Progress in Human Breast Profiling using Shape-From-Shading

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Abstract

Experiments have been undertaken in a continuation of a previously reported investigation into whether useful quantitative breast shape information may be deduced by numerical analysis of a single digital photograph of the breast. The work utilises the principle of extracting shape from image shading, known as shape-from-shading (SfS). The SfS method attempts to deduce surface gradients, and hence shape, across an object, by using the reflectance levels which are apparent in a monochrome digital image of an object. The method requires that the object has smooth physical texture and light even colouring. The significant feature of SfS is its simplicity, as it needs no special equipment, and involves the numerical analysis of a single digital photograph, which may be obtained with a mobile phone. The various features of SfS make it attractive for breast measurement. However, it is theoretically impossible to deduce two parameters of surface slope from one reflectance level, so the method faces difficulties which are prohibitive in many applications.

This major theoretical predicament may be overcome by using known surface shape information. The approach which has been investigated here involves obtaining profiles horizontally across the breast centre. This approach, which is feasible because of the regular geometry of the breast, has been proposed previously by the writer. The most recent tests of the technique, including both accuracy tests of the technique on objects of known shape and trials of breast profile measurement, are promising, and suggest that the concept is practicable. Sources of error are discussed. The impetus for further testing and development depends on the prospects of the use of breast information of this type, whether for medical or perhaps apparel purposes.

Keywords: shape-from-shading, digital imagery, breast measurement

1.Introduction

This paper describes progress in a project which has continued to evolve since a previous report [1]. Accordingly, much of this background explanation here has been changed from the previous report in minor ways only.

The technique of shape-from-shading (SfS) is an appealing means of seeking an object's three-dimensional surface shape. If an object has a smooth physical texture, meaning that it is free from discontinuities, and if it is also of light even colouring, SfS, which involves deducing shape from only the reflectance levels in a monochrome photographic image of an object, is attractive because of its simplicity. SfS involves nothing more than the numerical analysis of a single digital image of the object of interest. (Multiple images may be used, in what is often called "photometric stereo" but the simpler case of the single image is being pursued here.)

But, because measurement by SfS is limited to objects with specific physical and optical textures, its use is impracticable on many surfaces. As well, the SfS method suffers from another major disadvantage when analysing a single two-dimensional image: normally, there is an infinite number of solutions for the three-dimensional object shape. A solution is then only possible if some constraints are devised, which usually means having some prior knowledge of surface shape or making some assumptions about the three-dimensional characteristics of the object.

Despite these complications, the use of SfS for measurements of the three-dimensional shape of some areas of the human body may be viable, where the human skin surface colour is plain and where the body surfaces are not too convoluted. In particular, female breasts can generally be assumed to be smooth convex shape, which is advantageous here, although they have the complications of the areola region and often a discontinuity of a skin fold on the lower side.

It is hypothesised in this work that along certain lines over the female breasts, measurement of profiles is feasible. This is seen as a means of overcoming the problem of an infinite number of solutions. An approach to using SfS for the measurement of breast profiles is outlined here. with tests of the technique on geometrically shaped objects and some unverified tests on a human breast. The work assumes a demand for breast shape measurement of various kinds.

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2. Principles of SfS

2.1. Conventional SfS

SfS principles have been described in the previous paper. “The principle of SfS is that, if the object of interest is illuminated by a single light source (as distinct from general ambient lighting), then, at any pixel on a digital photographic image of that object, the image intensity value (i.e. grey-level or reflectance) is related by a known mathematical model to the surface gradient of that small element of the surface of the object. The goal of SfS is normally the determination of the surface gradients across the object from such an image, so that the three-dimensional surface shape can be deduced by numerical summation of the surface gradients. SfS theory mathematically relates the image reflectance at a pixel to the two gradients of the true surface at that pixel. The theory is easily uncovered via the usual searches.

The major predicament with the SfS method is that two gradients are needed to define the direction of the surface element at any one pixel, but only one reflectance value is available at each pixel, so that for any pixel there is an infinite number of solutions for the two gradients given the one reflectance. A solution seems to be apparent if an assumption can be made about the surface, e.g. where some prior surface shape information can be assumed, typically permitting the adoption of some surface model which relates the two gradients at one pixel to those at other nearby pixels. But the solution to the equations obtained in that way is only correct if the chosen constraint is perfectly valid. The constraining surface model may then be provided only by a surface which is so well known that measurement is not beneficial!”

This work looks at a different approach to the SfS dilemma.

2.2.Mathematical Model

The SfS model used in this work assumes that, if a uniformly coloured object is illuminated by light from a source at the camera lens, then the reflectance level which is recorded as grey-levels at any one pixel on a (monochrome) image, is related by a simple function to the angle between the light ray from the light source and its reflection from the object. This model describes the reflectance level as a function of the two directions which describe the direction of the reflected ray, hence the dilemma referred to in Section 2.1.

The model involves the focal distance of the camera (i.e. the distance between the lens and the sensor, which differs from the focal length if the camera is focussed by moving the lens) and, if object coordinates are deduced, the distance of the camera from the object. This simple model does not allow for any variation in the illumination source nor any variation in the reflectance level caused by the relative pixel sizes on the object due to the distance of the object from the camera. Smaller assumptions in the model are that the direction of the axis of the lens is known and that the centre of the image is the projection of the centre of the lens, and that there is no distortion of the lens, and so on.

2.3. The use of Profiles

The previous paper described this concept, explaining that “this work follows, firstly, a direction which may in practice be effective in various cases of human body measurement, and particularly in human breast shape measurement. That is, if, along a segment of the object, the gradient in one direction is known to be zero, then it permits a simple determination of the gradient in a perpendicular direction. In fact, if the cross-slope is not exactly zero but is even close to it, then the other gradient is only marginally affected. Moreover, the profile approach is made mathematically simple if that line is also radiating from the centre of the image. It seems reasonable to envisage that these conditions may occur along lines radiating from the highest point of a breast, if imaging can be organised so that the object’s closest point to the camera is located at the centre of the image. The method has the advantage that, not only is a solution possible, but the required equations become quite trivial.”

2.4. Function Fitting

The fact that the shape of the breast is almost invariably even and smooth suggests the prospect of defining the surface shape by fitting relatively simple mathematical functions along the profiles mentioned in the preceding Section.

Firstly, fitting functions has been investigated as a means of interpolating reflectance values across those areas (notably the areola), which are sources of discontinuity of either the physical surface or the surface colour.

Secondly, fitting function has also been usable to model the surface gradients derived from the reflectance levels.

3.Tests

3.1.Plane Surfaces

Tests of the validity of the proposed mathematical model for SfS measurement of axial profiles have been undertaken using plane surfaces. Plane objects have been used because they permit simple assessment of accuracy, because surface slope angles should all be the same. The plane object is a particularly valuable test of the mathematical model and its assumptions referred to in Section 2.2.

In each case, the plane has been imaged so that, as closely as can be judged, the surface gradient lies along one image axis, so that it satisfies the requirement that the gradients in the cross-direction are zero.

In the example reported here, a plain painted wall was imaged from a distance of about a metre, using the camera in an iPhone 4S mobile phone. The separation between the camera’s flash and the lens on this camera was regarded as insignificant at this object distance. The original colour image, at 1936 pixel columns x 2592 pixel rows (a 3:4 ratio), was transformed to a monochrome image (to impart a single grey-level value to each pixel) and reduced in size to 108 columns x 144 rows, simply to bring the file to a convenient and manageable array size for subsequent analysis via a spreadsheet; Figure 1. The re-scaling was undertaken using proprietary image-manipulation software (PaintShop Pro X6 software, version 16.2.0.20, from Corel Corporation, 1600 Carling Avenue, Ottawa, Ontario, K1Z 8R7, Canada).

Fig. 1. Image of a plane object, obtained using an iPhone camera with flash illumination.

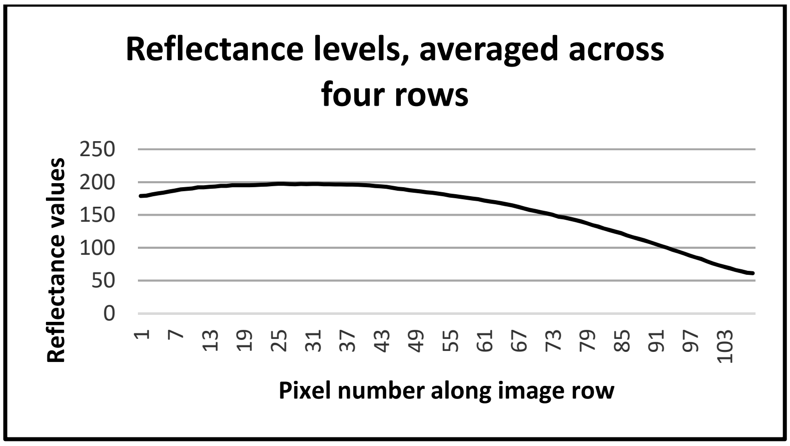

Fig. 2. Average reflectance levels along the central four rows of an image of a plane surface which is at an angle to the camera. Figure created in Microsoft Excel.

Figure 2 shows the reflectance levels for each of the 108 columns along the x-axis, given by averaging the reflectance values in the four adjacent rows 71 to 74, of the 144 rows of the image. It is important to observe that the reflectance levels do not immediately suggest that the object is plane, so that, in all cases, it must be remembered that the reflectances cannot be used to immediately infer the object's shape.

The maximum reflectance and its x coordinate (or pixel number along the row), both of which are needed in the calculation of surface gradients, have been obtained by fitting a quadratic function to the reflectance values shown in Figure2

Figure 3 shows the deduced surface slope angles (in degrees) along the surface, relative to the x-axis of the camera's sensor. Calculations were based on a camera focussing distance of 125 pixels, obtained by a calibration process (for an image size of 144 x 108 pixels). All surface slope angles should be the same for a plane object if the mathematical model is correct. These surface angles are seen in Figure 3 to suffer from errors which are not strictly random, with the greatest deviations occurring in the vicinity of the peak reflectance. The angles are not converted to a surface shape as this would simply be a surface with a gradient of 23.9°. The errors are not random, nor they do not immediately suggest errors in the mathematical model described above in Section 2.2. The average surface slope angle of the surface elements relative to the plane of the sensor over 108 pixels along the sensor's x-axis is 23.9°, with a standard deviation of ±1.3º.

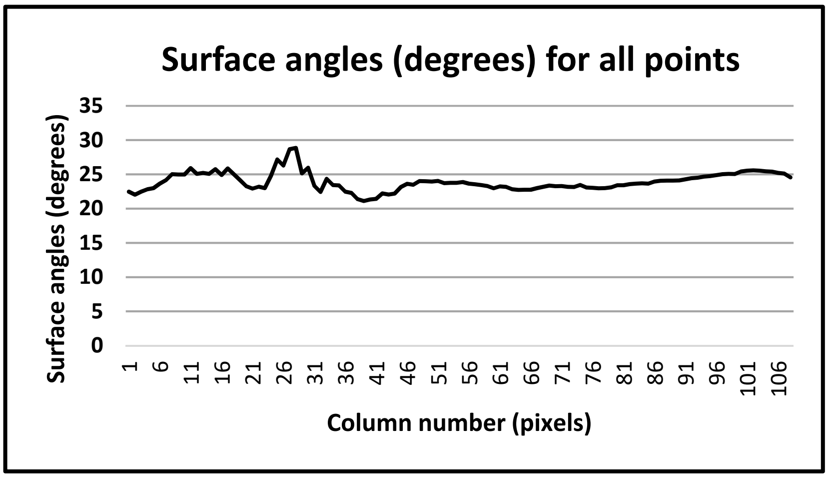

Fig. 3. The deduced angles between the wall surface and the plane of the sensor at all points along the x-axis of the image of the plane surface. The average surface slope angle of the surface elements relative to the plane of the sensor over 108 pixels along the sensor's x-axis is 23.9°, with a standard deviation of ±1.3º. Figure created in Microsoft Excel.

3.2. Cylinder

Further tests of the validity of the mathematical model for SfS profiling have been undertaken with an object of know shape, in this case a small metal cylinder, with a diameter of 107mm, positioned vertically, as in Figure 4. The aim was to see whether it was possible to recover the circular shape along a profile of the cylinder's cross-section.

The cylinder was covered with plain white paper around the appropriate diameter, to give it the necessary even light colour, and an image was taken with an Apple iPhone 4S mobile phone camera, with illumination by the camera's flash. The camera was at a measured distance of 210mm from the closest point of the cylinder, and oriented so that the flash was directed at centre of cylinder as closely as possible.

The surface gradients along the vertical axis of the cylinder should be close to zero, satisfying the requirements that all gradients occur in the direction along the row, thereby making it possible to determine those gradients by the specific SfS profiling method being proposed here.

The original JPEG colour image, of 1936 columns x 2592 rows (according to the image's Exchangeable Image File Format, EXIF), was reduced to a monochrome image of 108 columns x 144 rows, as used in the case of the plane object discussed above, for computing convenience in manipulation. Calculations were based on the camera focussing distance of 122 pixels which was used in the previous case of the plane object.

Figure 5 shows the reflectance values, averaged across the middle four rows of the image of the cylinder (as was done for the plane object, discussed above).

Fig. 4. Flash photograph image of paper covered cylinder, after reduction to 108 columns x 144 rows. The cylinder is marked with lines at 10 mm spacing.

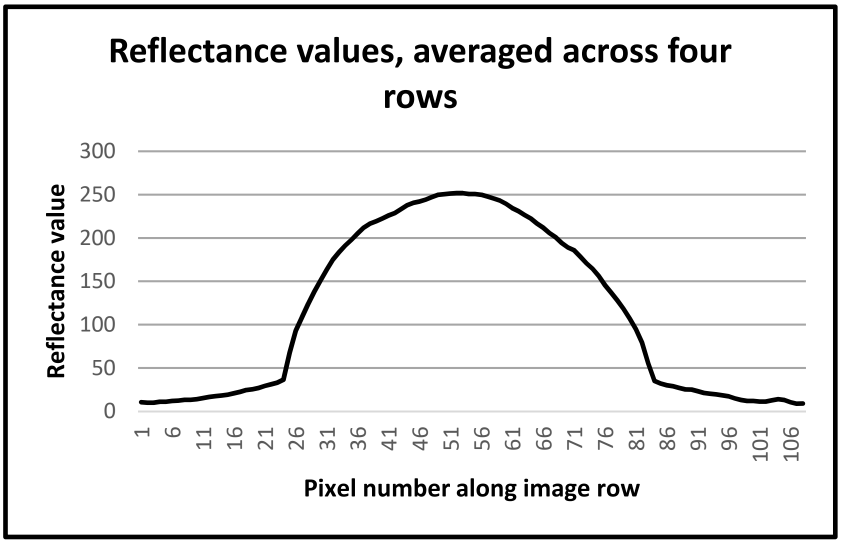

Fig. 5: The average reflectance values across the four adjacent rows at the centre of the image of the image of the cylinder at Figure 4. Figure by Microsoft Excel.

The peak reflectance value and the pixel coordinate of the peak were estimated by fitting a quadratic function to those reflectance values which were part of the cylinder: pixels in the image background, beyond the cylinder, are excluded from calculations, so the surface slope angles are deduced on the remaining 64 pixels only, (out of 108 pixels in the row). Figure 6 shows the angles of the surface slope (in degrees) over the cylinder's cross-section, deduced from the reflectances shown in Figure 5 by using the SfS profiling theory, as suggested in Section 2 above. The units on the horizontal axis are pixels.
It is important to observe that the slope angles in Figure 6 have a maximum value of around 50º, which is an unsurprising outcome in view of the optics of the reflections involved.

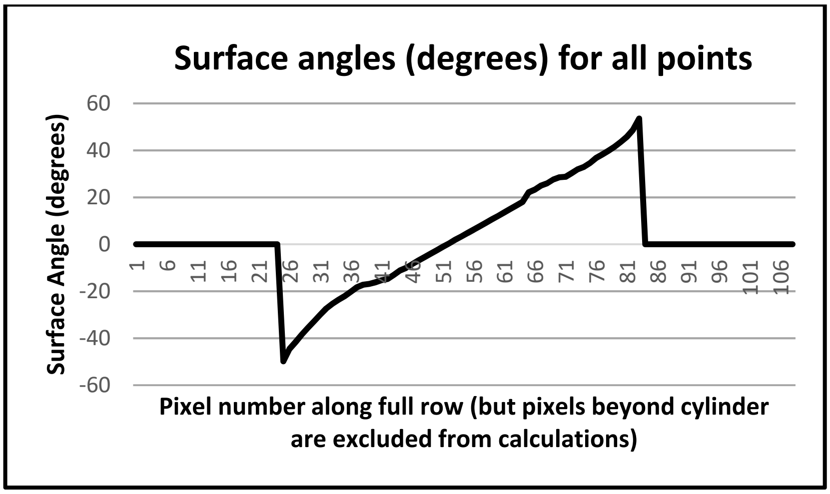

Fig. 6. The deduced surface angles for the pixels shown in Figure 5. Pixels beyond the cylinder are excluded from calculations, and have no surface angle. Figure by Microsoft Excel.

The surface slope angles which are shown in Figure 6 were converted to surface gradients by taking the trigonometric tangent of the surface slope angles, and these were numerically integrated, outwards from the closest point, to provide z-coordinates (still in pixels). Following that, the shape given by z and x-coordinates, in pixels, (regarded as being coordinates in "image space") is converted to Z and X coordinates, in millimetres, (regarded as in "object space"), by taking into account the distance to the object, including a perspective correction. Perspective calculations were based on a distance of 210 mm between the camera and the closest point on the cylinder. The cylinder profile in object space, as obtained from those points used in the calculations, is shown in Figure 7. The Z coordinates are assumed to increase away from the camera lens, so in this case, the object is convex downwards on the diagram.

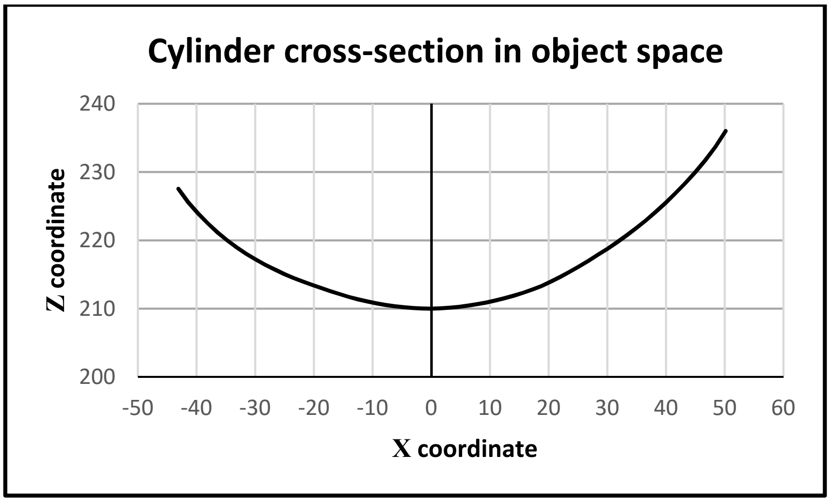

Fig. 7. Surface shape given by the summation of the tangents of the surface slope angles, in object space, including perspective correction. The shape is indicated by correlating the X and Z coordinates of all surface points. It should be noted that the scales on the axes are presented as closely as possible to being the same. Z coordinates increase in the direction away from the lens. Figure by Microsoft Excel.

To estimate accuracy of the results, the distances between the markers on the surface were calculated, and were on average ten percent greater than the correct values. The radius of the cylinder was calculated for each point using the Z and X coordinates which contributed to the shape in Figure 7. The average radius was 74.8 mm whereas the correct value was 53.5 mm. However, the standard deviation of the radii was only 0.4 mm, suggesting that the surface was circular. It appears that the surface shape is essentially correct, but a systematic error exists in the mathematical model. Anticipated sources of error include the lens' focal distance, the distance of the to the object from the lens, and non-verticality of the cylinder. Even so, the outcome for the cylinder is assumed to imply the possibility of measuring horizontal breast profiles by a similar process.

3.3. Horizontal Profile on Breast

The technique which was used in the case of the plane and cylinder has been developed with the specific goal of applying it to human female breast measurement. Exploratory tests of the feasibility of the SfS profiling have been undertaken on just two human female breast images. In neither case has the result been verified, because of the difficulty of obtaining confirmation by an alternative measurement technique.

In the example reported here, a Flexiscope brand Piccolo intra-oral dental camera, providing colour imagery at a size of 768 columns x 576 rows (i.e. at 4:3 ratio) was used for imaging a left breast. The camera had the advantages of being of high quality. The image was reduced to a monochrome image with 144 columns and 108 rows, its equivalent focal distance by calibration then being 125 pixels.

The image covers the left breast and extends into the left arm. Consequently, the calculations referred to below are based on pixels in columns numbered from 10 to 111 only: see Figure 8. The figure shows the reflectance values obtained by averaging, as for the case of the cylinder above, the reflectance levels in four adjacent rows through the centre of the areola region.

A quadratic function was fitted to the used pixels in order to interpolate across the excluded pixels on the areola. The function fitted to of those points which were then used in the profile reconstruction was used to deduce surface slope angles along the profile.

These angles were in turn used to deduce the profile of the surface as shown in Figure 9. The scale of the shape was not known exactly as the distance of the breast from the camera was not measured, so the scale is approximate.

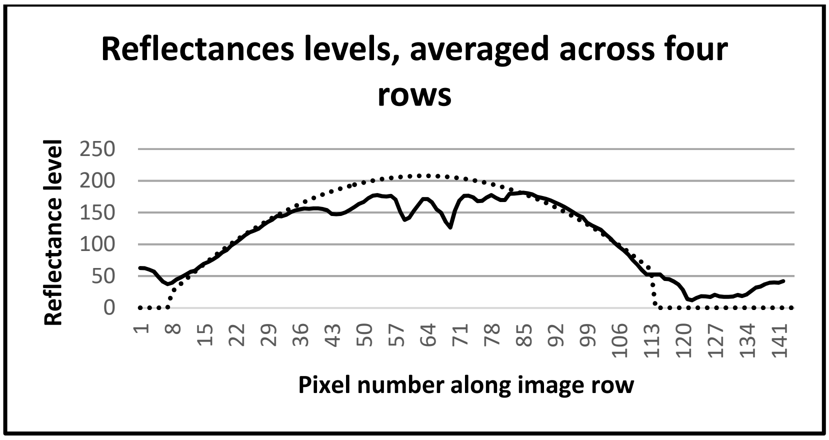

Fig. 8. Averaged reflectance levels along rows 47 to 50 of the breast image. The occurrence of the areola region from about columns 38 to 87 is apparent, and these points were excluded from all SfS calculations. As well, pixels at the edges, where the image reaches the edge of the breast, (less than pixel 8 and beyond pixel 113) were also excluded. The dotted line shows a quadratic function which was fitted to the remaining pixels. Figure by Microsoft Excel.

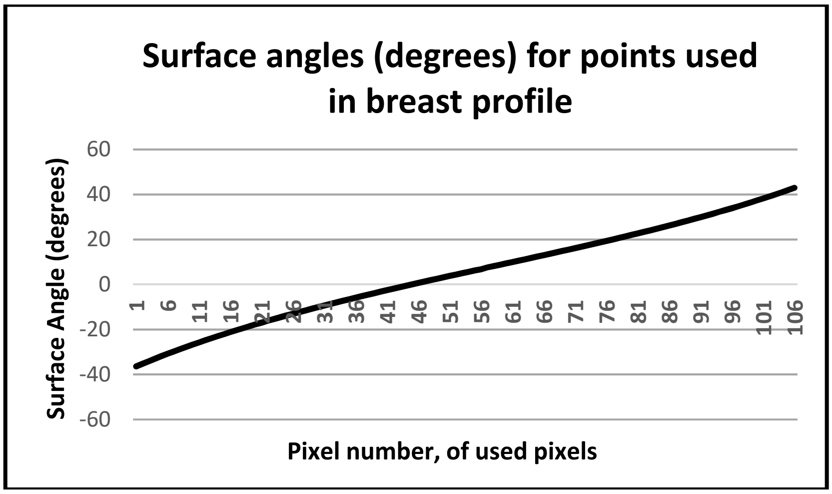

Fig. 9. The deduced surface angles across the breast profile for the pixels used in the shape calculations. Figure by Microsoft Excel.

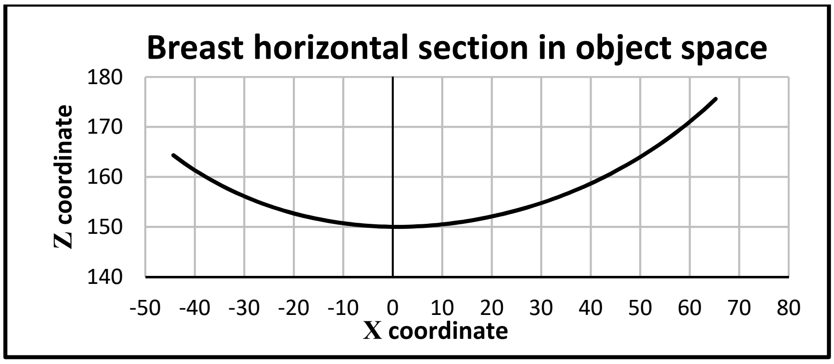

Fig. 10. The breast surface shape as given by a summation (outwards from the centre) of the gradients (tangent of the surface slope angles) derived from the curve which is shown dotted in Figure 8. It can be seen that the depth of the breast is less on the apparent left-hand side, where the smooth breast shape meets the chest. The grid spacings on the axes are as close as possible to being the same. As with Figure 7, Z coordinates increase in the direction away from the lens. Figure by Microsoft Excel.

3.4.Tests on Full Three-Dimensional Surface of a Breast

Determination of the surface angles over the complete breast can be undertaken if it is valid to assume that, along lines which radiate from the closest point of the object, the breast, the surface gradients are substantially radial. The subsequent step, computing surface heights by summations in the radial directions, is made difficult when the image is in a rectangular array, but that step may not be crucial if use can be made of the surface slope angles, rather than the surface shape itself. Calculations of the radial surface angles have been undertaken on the full breast used in the profiling example above, showing smoothly varying angles, but the results are difficult to depict. Instead, the profile obtained in the vertical direction of a breast is shown in Figure 11. The processes were essentially the same as those used in the case of the horizontal profile described above. Coverage on the lower side is restricted to surface slope angles less than about the 50º limit which was found with the cylinder discussed above.

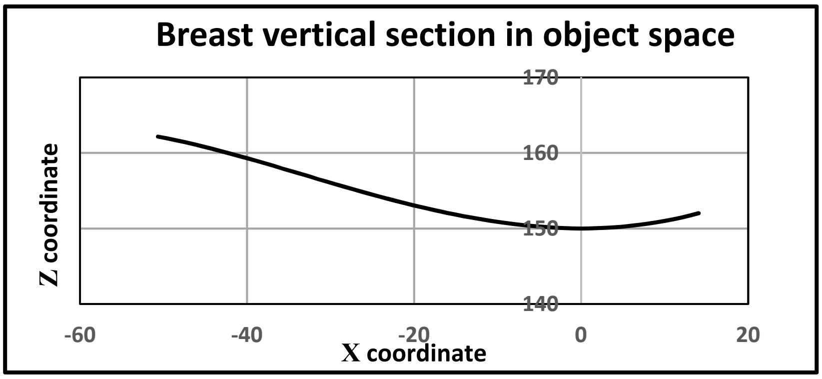

Fig. 11. The breast surface shape as given by a summation of the gradients (tangent of the surface angles) for a vertical profile. The summation covers a limited number of pixels which are seen to be in the breast area, but ends when breast curvature becomes large, and surface slope angles reach the 50º limit. The curve covers the areola using the interpolation methods described for the horizontal cross-section. The coordinates in image space are in pixels. Figure by Microsoft Excel.

3.5. Discussion of Results

The profiling technique appears to recover the broad surface shapes. Even though the mathematical model for the optics and perhaps even the perspective correction appears to be imperfect, results are encouraging. Deduced surface shapes are sensible. The plane surface shown here and others not reported here, reveal that deduced angles, like those in Figure 3, suffer from errors which are not purely random. This level of error may indicate the limiting accuracy of the surface measurement process, at least as executed with this lens, sensor and flash system.

Some outcomes are unexpected: the level of effectiveness of the mathematical function fitting to the human breast shape in these cases is seen as beneficial. A single uncomplicated function may effectively model the breast profile’s surface angles from one side to the other. These outcomes suggest that using the SfS results presented as surface angles may be easier and more useful that converting the angles to a surface shape (a process which can accumulate noise and errors).

The number and scope of the tests which have been undertaken so far is limited. More than anything else, the true accuracy of the SfS method used specifically for breast measurement under various conditions and with different equipment has not been established. The SfS profiling theory assumes that that along the radial lines of the image there is no transverse gradient on the object. On the female breast, that may or may not be precisely true, and it deserves to be ascertained.
Further testing is needed to extend and diversify the cases studies, with investigations into the repercussions of such matters as image noise levels, the repercussions of converting an original image from colour to monochrome and its re-sizing; the existence of and the effect of any misalignments between the flash axis and the camera lens axis; the nature of the illumination provided by a flash; the optimum number of pixels; and so on. Finally, it should be possible to determine the best mathematical functions which satisfactorily represent the breasts, either as profiles or in three-dimensions.
It is apparent that the steeper regions of the cylinder and the breast are not covered by the this SfS method, so there are limitations to the measured angles, perhaps because of the use of the flash lighting.
Motivation for further testing and development depends on its prospects for use. Breast measurement seems to be most suitable for measurement by the simple surface model based on the radial line assumption, i.e. that gradients are in the direction radial from the centre of an appropriately positioned camera and that mathematical functions can be fitted to the surface. Numerous questions arise about the demand for breast measurement, whether the appropriate shape information be deduced in practice from the measured profiles. No attempt has been made to isolate suitable applications of breast measurement, which are not an area of expertise of the writer, but the general existence of demand is apparent in the literature.
Specific requirements in terms of speed of analysis, accuracy, area coverage, output and cost need to be ascertained. The entire procedure would ideally be executed on a mobile phone, following an automated procedure from imaging to output of the appropriate breast parameters. Mobile phone cameras have the distinct advantage that the flash is located very close to the lens (but that does not ensure parallel alignment of the flash and lens axis).
A simple practical procedure for the determination of image scale is needed.
The image processing can be assumed to be successful only on bare human skin which has an even physical texture and light optical texture, free from colour variations. Testing has not been carried out on darker or varying colour skin, due to such things as pigment, tanning or tattoos. The option of wearing of tight, light coloured clothing has not been tried.
The SfS method’s simplicity, including the feasibility of using a simple mobile phone camera, and its quantitative output should make it superior to human examination of either imagery or the patients themselves, and may make it useful for various medical and para-medical purposes. SfS is not being proposed here as an alternative to laser scanning, which provides data which is clearly more accurate and comprehensive and more easily comprehended than the SfS method does. On the other hand, scanners are a resource which is relatively expensive and not necessarily as easily made available or operated, but they can be worth accessing in some situations. Other optical techniques, such as photogrammetric, structured light and moiré fringe methods, have also been proposed for breast measurement, but they do not appear to be in common use.

4.Conclusions

The work concentrates on the investigation of concepts, not on its practical implementation. Aspects of the apparent accuracy need to be resolved. Preliminary results suggest that the radial breast profile does appear to be measurable by a simple SfS algorithm. More than that, the breast profile appears to be modellable with simple mathematical functions.

References

[1] H. Mitchell, "Analysing Single Photographic Images using Shape-From-Shading to Quantify Human Breast Profiles", in *Proc. of 3DBODY.TECH 2017 - 8th Int. Conf. and Exh. on 3D Body Scanning and Processing Technologies*, Montreal QC, Canada, 11-12 Oct. 2017, pp. 154-162, https://doi.org/10.15221/17.154.