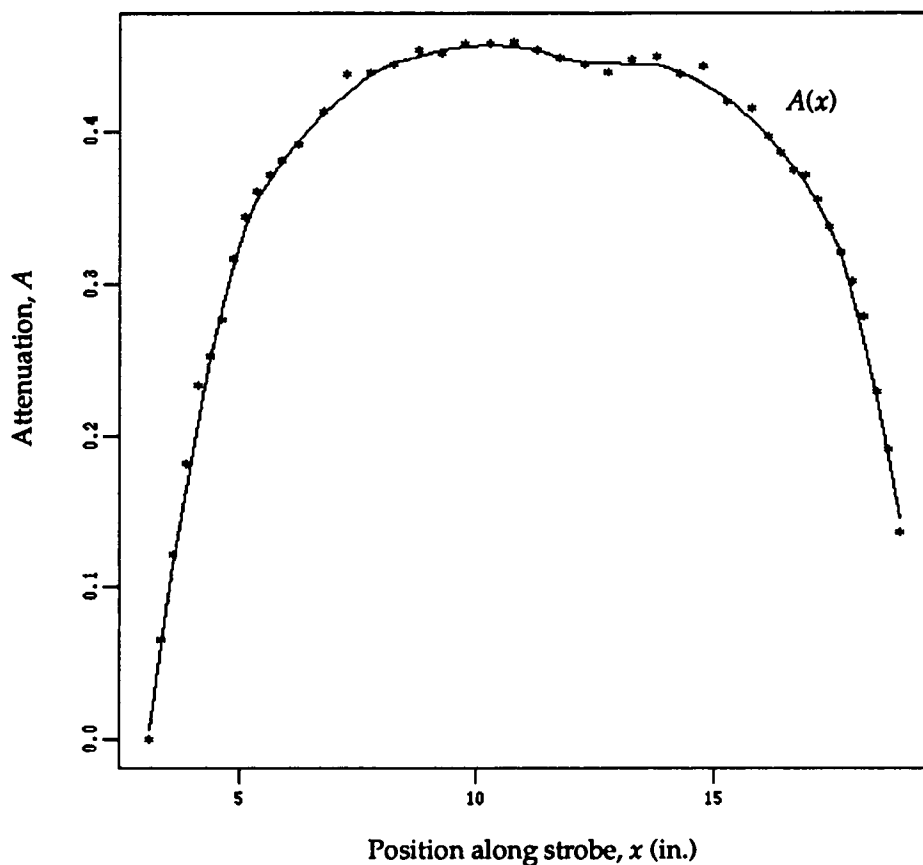


Figure 3.7. Attenuation function, $A(x)$.

A neutral density filter with the given attenuation characteristic was manufactured and attached to the surface of the strobe housing, flush against the mylar filter. The resulting illumination profile was uniform to within 8% across the surface of the strobe light casing.

Intensity Normalization

As mentioned previously, the intensity of the actual strobe flash varies on the order of 5%. This is typical of all machine vision strobe systems. To eliminate this variation in each acquired image, an intensity normalization path was implemented. A reference strip with one black and one white square of known reflectance was placed in the camera's field of view. After a new test stamp image is acquired, the intensity values of the black and white squares on the reference strip, T_b and T_w

were compared to the stored standard values R_b and R_w taken from the original reference image. A linear transformation N was created of the form

$$N(i) = mi + k \quad (3.8)$$

$$m = \frac{R_w - R_b}{T_w - T_b} \quad (3.9)$$

$$k = R_w - mT_w \quad (3.10)$$

where i is the measured intensity, m is the slope of the transformation, and k is an offset that corrects for a uniform shift in intensity amplitude. The transformation that results from the intensity normalization is illustrated by the example in Figure 3.8.

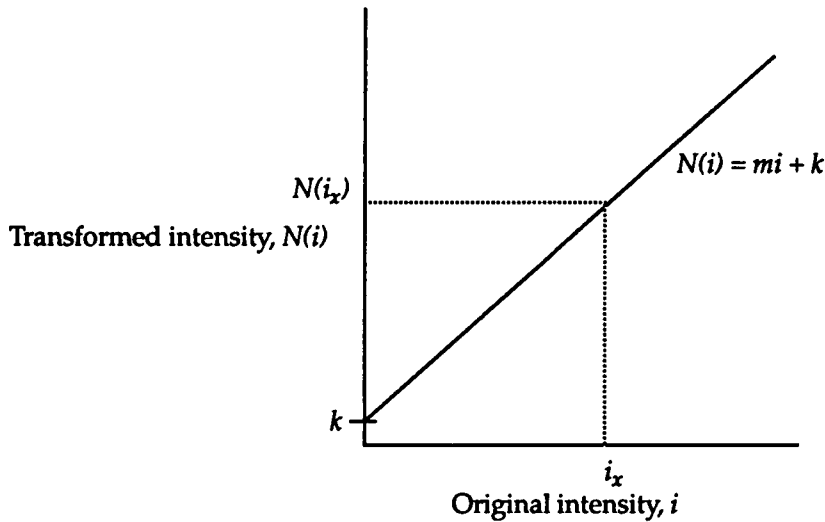


Figure 3.8. Intensity normalization transformation.

(m = slope of transformation, k = offset)

Image Digitization

The method of image digitization is very important to an image processing system because the quantized image data are the only representations of the actual illuminated object that the machine vision system can make decisions on. This may sound obvious, but in many cases the designer of an automated inspection system does not put forth enough effort to be sure the image

is being digitized in the most accurate way possible. There are two common types of analog-to-digital (A/D) converters that can be used with standard machine vision cameras. They differ in the way that the timing between the camera and the A/D converter is established. The two types of timing used are phase lock loop and pixel clock slave.

Phase Lock Loop

An A/D converter that employs phase-lock-loop (PLL) timing is usually an RS170-type A/D converter that derives its master timing signals from the horizontal and vertical synchronization pulses (H-sync, V-sync) in the video stream. Figure 3.9 illustrates a horizontal video line from an RS170 video signal with H-sync pulses.

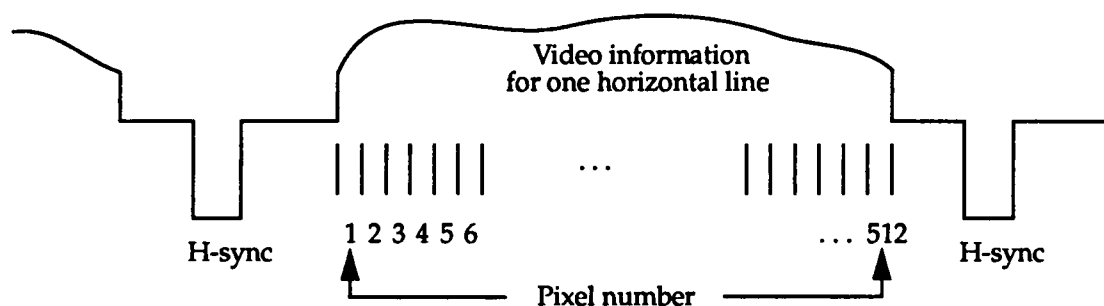


Figure 3.9. RS170 video signal.

The A/D converter using PLL timing must use sync-stripper circuitry to extract the H-sync pulses from the video signal shown in Figure 3.9. One problem with this type of timing circuitry is that synchronization between the camera and the A/D converter occurs at only the end of every line. In a typical image 512 pixels will be digitized in between H-sync pulses. This can lead to what is known as pixel jitter when the pixels on one line are shifted horizontally from the pixels below.

An experiment was carried out by acquiring an image of a vertical line pattern with an RS170 format camera and a Digimax RS170-type A/D converter. Two successive pictures were taken without moving the camera or the subject. It was found that successive video lines were displaced horizontally with respect to one another. The displacements were on the subpixel level but were large enough to cause significant measurement error. An illustration of this is shown in Figure

3.10. The figure shows a simple subtraction of the two images acquired one after another. Ideally, the result would be zero. In this case, however, horizontal pixel jitter in the two frames is evident in the nonzero result. Notice the four bands marked in the image that are slightly brighter than the rest of the image. Applications such as surveillance or human inspection of industrial processes can tolerate pixel jitter associated with PLL timing, but when the resulting image has to be processed at subpixel levels, another type of synchronization should be used.

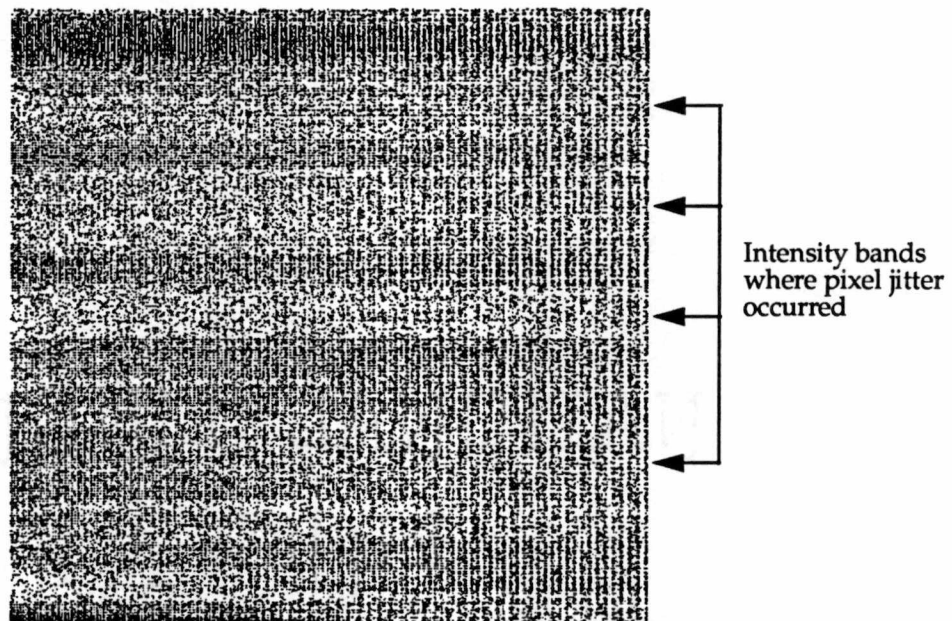


Figure 3.10. Difference image of two vertical line patterns.

Pixel Clock Slave

Another timing mechanism that is more suited to machine vision applications is that of pixel clock slave. An A/D converter employing this timing derives its master timing signals directly from the pixel clock output of the machine vision camera. This allows synchronization after every pixel in the image. Similar experiments with the vertical line pattern were conducted with an A/D converter slaved to a camera's pixel clock, and no pixel jitter was evident.

Summary of Acquisition System

The final configuration of the PRS acquisition system used a machine vision camera with a

CID solid state image sensor. The images of the stamps are focused on the sensor through a 55-mm macro lens that is specially designed to produce a flat field image (no geometric distortion) in close-up photography. Strobe lamps illuminate the stamp from above and below. The back-illuminating strobe has a mylar filter and a customized attenuating neutral density filter. An analog-to-digital converter digitizes the incoming image to 8-bit accuracy and derives its master timing signals from the CID camera's pixel clock to prevent pixel jitter. The image now has to be stored and processed on the basis algorithms presented in Chapter 2.

Chapter 4

Image Processing System

Hardware Architecture

Whenever one is building an image processing system that must perform at real-time rates to keep up with some industrial process, the need for high-speed hardware to implement processing and data throughput is usually essential because of the tremendous amount of data associated with digital images. One 512 by 512 image with 256 levels of gray occupies 262,144 bytes of memory. A high-speed, dedicated image bus and specialized processors are normally required to handle the inspection challenge. This chapter describes the overall hardware architecture of the PRS and describes some of the essential components that provide the processing power needed for continuous stamp inspection at 400 ft/min. Also, a discussion of the software methodology and how it was executed on specialized processors to achieve the goal of the registration measurement is presented.

VME Bus

One of the first decisions made in the design of the PRS hardware environment was the system bus architecture. The two main considerations in making this decision were the system had to allow great flexibility during the research and development stages of the design and had to be expandable to handle the compute power requirements anticipated for the final implementation. The VME bus has support from a multitude of different vendors offering a large variety of hardware modules of varying performance levels. One of the key reasons for choosing the VME environment over a PC-based environment was the availability of high-performance image processing hardware. The VME bus supports 8-, 16-, or 32-bit processors and data transfer paths, and a 32-bit processor was anticipated to be needed for the PRS. Also, because of the necessity for real-time measurements and the need for external synchronization to a moving object, the possibility of a multiprocessor environment needed to be supported. This prompted the need for data bus arbitration among more than one master and a sophisticated interrupt handling mechanism. The VME bus supports all of these requirements. Last, but not least, resources with VME knowledge and experience were immediately available for support in the event of problems.

A brief description of the signal types used in a VME bus system show how all of the anticipated needs are supported (Heath 1989). The data transfer bus (DTB) is the interface between different modules in the same chassis. It consists of 32 address lines and 32 data lines. The module in slot number one in a VME chassis is known as the system controller and performs bus arbitration when more than one module asks for control of the DTB. The arbitration of the DTB is carried out through the monitoring of four bus request lines and a daisy-chained bus grant line. If two modules request control of the bus at the same time, the system controller arbitrates control to the module in closest proximity. The VME bus also has a set of user-definable pins on a second connector (P2) through which the VSB bus can be implemented. Many designers of VME hardware use the VSB bus for heavy data I/O between multiple modules that would put too much traffic and be too slow on the VME data transfer bus.

Interrupt handling can be controlled by the system controller or any other module in the system with master capabilities. A module is considered a master if it has the capability to take control of the DTB. When a module generates an interrupt request on one of the seven interrupt lines, the module assigned as the interrupt handler immediately requests control of the DTB. Once control is gained, that interrupt handler generates an interrupt acknowledge signal, which is daisy-chained to each board in the system. When the interrupting module receives the interrupt acknowledge signal, it places its data on the DTB and tells the interrupt handler that the data are ready.

The overall architecture is shown in Figure 4.1. Each of the modules will be described in later sections of this chapter.

Host Computer

Host and Image Processing Computer

The main programming/development environment is provided by a SunTM 3/E system running the UNIX operating system. The Sun 3/E is a three-board set consisting of a CPU board, an SCSI/Ethernet module, and a color video board which plug directly into the VME bus. All of the programming was done in the C language. UNIX is a very powerful operating system and allows great flexibility during the development stages of the PRS. It is, however, not efficient at real-time processing.

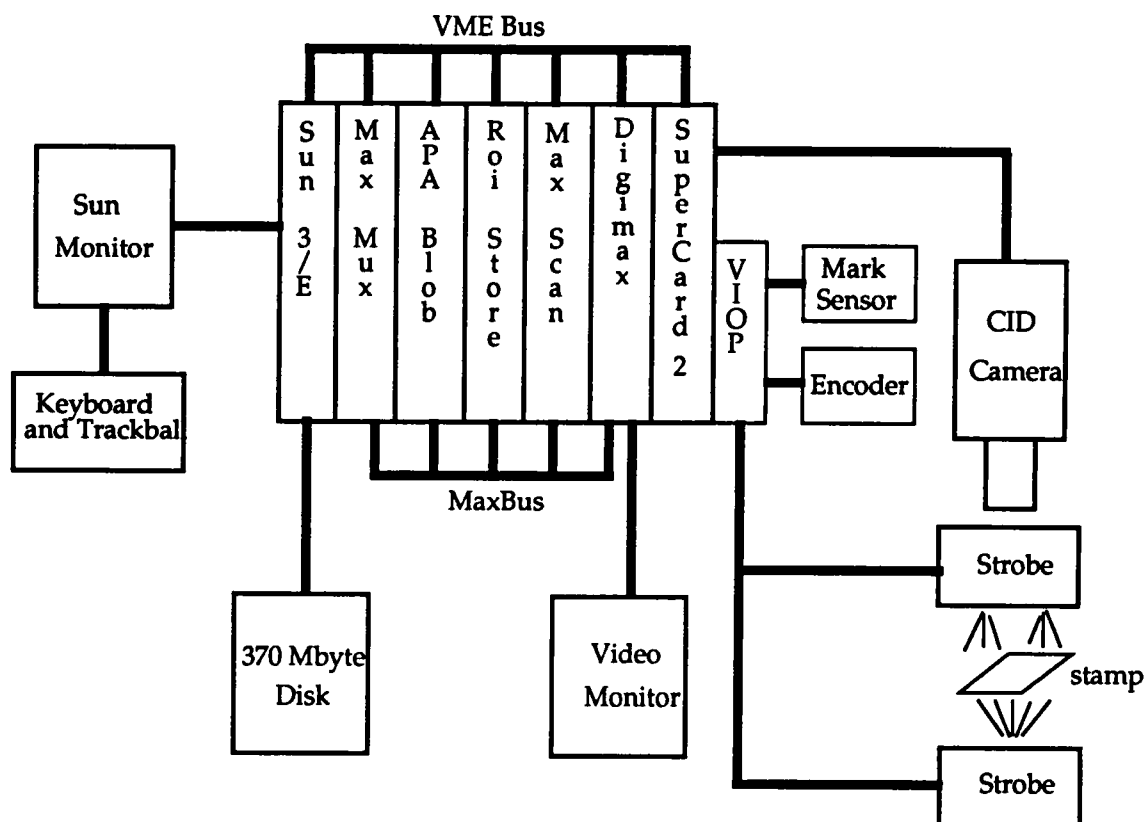


Figure 4.1. PRS overall hardware architecture.

There are too many background tasks associated with multi-user tasks, network traffic monitoring, etc., that steal CPU cycles and keep the rest of the system from responding at real-time rates. It was decided that in the final PRS implementation the Sun3/E would perform tasks that were not compute intensive and time critical.

When the PRS is running, the Sun 3/E system serves two purposes as shown in Figure 4.2. The Sun 3/E acting as a supervisor oversees the two components of the PRS machine vision system. The first is the image-acquisition hardware, which converts the physical stamp into an image in memory. The second subsystem is the image processing hardware which extracts the desired measurements from that digitized image. There is handshaking between the Sun 3/E host computer and several other modules in the VME chassis. The host computer issues supervisory start and stop commands to the other processing modules in the PRS system that will be described later.

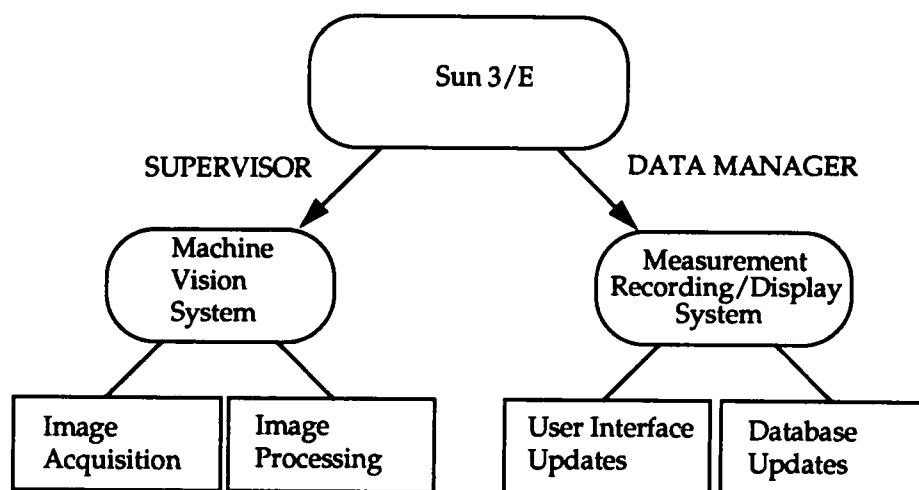


Figure 4.2. Sun 3/E tasks.

In addition to its duty as a supervisor, the Sun 3/E must act as a data manager. As the other processing modules calculate the perforation-to-image registration and deliver the information to the host computer, it must both update the operator interface display monitor as well as enter every registration measurement into the historical registration database. Remember that these are tasks that are not time critical. For example, if the operator interface updates 30 ms later than normal, the operator will not notice a difference in the flow of the PRS measurements.

CID Camera Configuration

The CID camera has a few special features that make it ideal for strobed image acquisition. These features will be briefly described here. The camera will free-run as soon as power is applied to it. Free-running means it is acquiring images continuously at 30 frames/s. The camera can then be asynchronously reset to start scanning at the beginning of the frame at any time by applying a signal on the frame reset line (FR). The camera's pointer will immediately return to the top of the sensor to begin scanning a new frame of data. A signal applied to the DUMP line in conjunction with the FR will dump all of the charge (image data) that had built up on the sensor. This lets the camera start with "a clean slate" before the next object is imaged. The inject inhibit line (I/I) is also used which, when held low, prevents any readout of the image data from the sensor. It can be used for continuous integration of up to 1 s before the image data are scanned out of the camera. The

coordination of all of these signals is described in detail in the Acquisition System Integration section later in this chapter.

Measurements of two stamps located in opposite corners of a sheet will give good data points to determine what the overall perforation-to-print registration is for that whole sheet. The registration values for the stamps in the middle of the sheet can be interpolated to get an estimate of the registration for every stamp. To get images on both sides (edges) of a web, two stationary cameras were positioned over the opposite sides as shown in Figure 4.3. The A/D converter module has two software-selectable analog input channels, so the input can switch back and forth between the cameras.

The only potential problem with this two camera setup is the small amount of time between when the last stamp on one sheet passes under the right camera and when the first stamp on the next sheet passes under the left camera (see Figure 4.3). There is not enough physical distance between the last stamp on a sheet and the first stamp on the next to allow complete measurement processing in between. This setup implies that two images have to be acquired and stored in memory separately before the processing can begin. It takes 33 ms to scan one image out of the camera. If the press were running at 400 ft/min, then the web would travel 2.64 in. in 33 ms. This amount of travel can be taken care of by offsetting the cameras by a small distance on the mount to be sure the first stamp on the next sheet will not be missed.

Dedicated Image Processing Hardware

Many of the modules in the PRS are specifically designed dedicated to image processing tasks. Each of these modules will be described in function. The interconnection of these modules is shown in Figure A.8 in the Appendix.

Image Bus

The MaxBusTM is a dedicated image bus that is used to pass image data between all of the image processing modules described in this section. The bus passes 8-bit data at a rate of 10 MHz. The MaxBus also carries the image transfer timing signals

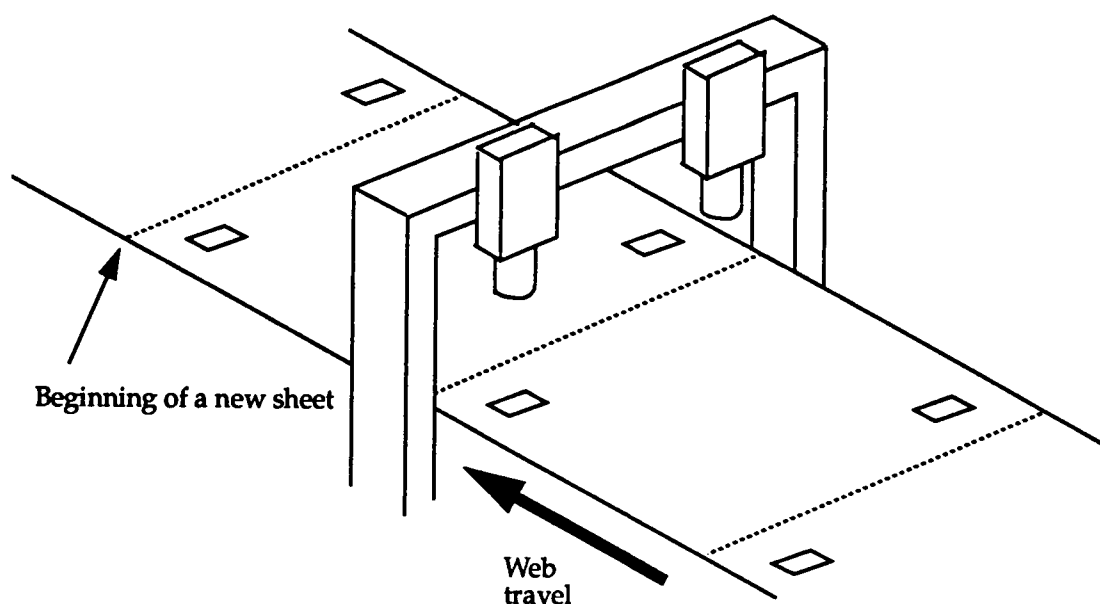


Figure 4.3. Two-camera setup on perforator/sheeter.

Image Digitizer

This is an analog-to-digital converter (ADC) that accepts the analog video signal from the CID camera and digitizes it into 8 bits of information (256 levels of gray). The MaxScan™ scanning format is software programmable, and image capture signals can be asynchronous. This is important in the case of the PRS because the speed of the stamp web is driving the timing of the image acquisitions. This is an external and unpredictable event. The MaxScan is a video digitizer that interfaces well with the CID camera because it accepts video in a noninterlaced format. Also, the MaxScan data timing is based on the pixel clock slave technique described in Chapter 3.

Another useful feature of the MaxScan board is the programmable horizontal (H) and vertical (V) look-up tables (LUTs). Figure 4.4 will help to explain the operation of the LUTs. The MaxScan has two 8-bit programmable LUTs that can generate pulses at either the pixel rate (HLUT) or line rate (VLUT) of the attached camera. These LUTs can be programmed to control internal or external processes at the pixel resolution of the camera. The board has a horizontal counter fed by the camera's pixel clock which runs from 0 to 511 counting pixels on the current line, and a vertical counter fed by the horizontal synchronization pulse (H-sync), which runs from 0 to 511 counting

the number of lines scanned in the frame. The outputs of the counters feed into the programmable LUTs. This feature is very useful in triggering outside events to occur at a particular point in the frame scan. Because the proper synchronization of the camera, the strobe light, and the stamp synchronization device is needed at the line resolution of the camera, the VLUT was programmed to generate the needed timing signals. Three of the output bits of the VLUT are available as inputs to a programmable array logic (PAL) device on the board, and TTL or differential-level signals can be tapped off the PAL outputs A, B, and C. The original PAL was removed, and a new one was programmed to generate the three VLUT bits as outputs to the camera and strobes. In the PRS, the MaxScan VLUT is programmed to send a fire signal to the strobe near the beginning of the frame. This feature as it is used in the synchronization system is described in more detail in the next section. The part-in-position (PIP) signal from the stamp synchronization device to be described later in this chapter is fed directly into the MaxScan's vertical drive line. Consequently, when the PIP goes low, indicating a stamp is in position to be acquired, this will reset the Max-Scan's vertical counter (sets it to line 0), which prepares the system for the next image acquisition.

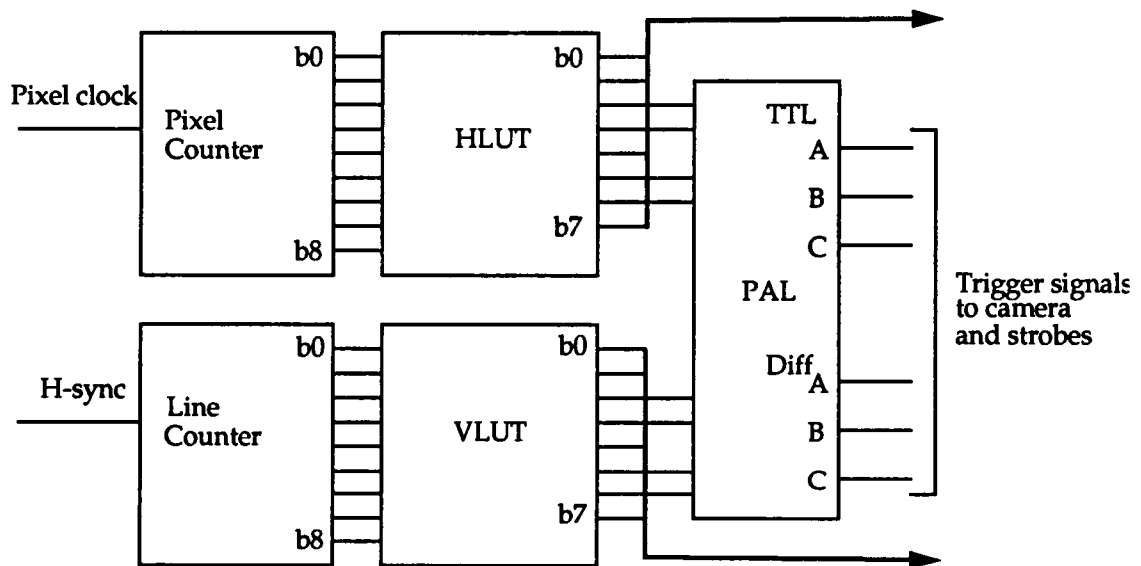


Figure 4.4. Analog-to-digital converter programmable look-up tables.

Image Look-Up Tables

Another module installed in the PRS is a MaxMuxTM. The board is a point pixel processor and has two 8-bit LUTs and one 16-bit LUT on-board. Because it is a point processor and does its pro-

cessing on the image data as the data passes through, the board does not need any image memory. The linear transformation given by Equation (3.8) is programmed into an LUT in the MaxMux, which normalizes the whole image to the standard intensity and removes 5% intensity variation caused by the strobe output inconsistency. The image data come to the MaxMux over the MaxBus and are processed at a rate of 10 MHz before they are passed on to a storage module.

Image Memory

After the image is normalized in intensity by the MaxMux, it is passed over the MaxBus to the ROlstore™ memory module for storage. The ROlstore model used in the PRS has 2 Mbytes of image memory. This allows storage of 8 images in 512 by 512 pixel format with 8-bit/pixel image data. The image memory is divided up and used according to Figure 4.5.

frame 3	Not currently used	Registration template overlay
frame 2	Not currently used	Live video
frame 1	Reference feature overlay	Reference image
frame 0	Registration line overlay	Normalized test image
	Most significant	Least significant

Figure 4.5. ROlstore image memory configuration.

The LS (least significant) side of the memory holds both the stored reference image as well as each new normalized test image as it comes in to the ROI Store. Frame 2 on the LS side is used for live video display during setup of the system for camera position and focus. Frame 3 in the LS side holds the registration template on which the error bars giving the registration are displayed. On the MS (most significant) side of memory, frame 0 is where the registration lines are drawn, which include lines through the perforation borders and perpendicular lines from the image feature to the perforation borders (similar to Figure 2.17). Frame 1 is where the rectangles that outline the chosen reference image feature are drawn. Both frame 1 and frame 0 on the MS side can overlay on top of the reference and test images respectively. For example, when a reference feature is chosen, the operator can see the bounding rectangle of the feature overlaying on top of the reference stamp image.

Feature Extraction Hardware

The two stamp objects that need to be extracted from the digitized image are a preselected image feature and the perforation border. The image feature is extracted by using the template-matching algorithm. To extract all of the perforations from the image at a high rate of speed, a connectivity analyzer or "blob board" was added to the PRS.

The perforation locations are measured by using the specialized image processing blob board. The blob board set used in the PRS is an APA512. Given a predetermined threshold value, the blob boards will threshold an 8-bit gray-scale image, converting it into binary form. The boards then do a neighborhood and connectivity analysis on the result and return parameters about each blob in the scene. All of these activities occur in 1/30 of a second. A blob can be defined as a group of adjacent pixels with the same value (0 or 1 in a binary image). This reveals why backlighting is such an advantage. The perforations are brighter than any other feature in the stamp, so they can be thresholded uniquely and analyzed by the blob boards. One of the parameters that is returned is the centroid (center of mass) of each blob. Figure 4.6 shows an example of an acquired image of the Grosbeak stamp. Notice the brightness of the perforations in the image.



Figure 4.6. Back-illuminated stamp image.

Once the APA512 boards return a list of centroids of all the perforations, they are passed on to the vector processor module to be described later in this chapter. The vector accelerator is where the perforations are grouped into borders, and the least-squares line is calculated to fit through the centroids.

Stamp Synchronization Device

Synchronizing the acquisition system to the motion of the stamp web allows the strobes to be fired at a point in time when a particular stamp is under the camera. The stamp synchronization device is a hardware design used to provide this function. The synchronizer consists of three major components: a fine-resolution encoder, a registration mark sensor, and a Motorola 68000-based intelligent I/O module called a VIOP (very intelligent input/output processor).

The fine-resolution encoder is attached to the end of one of the shafts of the perforator/sheeter press as shown in Figure 4.7. The output of this shaft encoder feeds one of the I/O pins on the VIOP. The basic function of the device is to keep track of web position by counting the encoder pulses with the 68000. The encoder outputs 1800 TTL-level pulses for every revolution of the 6-in.

shaft that it is attached to. This translates into 1 encoder pulse for every 0.005 in. of stamp web travel. Consider that the 68000 processor can be programmed to output any variety of signals at each encoder pulse. Different events can now occur within the 68000 processor at a resolution of 0.005 in. of stamp web travel. The 68000 is programmed to count these pulses and to output a PIP signal at the appropriate point on the stamp sheet to within 0.0025 in.

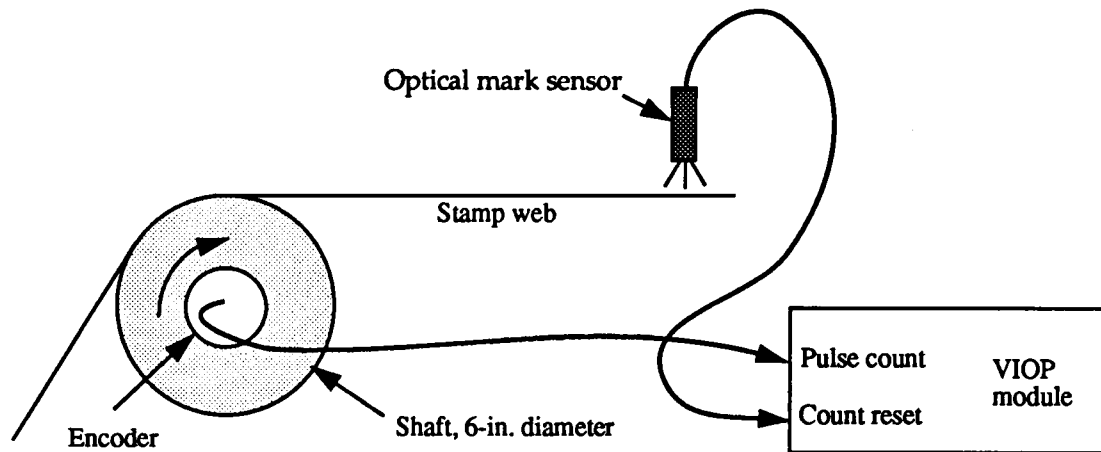


Figure 4.7. Stamp synchronization device.

VIOP = very intelligent input/output processor.

The optical mark sensor looks for color registration marks that indicate a new sheet. When the mark sensor detects a mark that indicates the beginning of a new sheet, the 68000 zeros the encoder count and begins counting again. With this implementation, the synchronization between the stamp web and the rest of the system is reset after each sheet. The 68000 can then be programmed to output a trigger signal to a sensor at any encoder pulse from the first pulse after a new sheet mark to the last pulse before the subsequent new sheet mark.

Acquisition System Integration

The synchronizing of the three parts of the acquisition system: the strobe lights, camera, and the stamp synchronization device will now be discussed. The requirements for equipment synchronization are given with reference to Figure 4.8. The horizontal drive (HDR), or H-Sync, from the CID camera is the timing baseline that must be used to successfully acquire a strobed image. HDR marks the end of a horizontal line of image data. The PIP signal comes from the stamp VIOP module when the desired image is under the camera and ready for acquisition. The frame reset

(FR) tells the camera to move its scanning pointer to the top left of the sensor and should be generated at the same time as PIP. Another signal that must be synchronized with PIP and FR is DUMP, which instructs the camera to dump all of its charge to start integrating with a clean sensor. The FR signal must remain high long enough (at least $63.5\ \mu\text{s}$) to sample the falling edge of an HDR signal. At this point, the camera resets the frame and outputs an end-of-frame (EOF) signal and it returns to the top left of the sensor. On the next rising edge of the HDR signal, the inject inhibit (I/I) for the camera should be activated. The I/I prevents the destructive readout of the individual pixels on the sensor until it is deactivated. The I/I is held low for three HDR pulses, and then the strobe is fired (FIRE). The I/I is then released, and the image data are scanned out of the camera in a progressive format (noninterlaced).

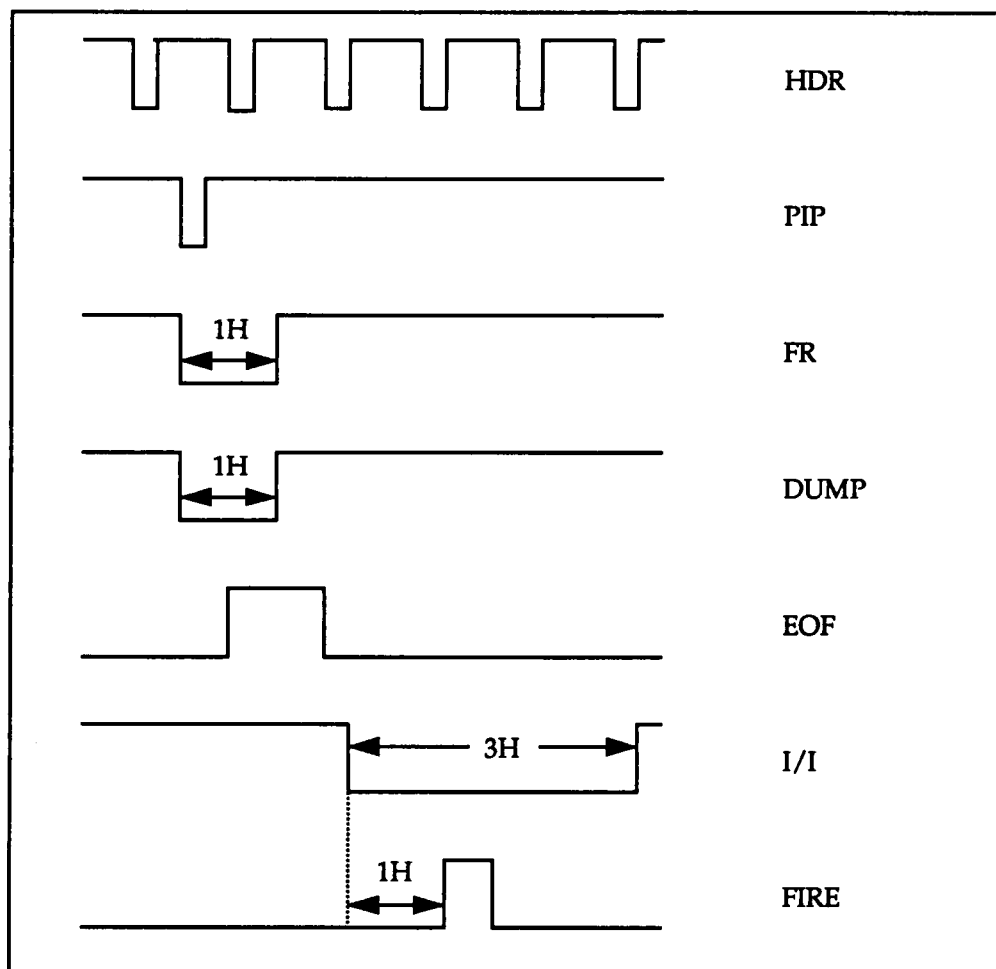


Figure 4.8. Timing diagram of image acquisition signals.

These timing and signal requirements (FR, DUMP, I/I, and FIRE) are generated by using the programmable vertical LUT available on the MaxScan image-acquisition board described earlier in this chapter.

Vector Accelerator

As discussed previously, a high-speed, dedicated piece of hardware was needed to execute the image-processing functions at high enough speeds to meet the 150-ms per measurement design goal. A vector accelerator was programmed to do this task. The accelerator is a VME-compatible module that runs independent of (in parallel with) the host computer. It has its own microprocessor, 2 Mbytes of dynamic RAM (random access memory) and master DMA (direct memory access) interface to the VME bus. It comes with a set of optimized one-dimensional signal-processing routines that can be called from a C program. These routines were hand coded in assembly language to take advantage of the RISC (reduced instruction set computer) architecture of the microprocessor. A block diagram of the vector accelerator is shown in Figure 4.9.

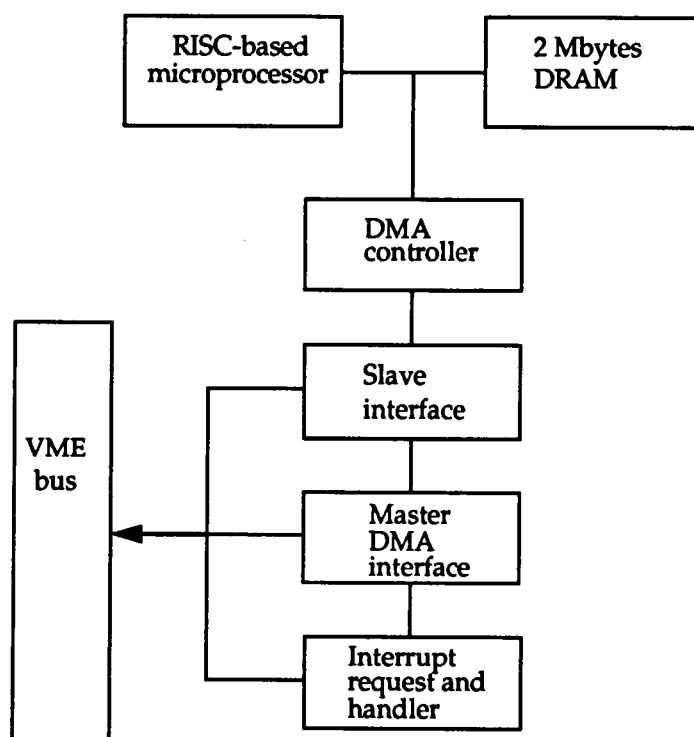


Figure 4.9. Vector accelerator block diagram.

RISC Microprocessor

The accelerator uses a 64-bit RISC-based microprocessor. The RISC architecture allows a multiply, an add, and an integer instruction to run in one clock cycle. Also, to accelerate the vector operation performance, the microprocessor uses instruction pipelining to ensure that instructions are executed on every clock cycle. No cycles are used specifically for instruction fetching only.

Host/Vector Accelerator Communication

The host computer communicates with the vector accelerator by a variety of techniques. These are illustrated in Figure 4.10 for simplification. A shared memory window can be set up between the accelerator microprocessor and the host microprocessor. This is an area of RAM on the vector accelerator that is accessible by the on-board RISC processor as well as the host processor over the VME bus. Certain memory location can be designated as mailboxes where messages can be sent back and forth.

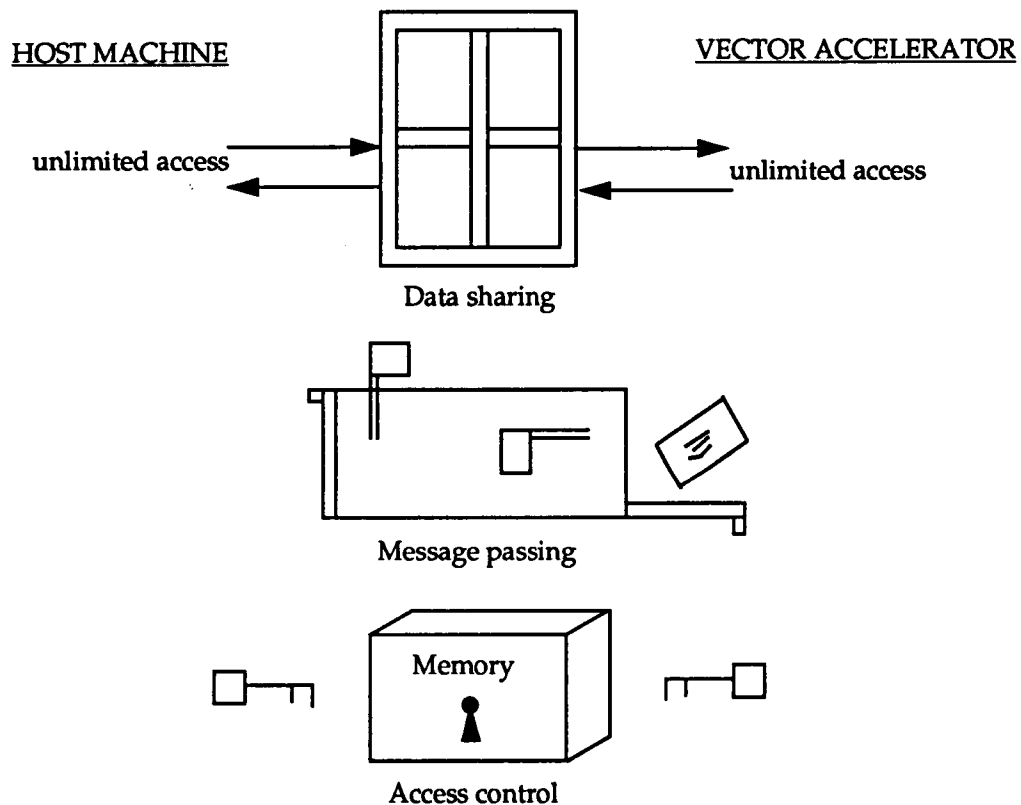


Figure 4.10. Host /vector accelerator communication.

This is a mechanism in which handshaking can be used to tell one processor or the other that a process is complete and the results are ready to be read by the other microprocessor. Finally, certain blocks of memory can be locked by the vector accelerator's microprocessor so that the host cannot access data before the data are ready.

Normalized Correlation Algorithm

The template-matching algorithm based on the normalized correlation used to find the best integer pixel match between two image features was implemented with a two-step resolution technique. This algorithm was described in detail in Chapter 2. The first step implemented on the vector accelerator is to correlate the images at a subset of every possible position. When a high degree of similarity is detected in a certain area, correlations are made at every position within that area. The result is the best integer pixel match between the images.

The image data are transferred from ROIstore image memory to the vector accelerator memory via a vector-accelerator-controlled DMA transfer over the VME bus. Using a DMA transfer here greatly reduces the load on the host computer CPU. While the DMA data transfer is occurring, the host can be tending to its supervisory and data management tasks. The provided one-dimensional vector processing routines that come with the module were used to carry out the two-dimensional correlation measurement. The result is used to find subpixel registration as described in the next section.

Subpixel Registration Algorithm

The results of the normalized correlation are passed to the subpixel registration program, which also executes on the vector accelerator module. This subpixel routine was not written by using the optimized routines provided with the board but were hand coded in C and cross compiled to run on the i860 board. The results of the subpixel measurement are sent to the Sun host memory through a shared memory window to be displayed on the operator interface.

Perforation Sorting Algorithm

After the image feature has been located, the image is sent through the APA512 to be analyzed. The list of perforation centroids that is returned is sent to the vector accelerator through a shared memory window. A sorting algorithm originally written in C to run on the host CPU was

cross compiled to run on the accelerator board. The technique uses the a priori knowledge about perforation border placement and shape to categorize this random list of perforation locations into four different groups corresponding to the four borders of the stamp.

Execution Time Results

The correlation routine (integer and subpixel) executing on the vector processor takes approximately 80 ms to complete. This translates to a 25-Mflops (millions of floating point operations per second) performance rate. The theoretical processing rate of the vector accelerator is 80 Mflops. Figure 4.11 shows the performance improvements for three algorithms implemented in the PRS.

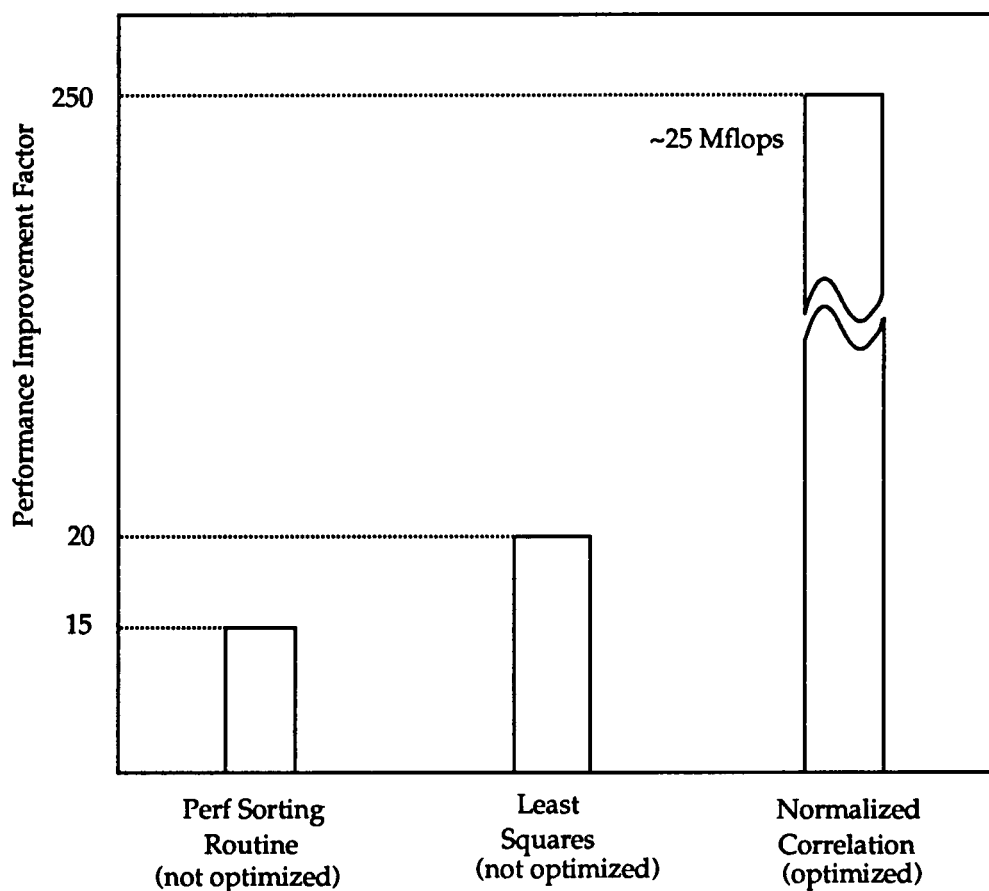


Figure 4.11. Performance improvement from host to vector accelerator.

The perforation sorting routine and the least-squares algorithms increased in speed by 15 and 20 times respectively. Neither one of these algorithms was implemented by using the optimized SSL's provided with the accelerator. The performance increase when the correlation routines were transferred from the Sun 3/E host computer to the accelerator was about 250 times. The reason for the large increase is twofold. First, the normalized correlation algorithm makes extensive use of multiply accumulate instructions which execute in parallel on the accelerator. Second, this algorithm was transformed to take advantage of the optimized SSL routines provided with the board.

Hardware/Task Integration

The relationship of all of the processes and their execution times is shown in Figure 4.12. The top box indicates algorithms and processes executed on the vector accelerator. The second box shows the host computer supervisory and data management tasks. The arrows indicate communication between the host processor and the other hardware in the system. The third box shows the processes carried out on the dedicated image processing hardware. In Figure 4.12 the time axis runs left to right. By looking at a vertical slice through the figure, one can see the processing going on in parallel in the different hardware components.

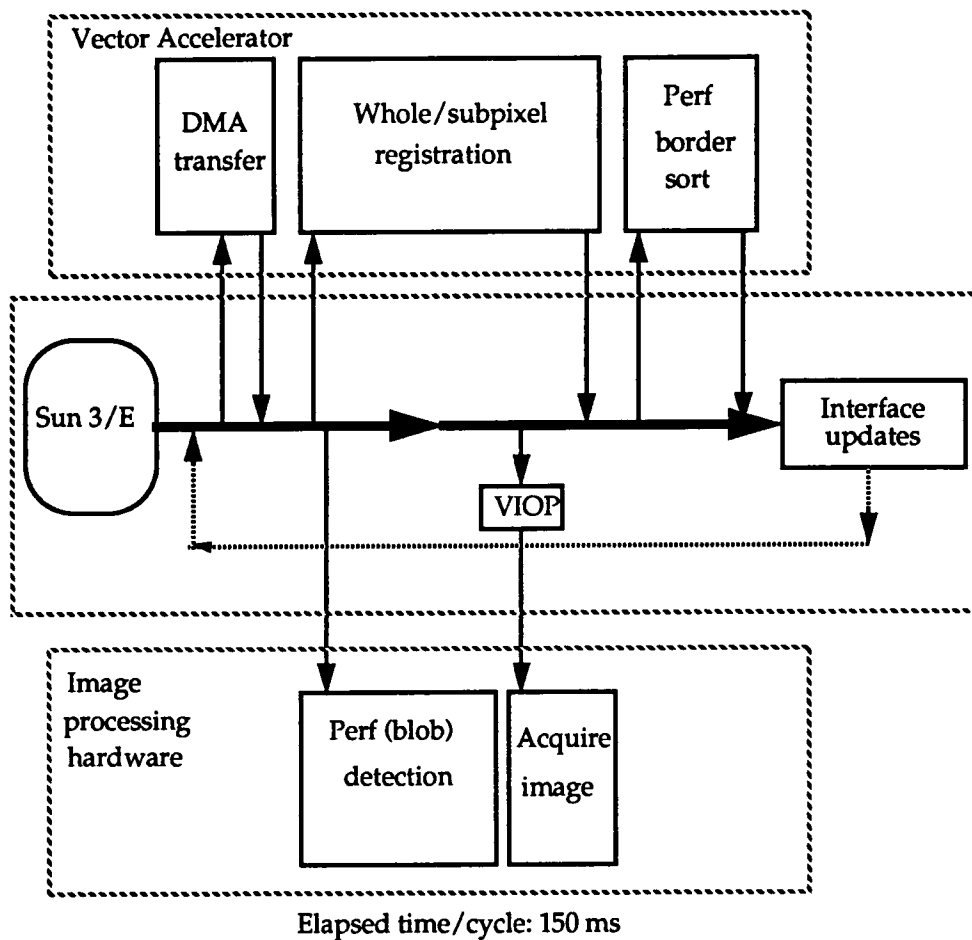


Figure 4.12. Parallel processing flow diagram.

DMA = direct memory access, VIOP = very intelligent input/output module.

Chapter 5

Conclusions

A perforation registration system was successfully implemented that allows measurements to be made on a stamp web moving at 400 ft/min. The accuracy to which the measurements were made is 0.001 in. under stable printing conditions. It is not evident at this point how the registration accuracy would be affected in the presence of gross color misregistration within the stamp images. All of the testing of the PRS was done with stamp images that were within acceptable limits of color registration.

The measurement procedure implemented consisted of two different techniques. The first, called the template-matching technique employed a normalized correlation calculation of a reference image template against a test image template. This was done at every other pixel location as a first step of a coarse correlation. The second step was to calculate the correlation at every pixel location in the vicinity of the best registration point to generate a normalized correlation data surface. The final step in the image location was to fit a three-dimensional paraboloid to the generated normalized correlation surface to interpolate the maximum. One conclusion that should be brought out at this point is that there is no way to program the PRS to pick the optimal feature within the image to use for correlation. The initial choice of a reference feature must be carried out by a human because of the subjectivity involved in the measurement. One person may pick the corner of the stamp border while another may choose the nose on a person's face as the image feature of interest.

The perforation borders were located with the help of the image acquisition system and the second registration technique called the centroid method. Backlighting the stamp was an efficient way to extract the perforation holes from the rest of the stamp image. The centroids of each perforation were found, and a least-squares line was fit through those centroids. The line then represents the average position of the stamp perforation border. This algorithm seems to be ideal for this measurement situation. This should help to emphasize the importance of a unique lighting arrangement in solving a machine vision problem.

The registration algorithms were implemented in a variety of hardware that was all governed by one host processor. Because this PRS was the first of its kind, a flexible environment had to be

set up to allow some research-and-development latitude. A second PRS could be made at a much lower cost because very specific hardware could be purchased to do the necessary jobs.

One of the unknowns in the final implementation is how the system would withstand a harsh industrial environment. A perforator/sheeter press vibrates tremendously, generates large volumes of dust, and is surrounded by high-voltage, electronically noisy machinery. The hardware could be protected fairly easily from dust, but the vibration and noise problems could possibly cause problems during the initial installation of such a PRS.

In the laboratory environment where the PRS was tested extensively on a variety of stamp issues and formats, it performed extremely well. The 0.001-in. accuracy requirement of the system was met as were the speed requirements of 150 ms per measurement. The operator interface, which was one of the last components completed, gave the perforator/sheeter operator a simple way to interface with the machine for measurement setup and execution.

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APPENDIX

Hardware Diagrams

PERFORATION REGISTRATION SYSTEM (PRS)
OVERALL CABLE LAYOUT

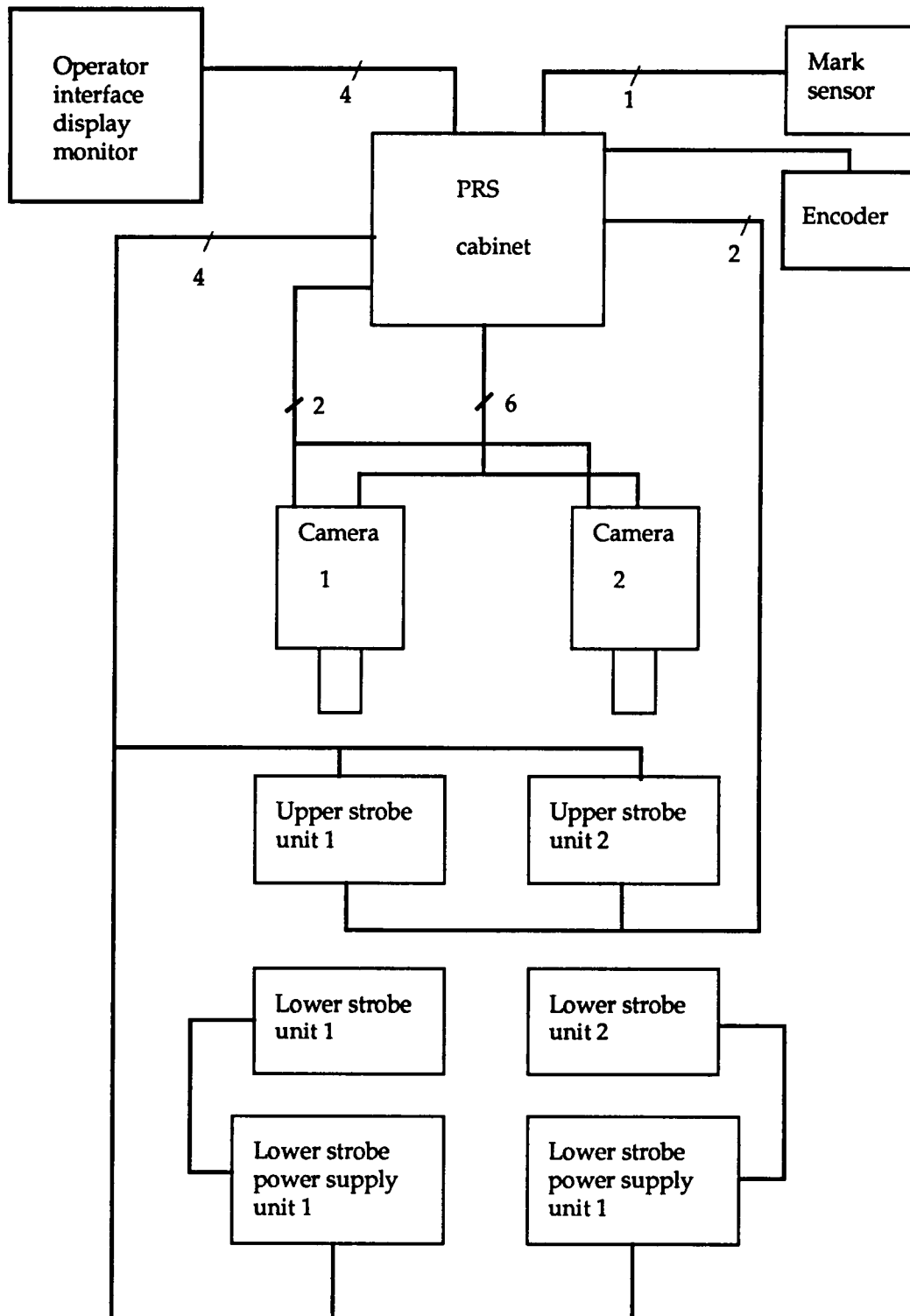


Figure A.1. Overall cable layout diagram.

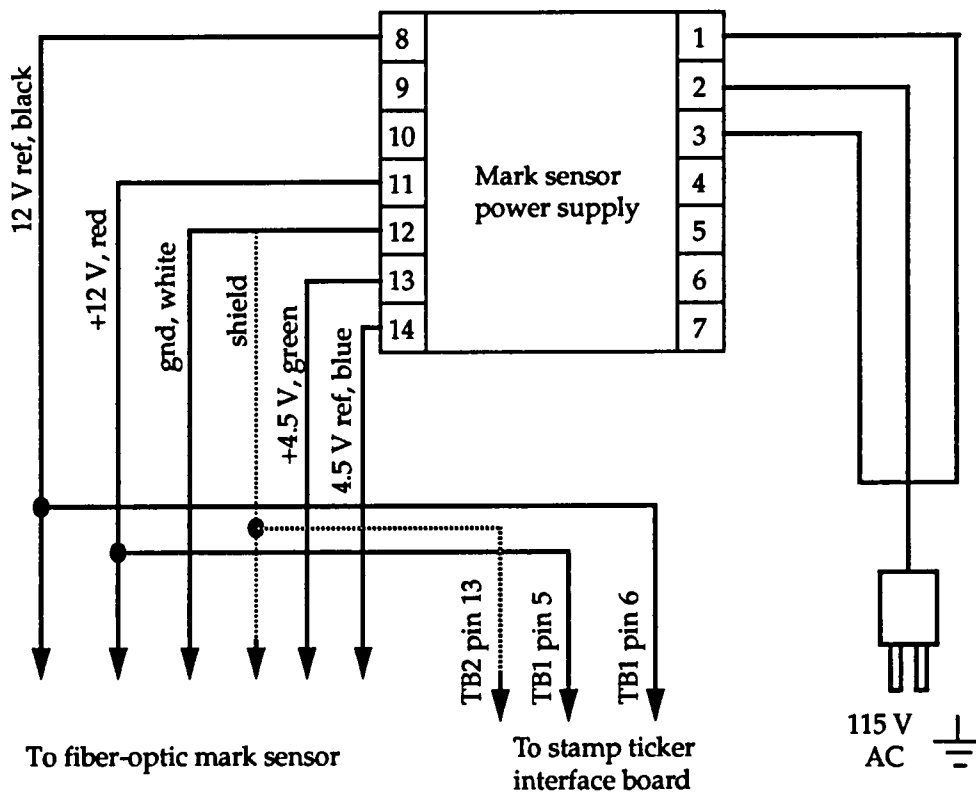
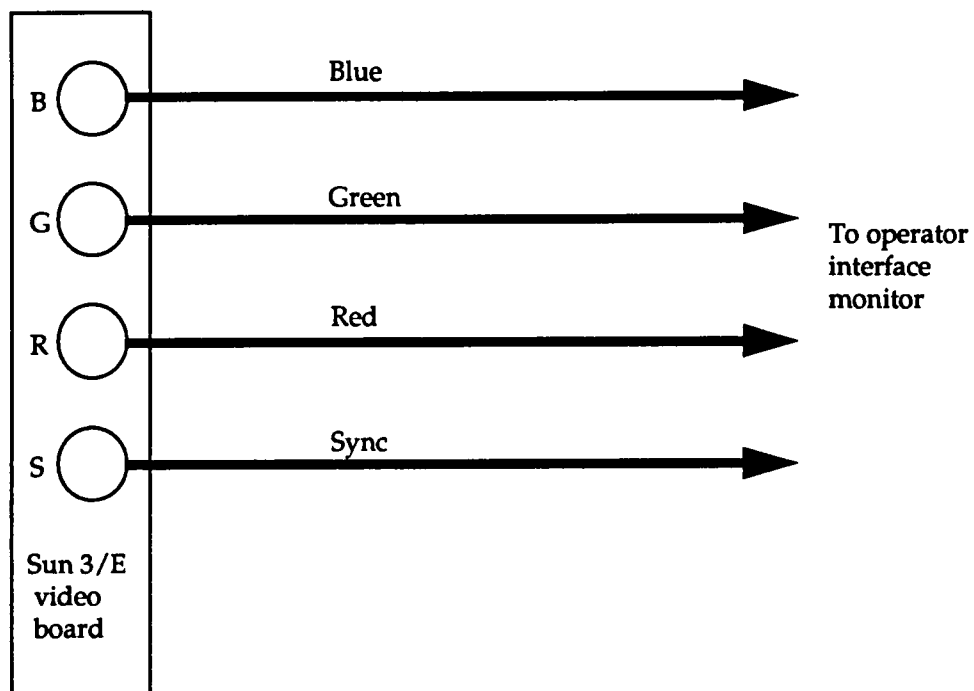


Figure A.2. Video board and mark sensor connection diagram.

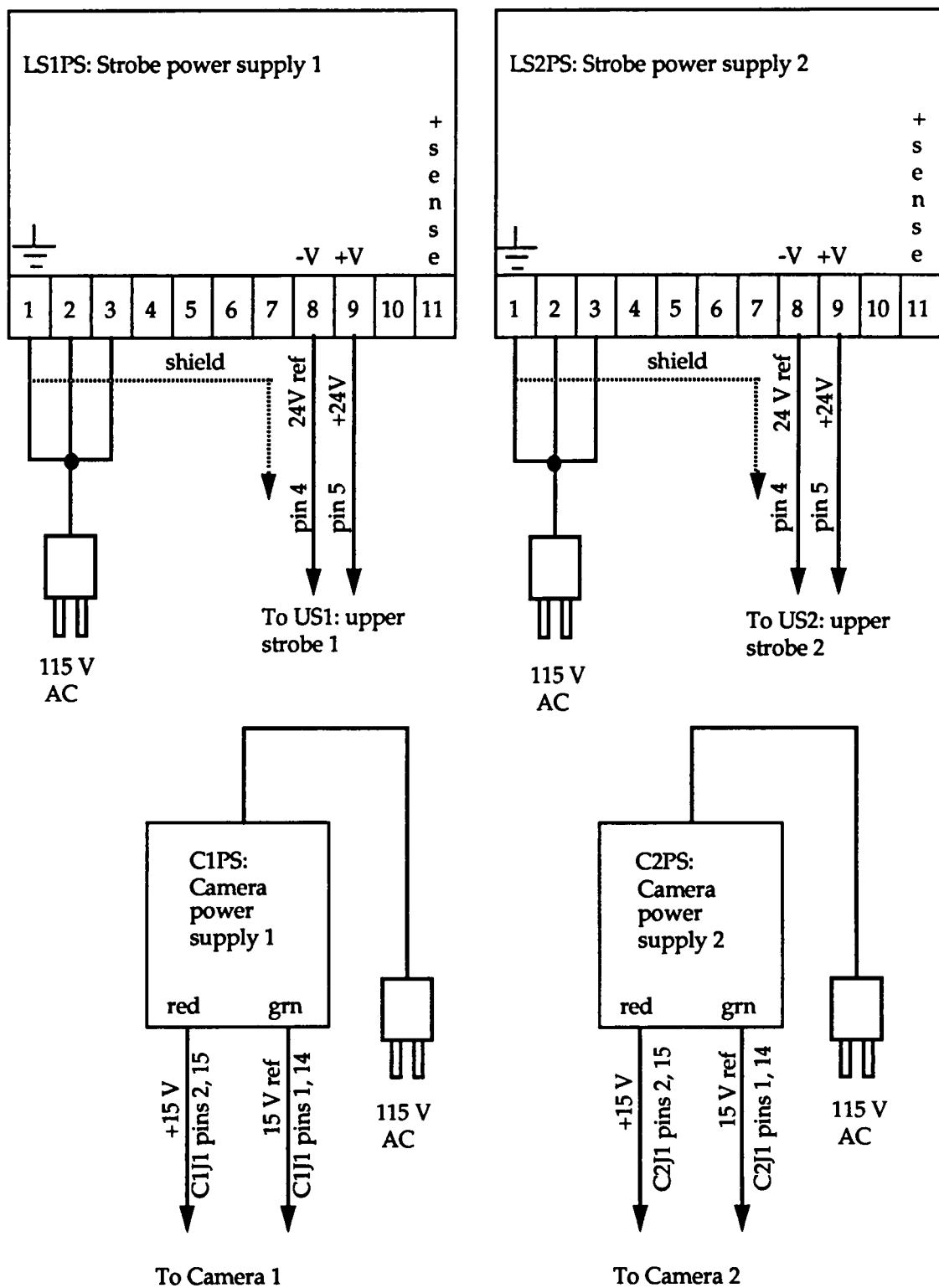
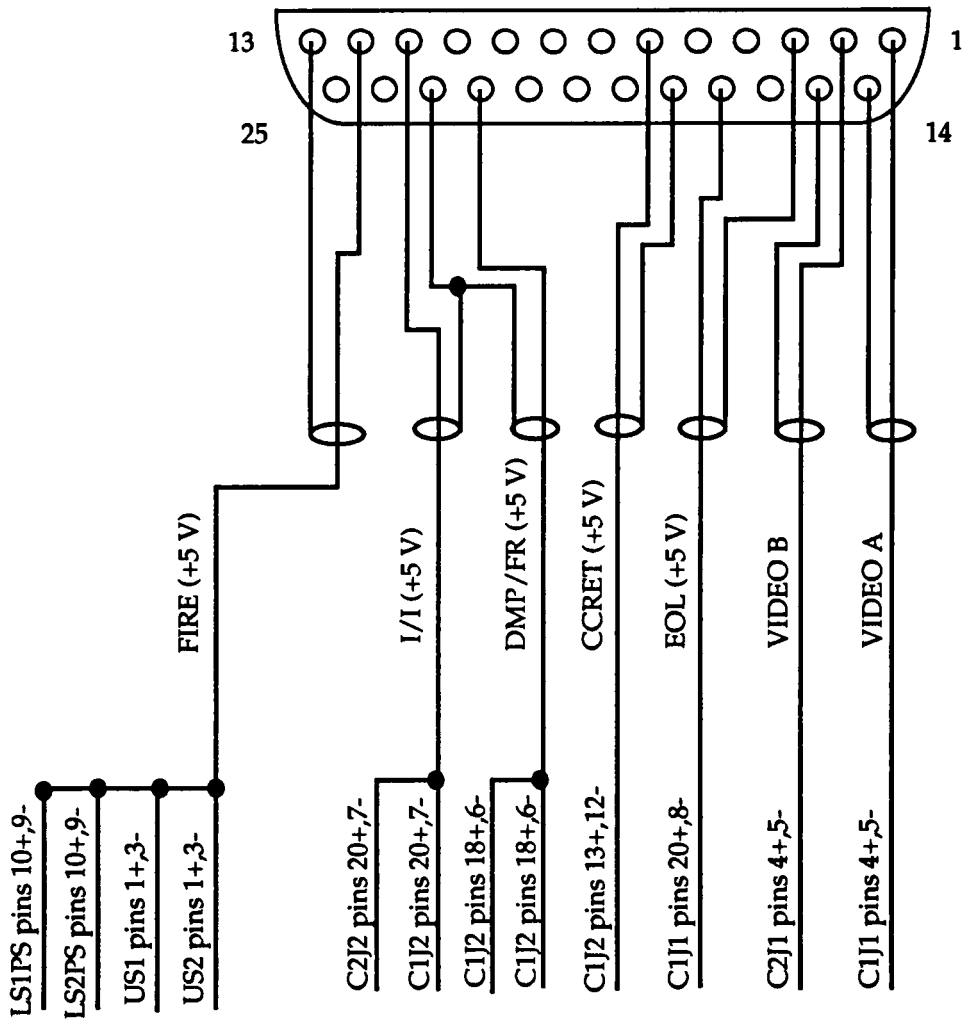


Figure A.3. Strobe power supply connection diagram.

P12: 25-pin D-type connector on MaxScan



To trigger inputs on:
 1. Lower strobe power supplies
 2. Upper strobe units

To cameras 1 and 2

P11: 34 pin-connector on ADC

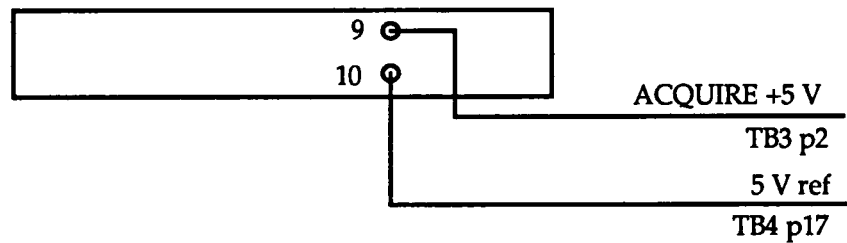


Figure A.4. Analog-to-digital converter (ADC) connection diagram.

C1J1: Camera 1 J1 connector

C2J1: Camera 2 J1 connector

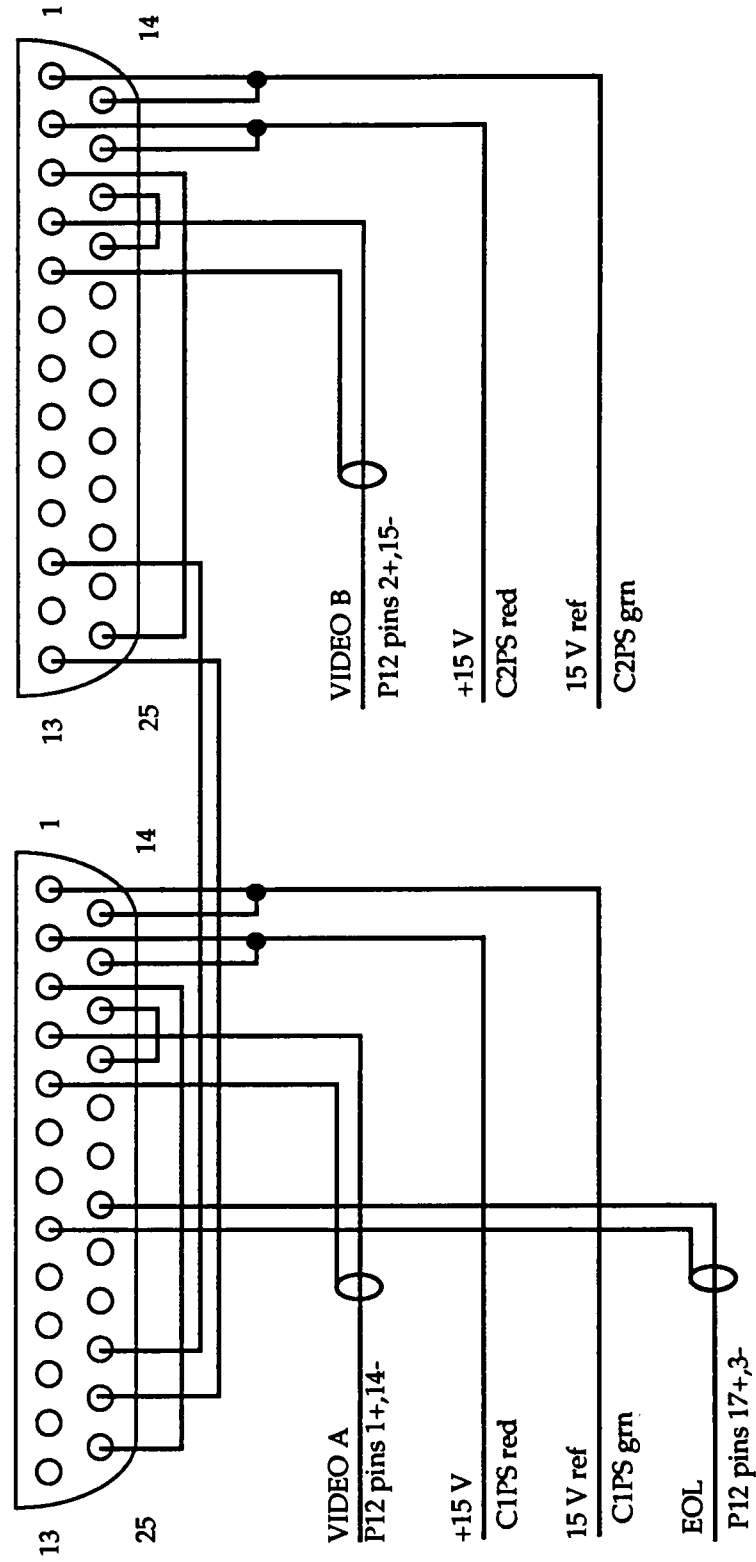


Figure A.5. Camera 1 connection diagram.

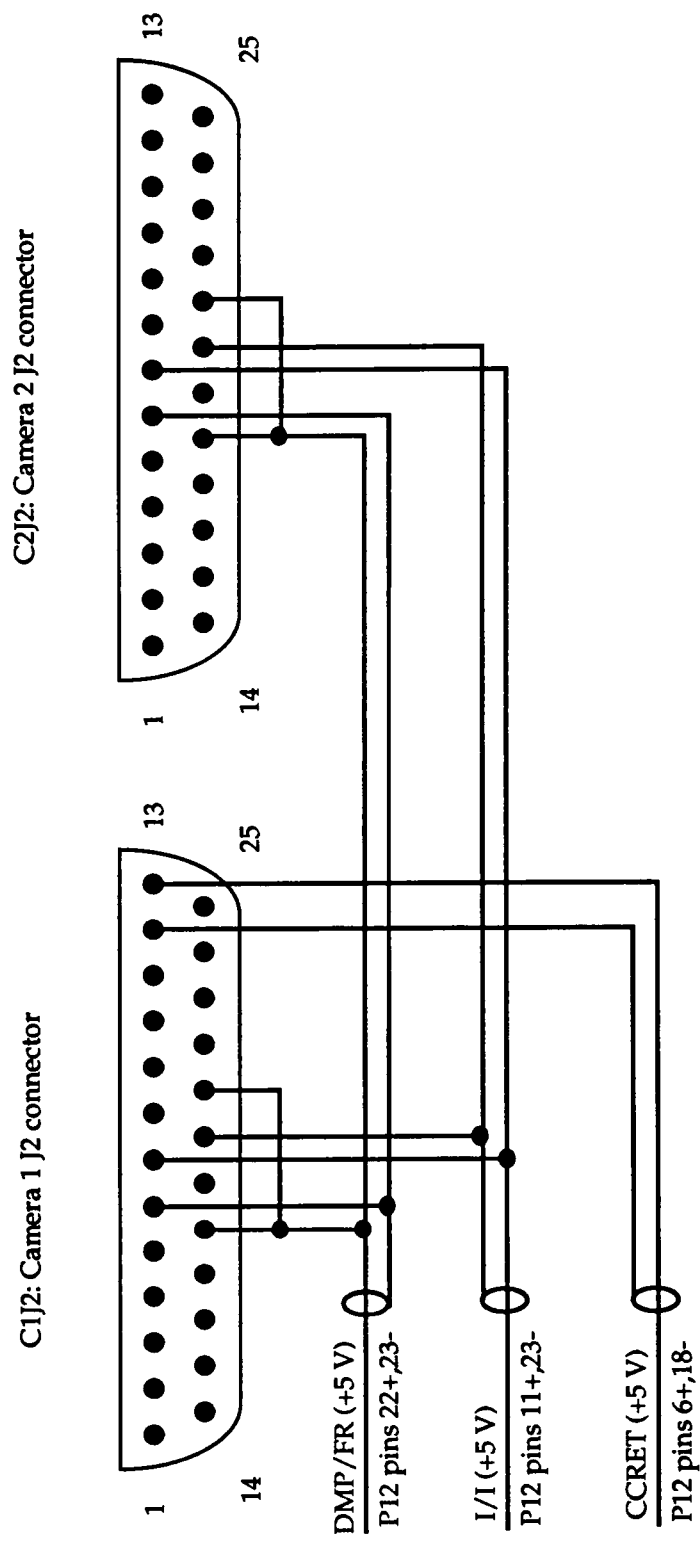


Figure A.6. Camera 2 connection diagram.

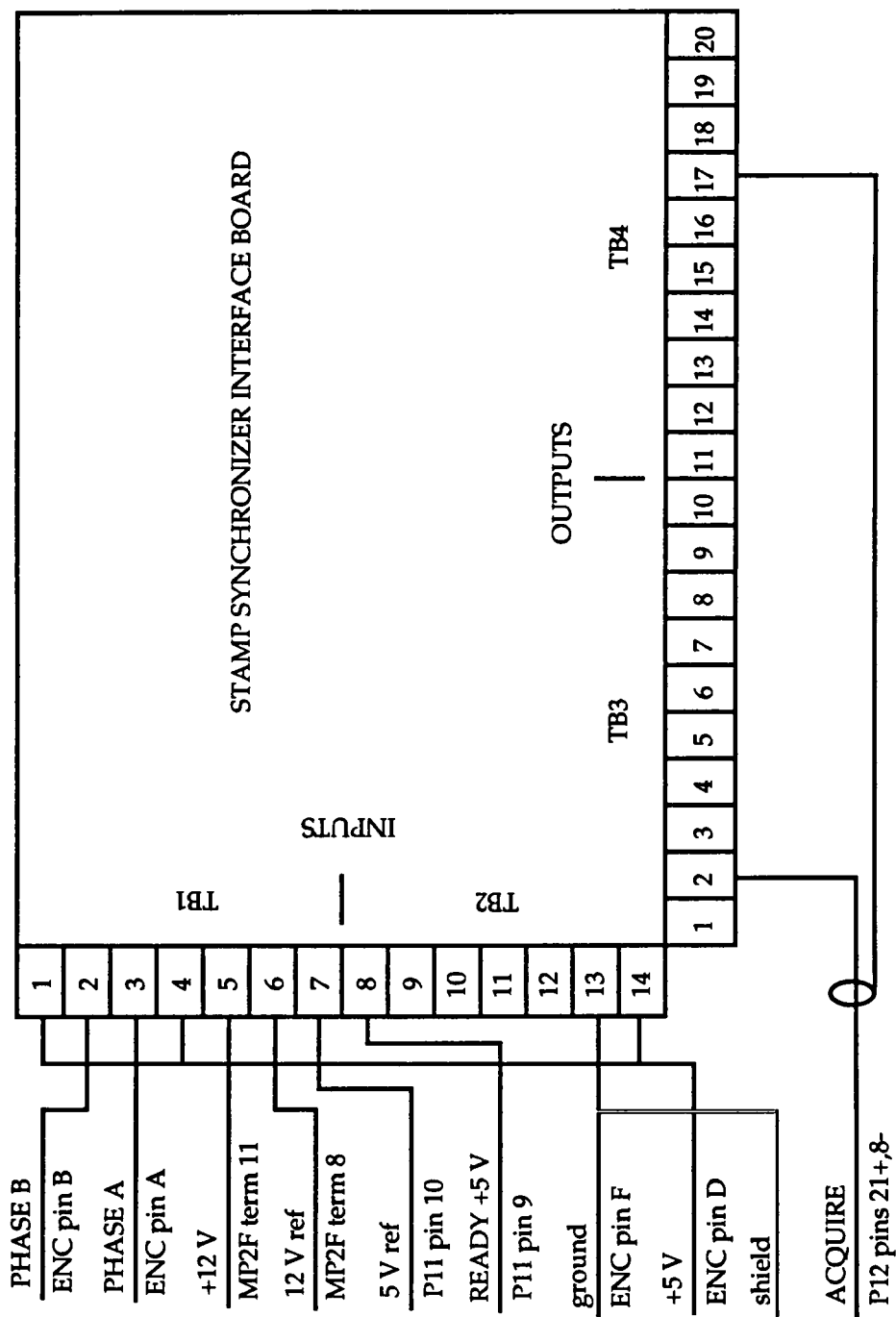


Figure A.7. Synchronization device I/O connection diagram.

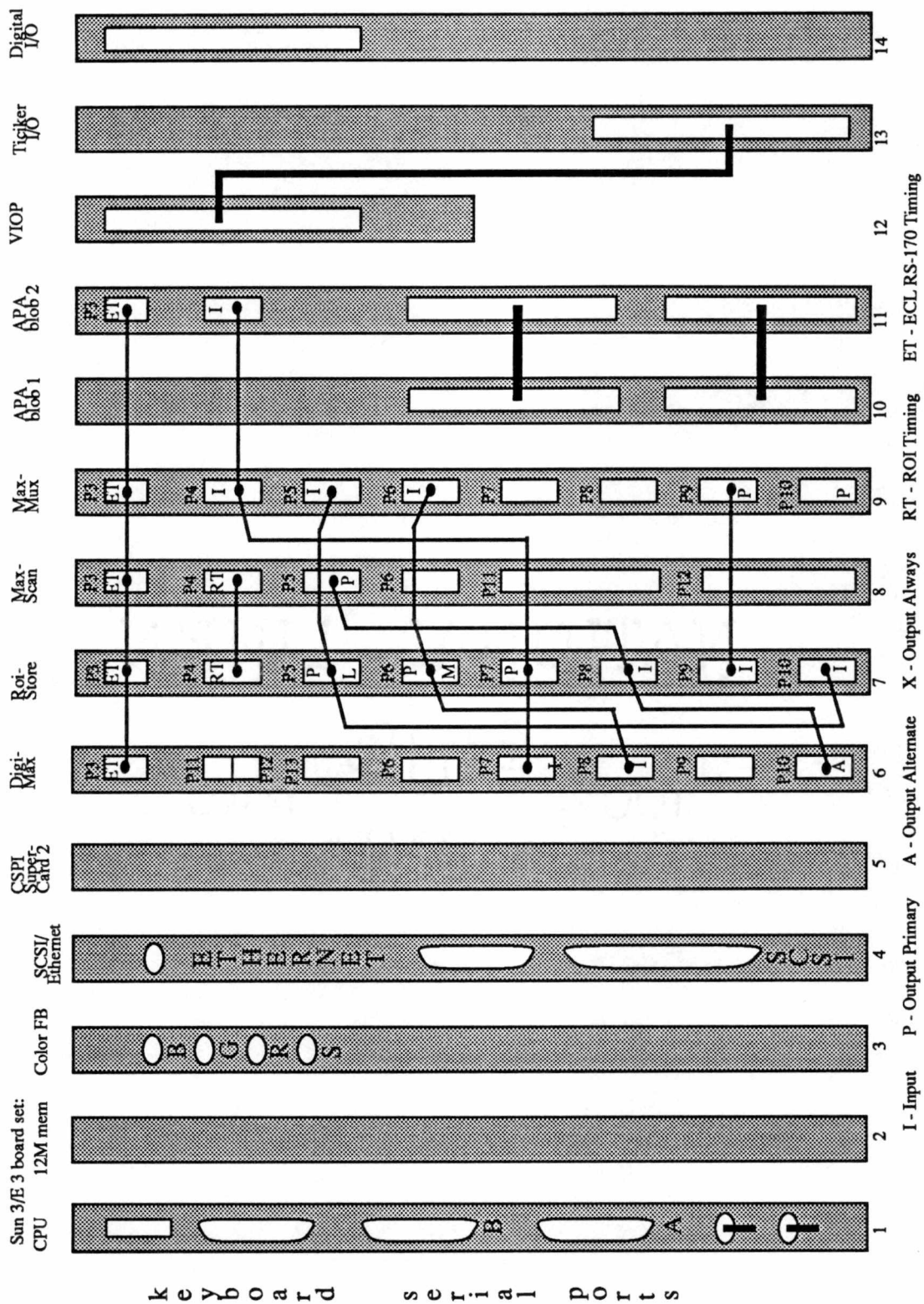


Figure A.8. VME chassis cards MaxBus interconnection diagram.

VITA

Shaun Scott Gleason was born on May 2, 1967 in Portland, Maine. He grew up in Knoxville, TN and graduated as Valedictorian from Farragut High School in 1985.

He started work on his undergraduate degree at the University of Tennessee, Knoxville in August, 1985. During the four years of his undergraduate career, he worked as a programmer in a nuclear physics research group. He received the B.S. degree in Electrical and Computer Engineering in May, 1989. As an undergraduate he was initiated as a member of Tau Beta Pi, Eta Kappa Nu, Phi Kappa Phi and Golden Key honor societies.

He was hired by Martin Marietta Energy Systems and presently works in the Instrumentation and Controls Division at Oak Ridge National Laboratory as a development engineer. His interests include machine vision, image processing, digital systems and computer architectures.

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