Fast Object Recognition using A Hybrid Optical/Digital Processor

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This paper presents a system currently being developed for reliably recognising objects in a random orientation at video rates. The system uses an optical processor to produce the power spectrum on a CCD sensor and specialised digital hardware to sample the CCD output in the desired wedge ring geometry. The resulting system has a high throughput and at a lower cost produces more flexible and accurate results than systems based on a hardware wedge ring detector. Results are presented of a system simulation which demonstrate the robust nature of the wedge ring algorithms employed. The system is capable of performing an alignment stage in an inspection scheme or of making an accept - reject judgement on a fast production line.

Hybrid optical/digital processors are being developed for use in industrial inspection [1], promising to integrate the flexibility of digital processing with the speed and parallelism of optical signal processing. The first task an inspection system must perform is recognition of the object and its orientation. This paper discusses a system to perform this task reliably and at video rates.

One of the simplest yet most elegant optical processing schemes is the use of a lens to produce the two dimensional Fourier spectrum of a coherently illuminated object. The power spectrum can then be sampled to produce a one dimensional signature characterising the object, so exploiting the data reduction properties of the Fourier spectrum [2]. The signature can then be input to the digital sub-system for comparison with reference signatures, and so identified. A particularly attractive scheme is that of wedge - ring sampling (see Fig 1). The ring signature is insensitive to object rotation, and the wedge signature is insensitive to object scale. Many successful experiments have been reported in the literature [3,4,5]. The system presented herein performs wedge ring sampling using only readily available components, and therefore benefits from the cost savings involved in mass production. When components with higher specifications become available, the system can be readily upgraded.

SYSTEM DESCRIPTION

In order to perform the recognition at video rates, custom optical and digital sub systems have been designed and are under development. The system has been extensively simulated using real images of an industrial component on an array processor machine vision system, which has proved the basic algorithm is suitably robust and has determined many implementation details. The system has been designed to recognise components from an overhead view obtained from a fixed camera. The objects are presented one at a time and can be in a random orientation. Diffuse overhead lighting obtained from two 60W fluorescent tubes was found to provide satisfactory images from a Philips CCD camera. To cope with moving components on a conveyor, strobe lighting triggered by a proximity sensor would be required. The video image thus obtained is presented to the optical subsystem.

Optical Subsystem

The basic optical system is shown in Fig 2. The video image of the object is input to the optical processor, where it is displayed on the spatial light modulator (SLM). The SLM image is illuminated with laser light from a 40mw laser diode and the spectrum is formed by the FT lens.

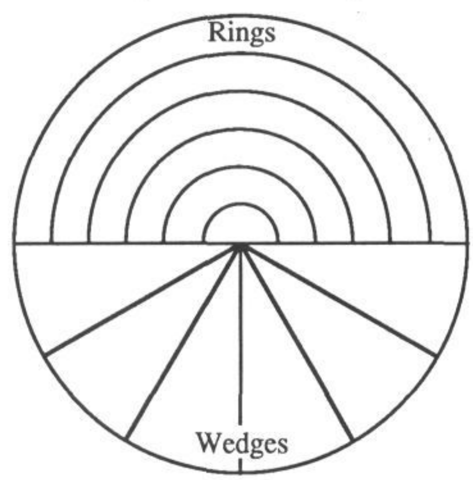

Figure 1 - Wedge Ring Sampling

The spectrum is then split and falls onto a CCD sensor and a wide area photodiode, which both have a spatial filter designed to:

i) Block the low frequencies, which, as they correspond to gross shading effects like shadows and varying ambient light levels, contribute little or no information.

ii) Compensate for the 1/f falloff characteristic of image spectra in the middle frequency range, thus optimising the dynamic range of the CCD.

The spectrum is scaled so that high frequencies fall outside the CCD, since these frequencies are dominated by noise signals. The useful mid range frequencies therefore take up the majority of the CCD area. The photodiode is used to set the gain of the CCD, the output of which is formed into a video data stream in the normal way for input to the digital subsystem.

The use of a standard CCD array, rather than a specialised wedge ring detector, is justified on grounds of flexibility and cost. Wedge ring detectors have a very small market in

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comparison to CCD arrays, and consequently are expensive and likely to remain so. The demands made of CCD sensor performance by the video industry has the effect of both continually reducing costs and improving the performance of CCD arrays. The emergence of HDTV also promises the development of greater than 1K by 1K resolution devices, and the demands of the expanding technical imaging market are fuelling the development of CCD arrays with improved (12 bit) dynamic ranges. It is reasonable to assume that such developments will continue apace.

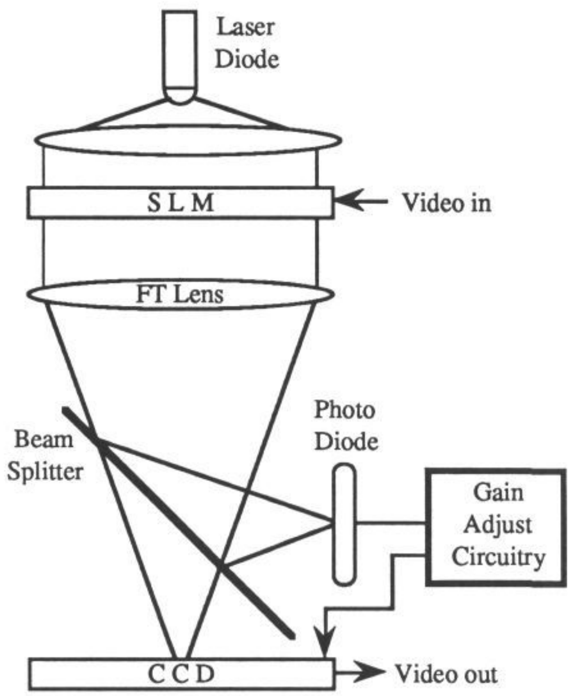


Figure 2 - Basic Optical System

For the system under discussion, the use of an array detector allows the approximation of any arbitrary sampling geometry, and as discussed below, the sampling can be carried out in real time. The number of wedges and rings implemented on the 512 by 512 CCD used in the system was 180, which gives better discrimination and angular resolution than the hardware 32 segment detector used in other systems.

Digital Subsystem

The digital system consists of two parts, the Sampler and the Identify unit, shown in Fig 3. The Sampler unit synchronises to the CCD video signal. As each pixel is being digitised, its x-y location is fed to a look-up table, which outputs the address of the appropriate signature element. The digitised pixel is then summed with the signature element in the ALU, and the result is stored back in the signature element memory.A look-up table is used because this substantially improves the speed of operation, and facilitates flexibility in the exact shape of the wedge and ring segments. The look-up table is initialised by the identify microprocessor prior to running. The added complexity this introduced in terms of dual porting the look-up memory was thought to be justified because of the increased programmability this introduced into the system - for example, changing the sampling geometry is simply a matter of changing the initialisation program.

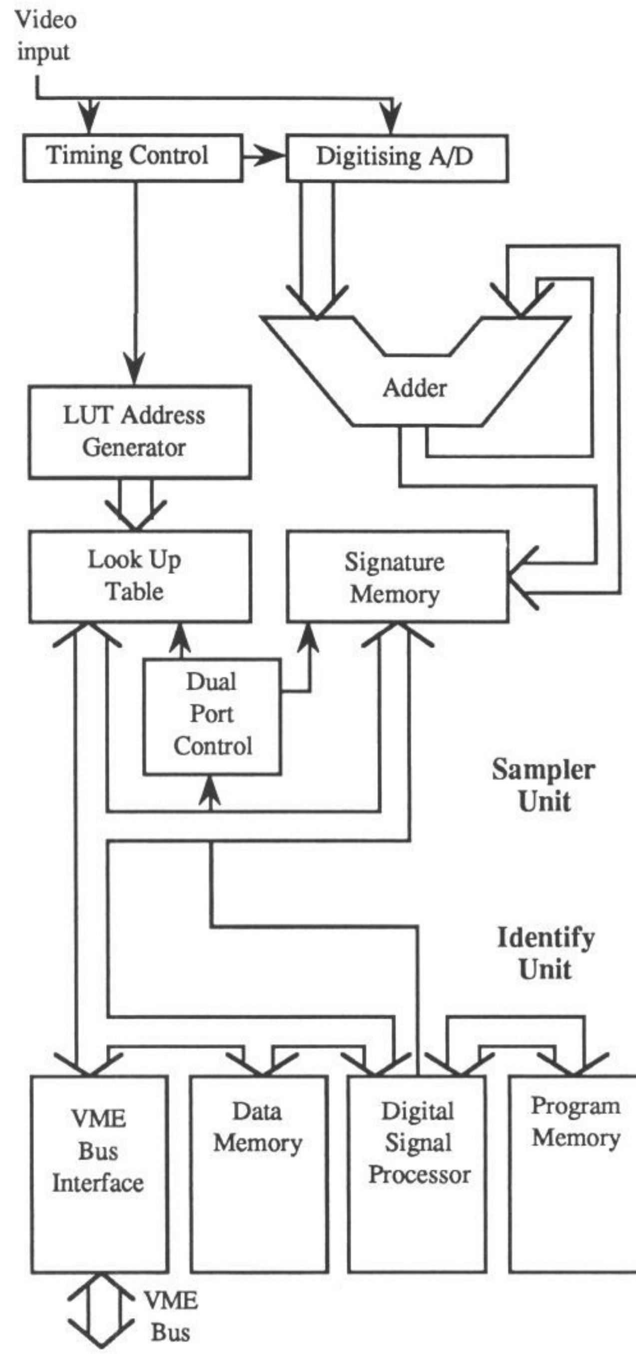


Figure 3 - Basic Digital System

The Identify unit reads the signatures from the sampler unit at the end of each frame during blanking, and then compares the ring signature to its library of references and finds the best match. The maximum of the wedge signature is then found in order to estimate the in-plane rotation of the object. The scale of the object is fixed since the camera is a fixed distance from the object. This unit is simply a dedicated microprocessor with dual port access to the signature memory and look-up table of the sampler unit, and a fast cache memory to hold the reference library. Using a fast microprocessor designed for digital signal processing means that up to 120 signatures can be checked in one frame time.

The reference library is calculated offline and held in mass storage by the host computer. At initialisation, the identify unit and the host communicate via the VME bus and the reference library, identification control program and look-up table are transferred to the Identify unit. This allows different system configurations to be held on the host's mass storage and loaded as required.

ALGORITHMS

Sampling Geometry

The system approximates the action of a wedge ring detector by summing together those pixels which are wholly contained within the particular region of interest. The digitiser is designed to suit the particular CCD array in use - that is, it digitises one CCD pixel per sample so the digitised signal has the same aspect ratio as the CCD pixels themselves. Because the CCD pixels are rectangular, the SLM image is prescaled to compensate. Previous work used 32 wedge and ring samples, but it was decided to use 180 samples in this system, since it would appear that performance is enhanced, it improves the angular resolution of the wedge sampling, and it optimises the use of the 512 by 512 picture size chosen for the system.

Wedge

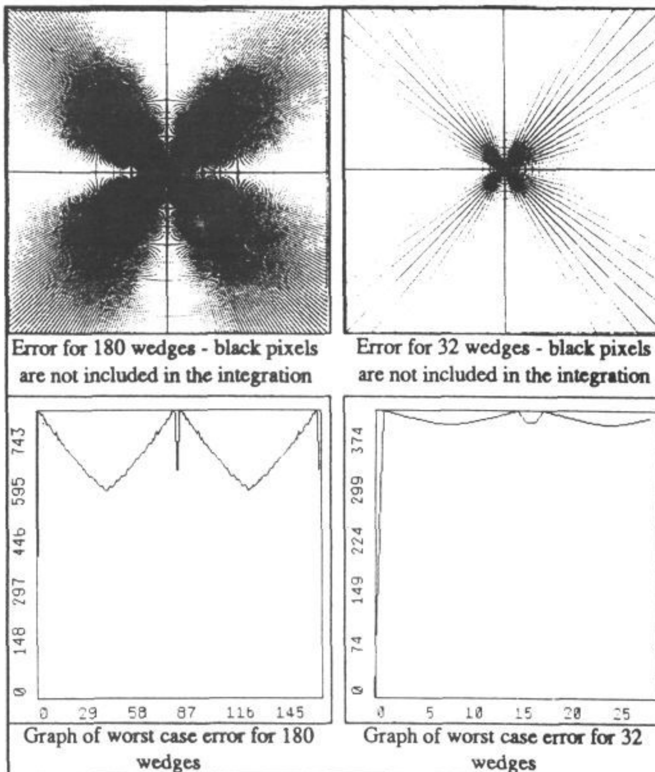
A simple algorithm is used to determine whether a particular pixel lies completely within a wedge. If it does, it is added to the list for that wedge, otherwise it is ignored. This has the effect of leaving pixel wide gaps between wedges, which was found to be preferable to counting the same pixel twice in two neighbouring wedges. The one degree wedges thus obtained contain ≈ 700 pixels each. The non - uniformities introduced by the grid produce a systematic error shown in Fig 4 which improves as the wedge width is increased. Figure 4 also shows 32 wedge sampling and the reduction in the error term can be clearly seen. In practice the distribution of the spectra reduces this systematic error and it was not found necessary to compensate, although this could easily be done.

Ring

The choice of 180 rings on the 512 by 512 array implies that the rings are one pixel wide. To avoid overlapping, the radius was incremented in steps of $\sqrt{2}$ pixels. The pixel list was obtained simply by visiting each pixel on that particular radius. As in the wedges case, some pixels are ignored because they are shared between rings. The number of pixels in the rings ranges from 15 to 750, with the simulation work showing that good discrimination is obtained with rings of over 60 pixels. The systematic error due to the array sampling is negligible for rings and does not appear to degrade system performance.

Reference Matching

In other systems [3], statistical pattern classification techniques [6] have been used to obtain adequate performance when working with difficult data sets. These techniques were not found necessary here, implying that the wedge ring technique is well suited to this industrial application. The raw ring signatures of different objects have been found to be sufficiently dissimilar to allow a simple euclidian distance measure to reliably discriminate amongst them.



Error for 180 wedges - black pixels are not included in the integration

Error for 32 wedges - black pixels are not included in the integration

Graph of worst case error for 180 wedges

Graph of worst case error for 32 wedges

Figure 4 - Wedge Discretisation Error

In order to reduce the computational load of reference matching, areas of the signature which did not on average differ from other signatures by a set threshold were ignored in the euclidian distance calculation. The information on which areas to use was held in a bit vector, with a 'one' meaning use this entry, and a 'zero' meaning ignore it.

Orientation Measurement

Once the object has been identified, the wedge signature can be used to ascertain its orientation. In this system, components with an overall rectangular shape are used (Fig.5), producing a spectrum dominated by a sinc function, which generates a wedge signature with two large peaks. The procedure chosen was to ascertain the two local maximum points in the signature, and use their position relative to the position of the reference signature's maxima to ascertain angular position. The sampling chosen allows accuracy of ± 1 degree. This fixes the objects position to θ or $\pi + \theta$. If higher accuracy is required, the estimate can be refined in a number of ways, for example interpolating to more accurately ascertain the peak position, or using a log-polar (Mellin) transform. This transform would be carried out in the optical processor, since it is computationally expensive digitally. Work is in progress to develop a line segment extraction method to obtain a refined orientation estimate.

DISCUSSION OF RESULTS

In order to verify the algorithm's suitability and stability, and optimise a large number of implementation details, the system has been implemented in software on an Imaging Technology Itex 150 machine vision system with IPA array processor, hosted by a Sun 4/110 workstation. By making effective use of the array processor, the entire acquire -

sample - identify cycle can be executed in under five seconds. The results presented below are for this 'software system'. The system proper, which will exhibit the same performance in one hundredth of the time, is under development.

The rig used to digitise the input images was deliberately crude, with no attempt made to ensure circular symmetry or diffuseness of the lighting. The lighting was sufficiently low level to render visible a systematic low frequency noise signal introduced by the digitising electronics. These degrading influences do not adversely affect the performance of the system, which implies that the techniques are robust in the presence of non ideal lighting. The test case was made even more difficult by using a cuboidal test component (Fig 5) and attempting to discriminate between two opposite faces, which differ only in internal features.Visually comparing the spectra of the two faces shown in Figure 5, it can be seen that they differ only in fine detail. Figure 6 shows the front face of the test component, its digitised power spectrum, and the corresponding ring and wedge signatures. The power spectrum shows the Sinc (cross shaped) function corresponding to the rectangular outline, and the Bessel (circular rings) functions corresponding to the circular internal features. The ring signature shows the characteristic $\frac{1}{f}$ fall off , and is invariant to in-plane rotation. The wedge signature has large peaks corresponding to the 'arms' of the Sinc function, and shifts cyclically when the object rotates.

Figure 7 shows the front face of the test component at various rotations, the power spectra, and the wedge and ring signatures. As can be seen, the power spectra rotate with the object, the ring signatures remain substantially the same, and the wedge signatures shift with angle. The average ring signature for the back face has been superimposed on the ring signatures for the front face to demonstrate the significant dissimilarities. The wedge signatures exhibit the modulation introduced by the systematic sampling error. This is not a significant difficulty, however, as local maxima are located reliably regardless of their amplitude.

Figure 8 shows the same data for the back face. Figure 9 shows the average ring signatures for the front and back faces and their difference vector.

The region containing the most useful information, and therefore giving rise to the largest differences, is the region of mid band frequency from ≈ ring 5 to ring 90. In the real system this region would be scaled to fall from ring 10 to ring 180, so maximising the information content of the vector.

Figure 10 shows the discrimination performance with the test data, which, as previously explained, is of poor quality. The bottom right graph shows the euclidian distance of the vectors from the average front face vector along the X axis, and the euclidian distance of the vectors from the average back face vector along the Y axis.

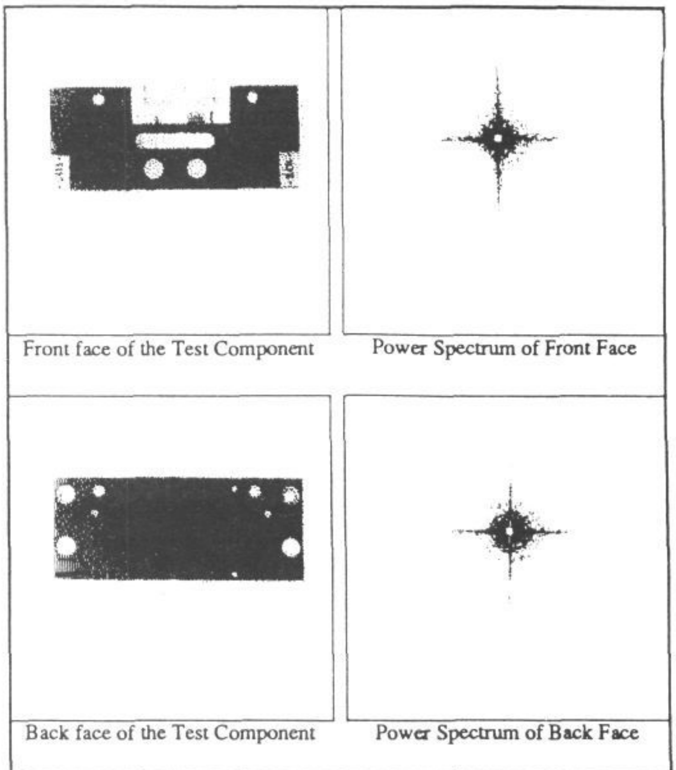
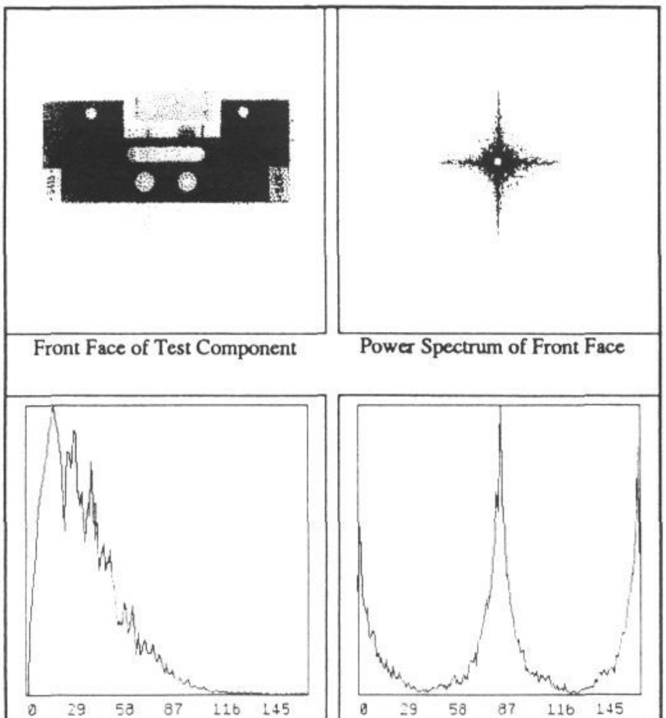


Figure 5- Test Component and Spectra

Crosses signify front face vectors and stars signify back face vectors. As can be seen, there is an 8.5 dB safety margin using distance from the front face vector, and a 7.8 dB safety margin using distance from the back face vector, which is more than adequate for reliable discrimination. Bearing in mind that the images were of poor quality, and that the system was discriminating between two opposite faces of the same cuboidal object (i.e. images have identical dimensions of outline and differ only in internal features), good performance in discriminating between different objects and faces can be predicted in future applications.

CONCLUSIONS

The system discussed above is capable of identifying a component and ascertaining its orientation reliably and in poorly controlled lighting conditions, using wedge-ring signature analysis. The 'software system', implemented on an Imaging Technology Series 150 macine vision system with IPA array processor, is capable of performing the identification task in under five seconds, a cycle time low enough to allow its industrial application in automatic palletising, for example. The hybrid optical digital processor, which is currently under development, is capable of performing the same task in a single frame time (40ms pipelined), through the use of coherent optical processing and high performance digital signal processing technology. This speed of operation is sufficient for many tasks on high volume production lines, and it is anticipated that refined versions of this system will find significant industrial application.



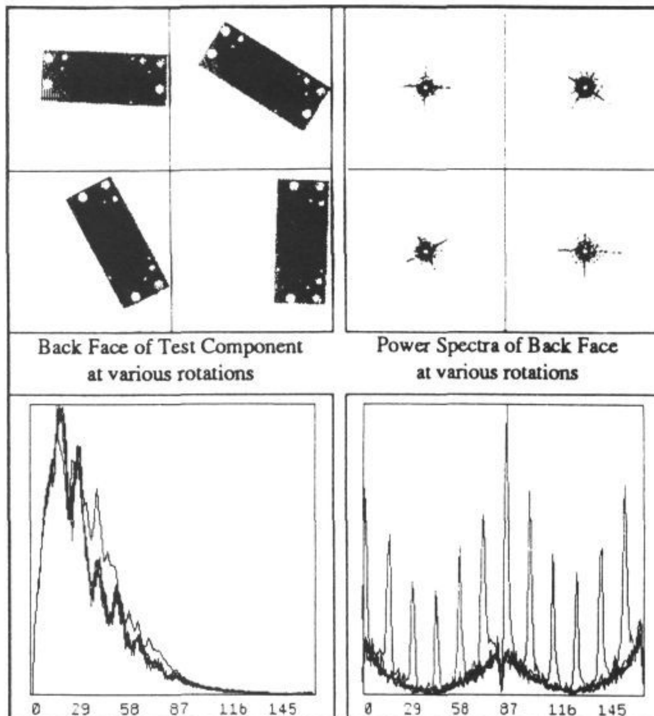
Front Face of Test Component

Power Spectrum of Front Face

Ring Signature for Front Face

Wedge Signature for Front Face

Figure 6 - Wedge Ring Signature



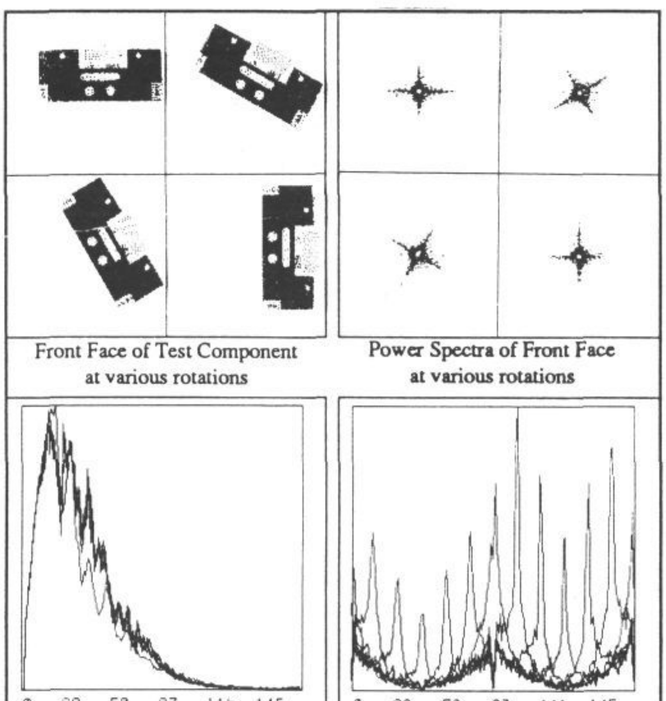
Back Face of Test Component at various rotations

Power Spectra of Back Face at various rotations

Ring Signatures for Back Face at various rotations. The average front face signature has been superimposed for comparision

Wedge Signatures for Back Face at various rotations. Note the cyclical shift in peak position with angle

Figure 8 - Back Face Wedge Rings



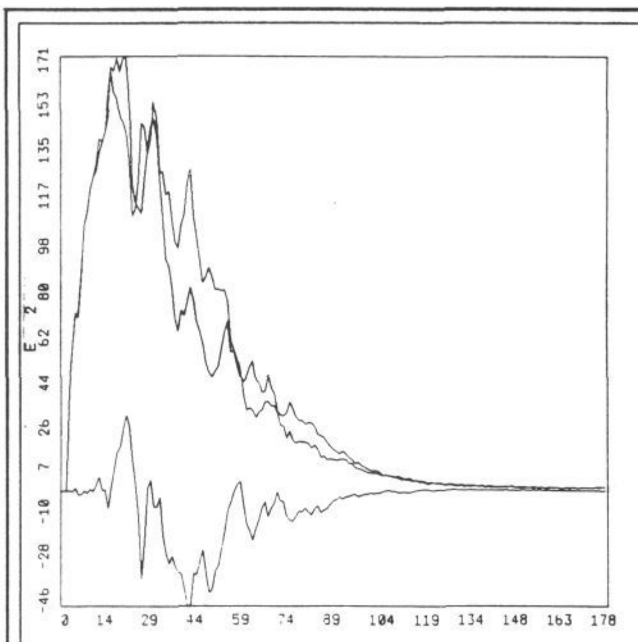
Front Face of Test Component at various rotations

Power Spectra of Front Face at various rotations

Ring Signatures for Front Face at various rotations. The average back face signature has been superimposed for comparision

Wedge Signatures for Front Face at various rotations. Note the cyclical shift in peak position with angle

Figure 7 - Front Face Wedge Rings



The graph shows the average ring signatures for the front and back face and their difference vector. Discrimination is performed by calculating the difference vector between the input signature and one of the average signatures and thresholding on its magnitude.

Figure 9 - Average Difference Vector

Figures 6 - 9

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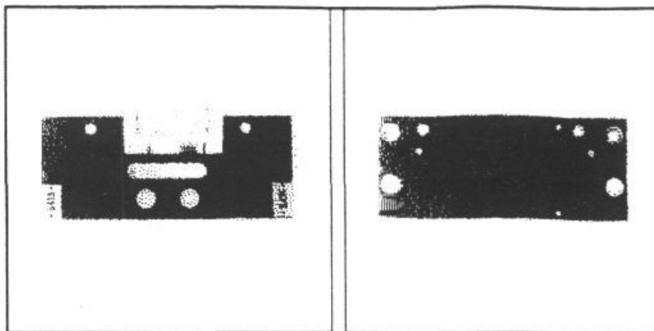
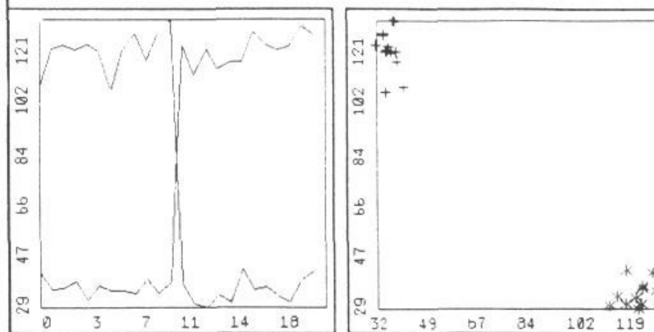


Front face of the Test Component | Back face of the Test Component



Distance of front and back faces at various rotations from average front face vector and average back face vector. Discrimination is symmetrical at around 8dB

Scatter graph of distance from the average vectors. Crosses are the front face at various rotations, stars are the back face.

Figure 10- Discrimination Performance