Real-time optically processed face recognition system based on arbitrary moiré contours

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Abstract. We demonstrate a hybrid electronic-optical real-time system that performs 3-D face recognition. We constructed custom reference gratings that formed a desired moiré pattern when mixed with images of structurally illuminated faces. The moiré patterns could be in any form such as, equal depth contours, error maps, or any arbitrary pattern. We demonstrate video methods to generate such error maps in real time, thus developing a real-time automated face recognition system based on the optical processing of arbitrary moiré contours. We chose the moiré pattern to be in the form of a Fresnel zone plate, which is displayed on a liquid crystal television. Illumination of this zone plate with parallel coherent light results in a diffracted beam that produces a focused line on a detector. For the matching process, the focal line is compared against a preset threshold. If the confidence is above the threshold, the face is recognized, otherwise it is not. *© 1996 Society of Photo-Optical Instrumentation Engineers.*

Subject terms: optical security; Fresnel zone plate; moiré; spatial light modulator; video.

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1 Introduction

Face recognition can be an important aspect of security systems used to prevent fraudulent access across a broad spectrum of businesses. Some applications include verification for security screening for buildings, laboratories, or other sensitive areas. Face recognition is often more secure than passwords or personal identification numbers (PINs), which can be lost or stolen. Optical techniques have been demonstrated to perform face recognition on images of faces.[1–3] For example, a joint-transform correlator system associated with a neural network has been proposed for optical face recognition.[1] The system uses a supervised learning algorithm for real-time operation. In addition, a two-layer optical network that uses photorefractive holograms for real-time operation has also been demonstrated.[2] Furthermore, a phase-encoded image placed on an ID card to be used in an optical correlator has also been proposed.[3]

Although these systems have shown to be useful they are inherently 2-D in that they use images of faces which are the projection of a 3-dimensional (3-D) object onto two dimensions. For increased security we propose a 3-D face recognition system that operates in real time. Even though a person's appearance can change due to factors such as hair style and lighting, the contours of one's face do not usually change from day to day. Using standard optical, video and computer hardware, we used a moiré technique to compare a face with a previously recorded face contour-mask to determine if they came from the same person.

In this paper, we demonstrate a hybrid electronic-optical real-time system that performs face recognition. The real-time feature of this system relies on the focusing properties of a Fresnel zone plate[4,5] (FZP) and the light modulating properties of a commercially available liquid crystal television (LCTV). A variable resolution video moiré system[6] was used to project fringes on a known face (structural illumination) and to generate a set of images of that face. The set of images and a specified desired arbitrary moiré output (FZP) were computer processed off-line to generate a mask video image. When an unknown face was presented to the recognition system, it was structurally illuminated and its video image mixed with the mask generated from the known face to generate a video moiré pattern that was displayed on a coherently illuminated LCTV. If the 3-D shape of the face presented was the same as that of the known image, an FZP was produced and the result was a focusing of light at the focal plane. For the matching process, the focal spot is compared against a preset threshold. If the confidence is above the threshold, the face is recognized, otherwise it is not. Generally, if a structurally illuminated ''incorrect'' face is presented, no FZP moiré is produced and there is no focusing of light at the output.

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2 Theory of Operation and Experiment

The operation of the face recognition system is based on the generation of arbitrary moiré contours. To explain the arbitrary moiré operation, it is first necessary to discuss how our variable resolution video moiré system works. Our variable resolution video moiré system uses either an argon-ion illuminated Michelson[6] interferometer or a He-Ne illuminated Mach-Zender interferometer (described later) operated off axis to project straight interference fringes on a face target. By varying the tilt of one of the interferometer mirrors, one can change the spatial frequency of the structured illumination (i.e., the spacing of the interference fringes can be changed). In the case of the Michelson fringe projector, a special lens system is needed to eliminate the beam steering caused when the interferometer mirror is tilted. A video camera captures images of the structurally illuminated target. If the target video image is mixed in a special way with a second video image of the interference fringes projected on a flat plate, variable resolution moiré depth contours are produced. This is done using a video special effects generator, where the flat plate (straight grating) video signal is used to chroma-key the target video signal. In this operation, a threshold intensity level in the chroma-key signal is used to gate (or switch) the target camera signal. Thus the target camera signal is seen wherever the chroma-key signal is above a certain level, effectively substituting the target camera signal for the bright bars in the plane grating chroma-key signal. The mix process can be modeled as a thresholded exclusive-OR function. This has the effect of mixing the plane grating seen on the flat plate (reference signal) with the distorted grating seen on the target. The result of this mix is a set of low spatial frequency spatial beat patterns, or moiré patterns. These patterns are effectively intersections of the 3-D target with the reference surface, and are equal depth contours whose depth spacing is a function of the original projected grating (interference fringe) spatial frequency, thus variable resolution moiré contours. A feedback circuit can suppress the original gratings, thus improving the SNR of the moiré contours.[6] Either the moiré contours or a set of the structurally illuminated images can be used to generate the 3-D shape of the target.[7]

To recognize an object, a mask must be created for that object. One of the things that makes our variable resolution projection moiré system work is the presence of a flat physical reference surface on which the straight gratings are projected. The straight grating image is mixed with the distorted grating target image to generate the moiré contours. Since both surfaces (reference and target) are illuminated by the same interferometer, the gratings projected on both surfaces have the same spatial frequency, and we generate moiré contours whose depth resolution can be dynamically varied by changing the grating spacing. It was mentioned that when the reference surface was a flat plate, the moiré contours seen are equal depth contours, and are also intersections of the target surface with the reference surface. The existence of a physical reference surface enables the generation of some unique moiré contours. If an object is to be inspected for defects, for example, a perfect object can be used for the reference surface, and moiré contours (error maps) of the differences between the two surfaces are seen in real time.[8] Finally, what we are seeking to discover is what shape of a structurally illuminated reference surface will generate a given set of moiré contours (say, for example, a FZP) when mixed with the structured illumination of a target to be recognized. To do this we work backward, first calculating the shape of a surface having the desired output moiré contours, and then subtracting that shape from the recognition target shape. The final step is to compute the appearance of the projected illumination on the difference shape and convert the image into composite video. The hardware and procedure that accomplishes this is described next.

The face recognition system can be divided into two parts: the filter grating (mask) generating system and the optical processor. The mask generating system captures the desired 3-D face contour images, and once the desired output image is determined, computes the filter grating that will be video-mixed in real time with an input contour image. The video moiré system[6] consists of an interferometer fringe (grating) projector and two TV cameras to view the target and reference surfaces from symmetric angles. As described, one mirror on the interferometer fringe projector can be tilted to vary the grating spatial frequency. In this experiment, we use a Mach-Zender interferometer to generate and project the variable spatial frequency gratings on an input and reference surface. The advantage of the Mach-Zender interferometer is that there is no feedback to the laser and it automatically generates two output beams without the additional beamsplitter that the Michelson interferometer requires. The two video camera signals are fed to a video mixer or special effects generator. We operate the system in two modes. In the ''unmodified,'' or ''structured illumination'' mode, a series of images of the distorted structured illumination on the target is used to generate the shape of the target as described later.[7] In the ''moiré'' or ''modified'' mode, the moiré contours are used to generate the target shape.[7] The modified and unmodified video output from the mixer are delivered to two monitors and to a Macintosh IIci, which is used to collect and store data in the form of images through its Data Translation frame grabber board.

The Mach-Zender interferometer generates and projects variable spatial frequency gratings on the target. The gratings projected on the target will look distorted unless the target is flat. Five images of these distorted gratings on the input object are captured by piezoelectrically shifting the reference (and input object) gratings by $\pi/2$ four times. Video images of the shifted gratings along the reference surface enables precise adjustment of the phase shifts. A total of five images are captured with phases of $-\pi$, $-\pi/2$, 0, $+\pi/2$, and $+\pi$, each with a phase difference of $\pi/2$ from the previous one (the $-\pi$ image will be identical to the $+\pi$ image if the shifts are exactly $\pi/2$—the reason for the five shifts is to reduce the sensitivity to phase errors if the shifts are not exactly $\pi/2$). These images are then used to compute a phase mask and the 3-D surface shape.[9] The filter grating is produced by combining this phase information and the desired FZP, as described. This off line operation is the basis of arbitrary moiré and can also be thought of as asking what mask pattern do I need to mix with my structurally illuminated correct target image to get the desired output (in this case, a FZP)? As described, the mix process can be modeled as a thresholded XOR. The

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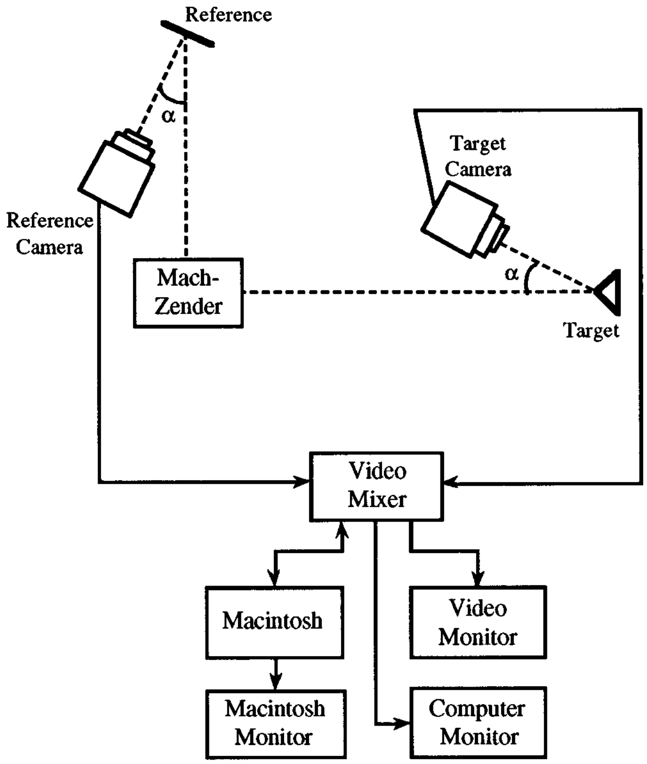

Fig. 1 Filter grating generating system.

filter grating image is then converted to composite video using a Scion TV3 video output board and sent directly to the video mixer. This filter grating produces the desired real-time Fresnel zone plate when mixed in live video with the structurally illuminated input object. In other words, if the test object matches the correct input, the Fresnel zone plate moiré output pattern is produced. Figure 1 illustrates the video and optical parts of the mask generating system.

The optical processor portion of the system identifies an input object in real time. The input to this portion of the system is the arbitrary moiré interferogram in the shape of a zone plate, which is displayed on an LCTV. The output is light focused by the FZP and recorded with a detector. If the input face is not recognized, a zone plate is not generated, and focusing does not take place. Figure 2 illustrates the optical processing system. By using a camera at the FZP focal plane it was possible to obtain images of the focal point of the zone plate. These images are shown in the next section.

The optical system relies on Fresnel diffraction and geometrical optics as the means for real-time optical processing. If one places a circular Fresnel zone plate (a concentric series of clear and opaque half period zones) in a coherent beam, a bright focal spot appears on the axis at a distance related to the radius of the first Fresnel zone and the wavelength.[4] The irradiance at the focal spot is much higher than it would be in the absence of the zone plate. The same theory applies for a half period, 1-D (cylindrical) zone plate (shown in Figure 3). Illumination of a cylindrical FZP with parallel coherent light results in a line focus at the focal plane.

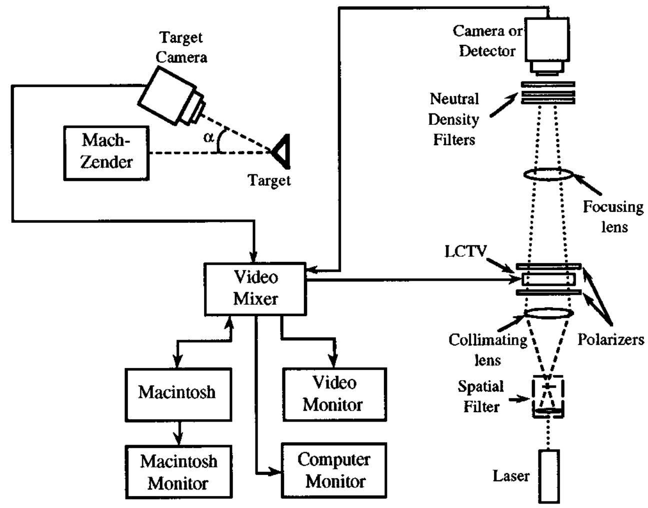

Fig. 2 Optical processor.

The theory of operation of the FZP applies for a half period, 1-D (cylindrical) zone plate shown in Fig. 3, which was used by our system.

A bright line should occur at the focal plane of the FZP if a face is recognized. The focal distance of the FZP is given as

$$f = R^2/\lambda, \tag{1}$$

where R is the radius of the first Fresnel zone, and λ is the wavelength of the source. For example, if $R = 0.4$ mm, then the focal length of the corresponding zone plate would be 25.27 m. To decrease the focal length we added a lens between the LCTV and detector to reduce f to 0.45 m. As long as the zone plate is present, focusing of light will occur at this distance. If the zone plate is absent, focusing will occur at the focal length of the lens.

Due to the operation of the chroma-key circuit, our video mixer produced circular FZPs that ''jittered'' on the LCTV. We found that 1-D (cylindrical) FZPs were much more stable when compared to the circular FZPs. Because the focal distance is directly proportional to the square of the zone plate's radius, the smaller the zone plate, the smaller the focal distance. The pixel size of the Radio

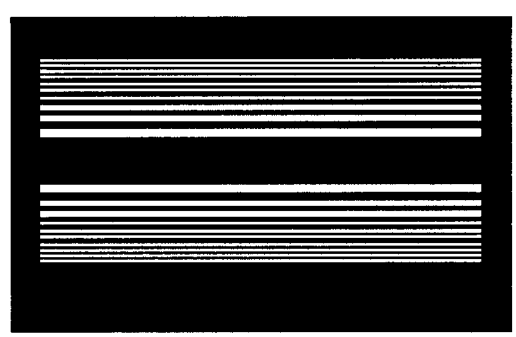

Fig. 3 Cylindrical FZP and the desired output to the SLM.

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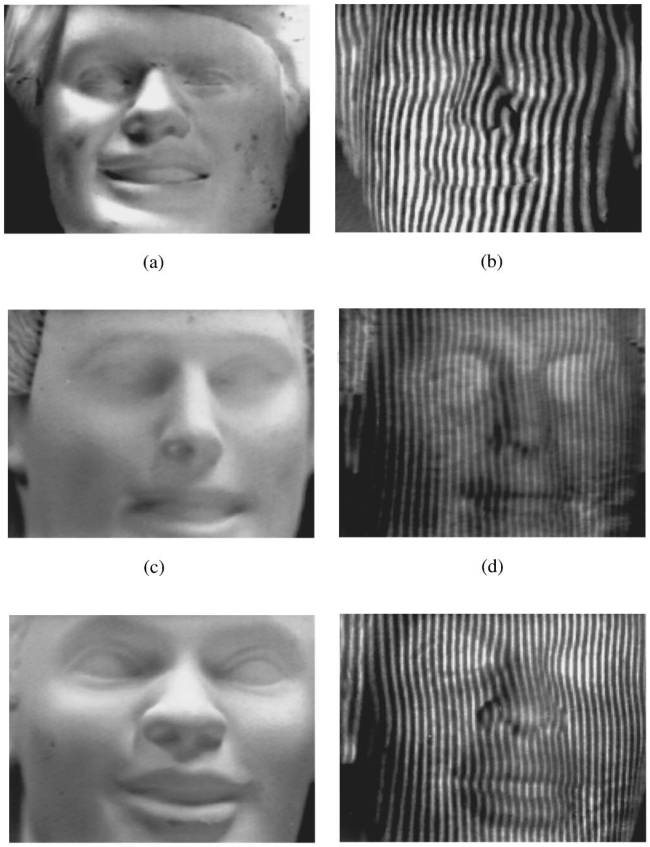

Fig. 4 Faces used in experiment in standard and structured illumination: (a) and (b) known face, (c) and (d) second face, and (e) and (f) third face.

Shack LCTV is a limiting factor when considering a small zone plate (pixel size ≈330 μm). A higher quality SLM would provide better resolution, better contrast, less pixel noise, and shorter focal distance.

3 Experimental Results

The performance of the system depends on the quality of the SLM used. Since these devices are not manufactured

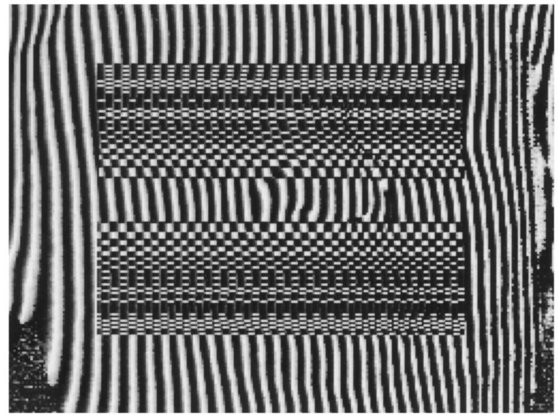

Fig. 6 Filter grating obtained by combining the phase information in Fig. 5 and the cylindrical zone plate.

for optical processing purposes, they have limited dynamic range and add significant noise to the information carrier, thus reducing the SNR in the results. Figure 4 shows the three different faces to be identified under standard room illumination and structured illumination from the interferometer.

We selected the face in Fig. 4(a) to be our known face; therefore, the filter grating was generated to only identify this face. The other two faces in Figs. 4(c) and 4(e) were faces selected to discriminate against. The faces are shown in structured illumination in Figs. 4(b), 4(d), and 4(f). To obtain the filter grating, the phase information had to be captured. This information is shown in Fig. 5. The corresponding filter grating or mask is shown in Fig. 6. This filter grating was obtained by combining the phase information in Fig. 5 and the desired cylindrical zone plate output.

The filter grating in Fig. 6 produces the desired moiré pattern when mixed with the structurally illuminated face. The system uses the live chroma-key operation to perform this mix in real time. The resulting output video signal will have background noise, but it will not be of any significance. Figure 7 shows the live video mix (moiré pattern) that is sent to the SLM.

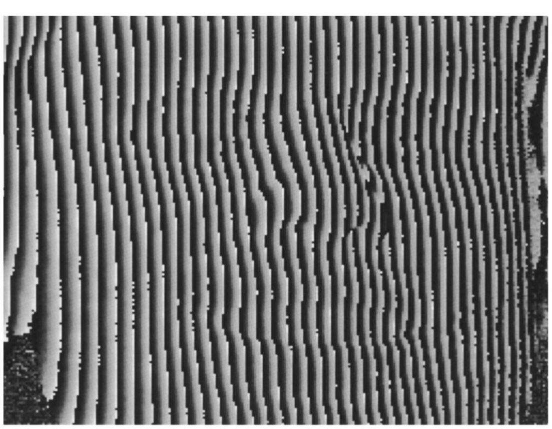

Fig. 5 Phase information corresponding to the known face.

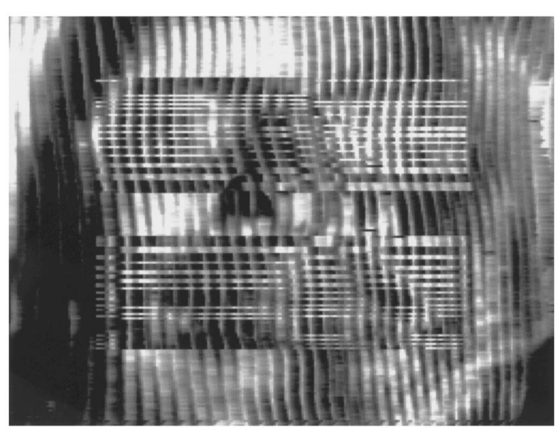

Fig. 7 Moiré pattern output (live video mix) and input to the LCTV.

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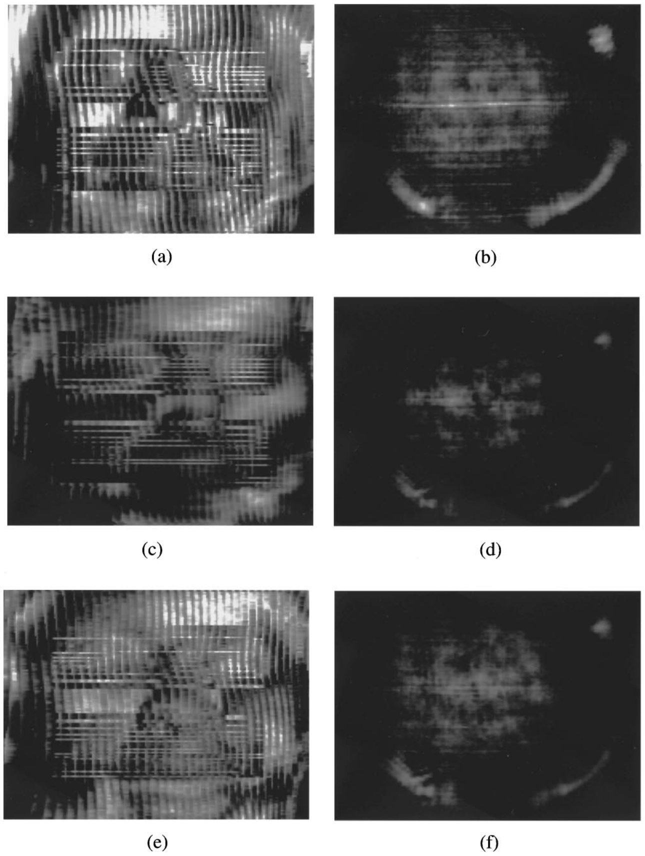

Fig. 8 Results of face recognition experiment: (a) live mix as shown in Fig. 7, (b) output of the system indicating correct recognition, (c) live mix of filter grating with an incorrect face, (d) output of the system indicating no recognition, (e) live mix of filter grating with another incorrect face, and (f) output of the system indicating no recognition.

The results of the system when the structurally illuminated faces from Fig. 4 are input to the system are shown in Fig. 8. On the left side of Fig. 8 is shown the live video mix of the three faces in Figs. 4(a), 4(c), and 4(e) as Figs. 8(a), 8(c), and 8(e), respectively. The output of the system is shown in Figs. 8(b), 8(d), and 8(f), respectively. Fig. 8(b) indicates correct recognition due to the bright line shown. Figs 8(d), and 8(f) indicate no match with Fig. 4(a) because of the absence of a bright focal line.

Fig. 9 shows the three output video signals side by side and Fig. 10 shows an intensity plot of this output for the

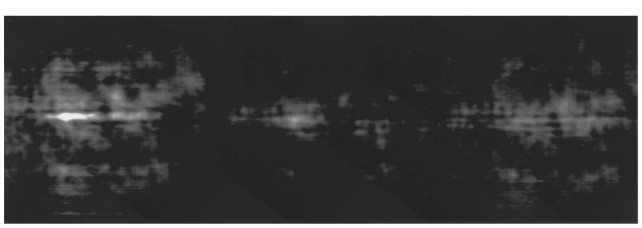

Fig. 9 Outputs obtained with faces of Figs. 4(a), 4(c), and 4(e), respectively.

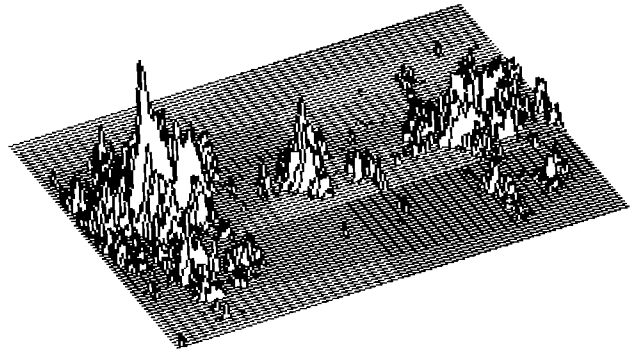

Fig. 10 Surface plots of the three focus lines.

correct and incorrect faces. The resultant outputs of the incorrect target mix are shown in Fig. 9, center and right. These live mixes were obtained with different but very similar faces. As can be seen, neither the center nor the right output shows a distinct focus line. This proves that the system is sensitive to slight differences between objects. The difference between the three output images in Fig. 9 might not be very apparent to the human eye. Consequently, a surface plot is presented in Fig. 10. The system's detector can be calibrated to differentiate these three distinct but similar outputs. As long as the expected zone plate foci are aligned along the pixel readout direction, a simple analog integrator or adder followed by a comparator could be used for recognition.

4 Alignment Tolerances and Limitations

A brief experimental study was made of the tolerance of the recognition system to misalignment. We found that the alignment tolerances were not as severe as we had anticipated. Fig. 11 shows the axes and translational and rotational alignment tolerances. The shifts and rotations shown were sufficient to cause the visual loss of the focused line for the correct target. The structured illumination was aligned along the *Z* axis and the FZP pattern sent to the SLM was aligned along the *Y* axis. It is possible that a different choice of mask or output pattern could improve the misalignment tolerances.

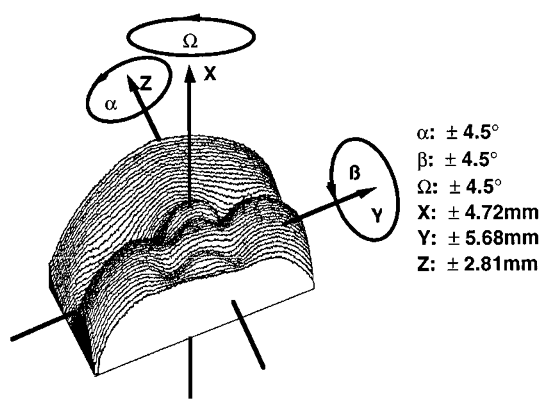

Fig. 11 Recognition tolerances.

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It is clear that the only area being inspected by the system so far is the area covered by the zone plate. This problem can be addressed by choosing our desired output to be a set of gratings (tilted at a specific angle) that would cover a complete screen and leave less room for unaccounted target variations. This requires small modifications to our system. A focusing lens is needed in front of the LCTV and a camera with a microscope objective is needed to observe the elements in the Fourier plane. In addition, we inspected only doll's heads, and not real people with facial hair, eyebrows and lashes, and beards. We suspect that although a beard would change the face contours, the 3-D shape in the areas of the eyes and nose would remain the same. In a security face recognition scenario, it would not be unreasonable to expect someone who needed access to a secure area to request a new recognition mask to be made if they grew (or shaved off) a beard. In the future, we intend to extend the research to recognition of real faces.

5 Conclusion

A hybrid electronic-optical real-time 3-D face recognition system has been demonstrated. We showed that it is possible to construct custom reference gratings that form a desired moiré pattern when mixed with images of structurally illuminated input objects. By selecting the moiré pattern to be a Fresnel zone plate we were able, through basic diffraction, to optically process information without major computer intervention. Finally, the restrictions on the shape of the output moiré contours were removed, producing a real-time automated inspection system based on optical processing of arbitrary moiré contours. Furthermore, by selecting a high quality SLM, a compact portable system is feasible. Although in its present form the system is not shift-invariant, placing a face in a particular position is not unreasonable for security applications. Using improved video circuitry should allow circular zone plates to be produced that would create brighter focal images and an increased probability of recognition.

Finally, note that the variable resolution feature of the system requiring the coherently illuminated interferometer to project the structured illumination, would not be needed in a production inspection system, although the laser illuminated SLM optical processor would still be essential. The variable resolution enables us to inspect targets of different sizes and at different ranges, while having dynamic control of the depth resolution. A production system would have a fixed inspection distance, fixed depth resolution, and could use a fixed spatial frequency (and incoherent) grating projector.

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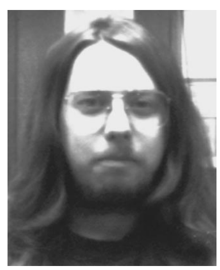

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