INVESTIGATION OF OBJECTS PERFILOMETRY USING DIGITAL SHADOW MOIRÉ EXPERIMENTAL TECHNIQUE

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Abstract. *Surface topography can be conveniently investigated by Classical Shadow Moire technique. Moiré is a non contact and non destructive technique, with a fast digitisation process. It has measurement accuracy comparable to other systems and also low cost. It is relatively free from stringent requirements on stability of instrumentation and quality of light source, however, presents relatively low resolution. The objective of this paper was the application of Classical Shadow Moiré and Phase Shifting technique to generation of digital model. The resolution of Shadow Moiré measurement depends also on the pitch of reference grating. Model used in this research was an opaque white mannequin. Experimental setup used a high resolution digital camera,an illumination system and reference grid with period of 1.0 mm. Four images were taken from Phase Shifting technique. Fringes were moved ¼ phase among each photography. A software was developed to use this technique with a Matlab program. Results obtained were compared with another commercial Rising Sun software. Results comparing real profile with digitalized images proved the accuracy and precision of experimental results. Classical Shadow Moiré presents to be simple but need precise operation and becomes quite accessible using computational programs. A special attention is given to new the methods of unwrapped phase. The suggested approach presented in this paper was used for a tri-dimensional curved surface displacement.*

Keywords*: Moiré, Phase Shifting, Shadow, Measurement, Carre Technique, Perfilometry*

1. INTRODUCTION

The moiré effect is the mechanical interference of light by superimposed networks of lines. The pattern of broad dark lines that is observed is called a moiré pattern. Only a little study of moiré effect uncovers a very striking and useful characteristic: a very large shift in moiré pattern is obtained from only a small relative motion between the superimposed networks. A logical conclusion is that the moiré pattern is a sort of motion magnifier, which might be used to give a highly sensitive measurement of relative motion.

The interferogram is the optical signal that may yield the desired optical metrology result through some signal processing techniques. The processing techniques usually involve identifying and tracking the fringes in an interferogram, assigning the correct fringe order numbers, and applying the necessary operations to extract the fringe data. For many years, the processing of interferograms has been a matter of manually identifying of the fringes. The mayor disadvantage of manual processing is that the resolution of the fringe data is too low and is not suitable for accurate measurement. With the development and decreasing cost of digital image processing equipment, a lot of effort has been made into what is termed digital fringe pattern measurement techniques. Some major reasons of this effort are to obtain better accuracy, to increase the processing speed; to automate the process. There are lot of works done extensively to develop the semi-auto as well as automatic procedures for optical signal processing.

The objective of this research is the application of Shadow Moiré technique classic and phase shifting , as methodologies for the generation of topographical digital models. It was used a opaque white mannequin, as methodology for the generation of topographical digital models. .Optical methods, as Moiré Techniques have been used for investigation of objects perfilometry with diffuse or irregular surface on industrial design. The resolution of the shadow moiré measurement depends on the pitch (or frequency) of the reference grating. In the resulting fringe images, each fringe represents one pitch distance of the out of plane displacement. A software program was developed using MatLab.

2. THEORY

The fringe pattern is a sinusoidal function and represented by intensity distribution I(x,y). This function can be written in general form as:

$$I(x, y) = I_m(x, y) + I_a(x, y).\cos[\phi(x, y) + \delta] \quad (1)$$

where, I_m is background intensity variation, I_a is the modulation strength, $\phi(x,y)$ is the phase at origin and δ is the phase shift with respect to the origin.

The general theory of synchronous detection can be applied to discrete sampling procedure, with only a few sample points. There are only minimum four signal measurements needed to determine the phase ϕ and the term δ. Phase Shifting Interferometry is preferred technique whenever the external turbulence and mechanical conditions of the interferometer remain constant over the time required to obtain the four phase-shifted interferograms. Typically, the technique used in this experiment is called Carre method. By solving the equation (1) above, the phase ϕ can be determined. The intensity distribution of fringe pattern in a pixel may be represented by gray level, which vary from 0 to 255. With Carre method, the phase shift (δ) amount is treated as an unknown. The methods uses four phase-shifted images as

$$\begin{cases} I_1(x,y) = I_m(x,y) + I_a(x,y).\cos\left[\phi(x,y) - 3\delta/2\right] \\ I_2(x,y) = I_m(x,y) + I_a(x,y).\cos\left[\phi(x,y) - \delta/2\right] \\ I_3(x,y) = I_m(x,y) + I_a(x,y).\cos\left[\phi(x,y) + \delta/2\right] \\ I_4(x,y) = I_m(x,y) + I_a(x,y).\cos\left[\phi(x,y) + 3\delta/2\right] \end{cases} \qquad (2)$$

Assuming the phase shift is linear and does not change during the measurements, the amount of phase shift can be calculated as

$$\delta = 2\tan^{-1}\left[\sqrt{\left|\frac{3(I_2 - I_3) - (I_1 - I_4)}{(I_2 - I_3) + (I_1 - I_4)}\right|}\right] \qquad (3)$$

and the phase at each point is determined as

$$\phi = \tan^{-1}\left\{\tan(\delta/2).\left[\frac{(I_1 - I_4) + (I_2 - I_3)}{(I_2 + I_3) - (I_1 + I_4)}\right]\right\} \qquad (4)$$

The advantage of Carre algorithm is clear; it does not require accurate calibration of the phase shifting mechanism as long as it is linear and stable during the measurement.

The phase ϕ obtained from the Phase Shifting Algorithm above is a wrapped phase, which vary from $-\pi/2$ to $\pi/2$. A wrapped phase has to be unwrapped so that phase value increases with a factor $2\pi k$. The relationship between the wrapped phase and the unwrapped phase may thus be stated as:

$$\begin{cases} \Psi = W(\phi) \\ W(\phi) = 2\phi + 2\pi k \end{cases} \qquad (5)$$

where W is the wrap function and k is an integer number, ϕ is a wrapped phase and ψ is a unwrapped phase

$$\Psi(x,y) = 2\phi(x,y) + 2\pi.k(x,y) \qquad (6)$$

The processing algorithm can be divided into two major parts and is coded into a Matlab program. The first part of the algorithm is to process the optical signal or fringe data in phase map:

```
PHI = im2double( I1 );
PHI = 0.0 * PHI;
[m,n] = size(I1);
for i=1:1:m
    for j=1:1:n
        FI1 = double( I1(i,j) ); FI2 = double( I2(i,j) );
        FI3 = double( I3(i,j) ); FI4 = double( I4(i,j) );
        Numer = 3.0*(FI2-FI3)-(FI1-FI4);
        Denom = (FI2-FI3)+(FI1-FI4);
        if (Denom==0)
            ang = sqrt( abs( Numer / 1.0E-15 ) );
        else
            ang = sqrt( abs( Numer / Denom ) );
        end
        Numer = ang * ((FI1-FI4)+(FI2-FI3));
        Denom = (FI2+FI3)-(FI1+FI4);
        if (Denom==0)
            PHI(i,j) = atan( Numer / 1.0E-15 );
        else
            PHI(i,j) = atan( Numer / Denom );
        end
    end
end
```

Figure 1: First part of the algorithm in Matlab. (Carre Method)

The second part of algorithm is to unwrap the wrapped phase map. When unwrapping, several of the phase value should be shifted by an integer multiple of 2π. Unwrapping is thus adding or subtracting 2π offsets at each discontinuity encountered in phase data. The unwrapping procedure consists in finding the correct field number for each phase measurement. Taking k(x,y)=0, the field number has only three possibilities at each pixel.

This methods assumes that the phase image is continuous, and that the sampling is dense enough so that the true phase values between two adjacent points do not differ by more than π. The wrapped, principal, phase value is denoted ϕ, and ψ is the true phase value. The phase differences in the horizontal and the vertical direction are estimated by

$$\begin{cases} \Delta^x_{i,j} = W\left(\phi_{i+1,j} - \phi_{i,j}\right) \\ \Delta^y_{i,j} = W\left(\phi_{i,j+1} - \phi_{i,j}\right) \end{cases} \tag{7}$$

The least squares error is

$$S = \sum_{i=1}^{M-1}\sum_{j=1}^{N}\left(\phi_{i+1,j} - \phi_{i,j} - \Delta^x_{i,j}\right)^2 + \sum_{i=1}^{M}\sum_{j=1}^{N-1}\left(\phi_{i,j+1} - \phi_{i,j} - \Delta^y_{i,j}\right)^2 \tag{8}$$

Applying the least squares criteria gives

$$\begin{cases} Q.\Psi = C \\ where \\ Q.\Psi_{i,j} = \min(\phi^2_{i+1,j};\phi^2_{i,j}).(\Psi_{i+1,j} - \Psi_{i,j}) - \min(\phi^2_{i,j};\phi^2_{i-1,j}).(\Psi_{i,j} - \Psi_{i-1,j}) \\ + \min(\phi^2_{i,j+1};\phi^2_{i,j}).(\Psi_{i,j+1} - \Psi_{i,j}) - \min(\phi^2_{i,j};\phi^2_{i,j-1}).(\Psi_{i,j} - \Psi_{i,j-1}) \\ C = \min(\phi^2_{i+1,j};\phi^2_{i,j}).\Delta^x_{i,j} - \min(\phi^2_{i,j};\phi^2_{i-1,j}).\Delta^x_{i-1,j} + \min(\phi^2_{i,j+1};\phi^2_{i,j}).\Delta^y_{i,j} \\ - \min(\phi^2_{i,j};\phi^2_{i,j-1}).\Delta^y_{i,j-1} \end{cases} \tag{9}$$

The second part of algorithm in MatLab is to unwrap the wrapped phase map:

```
 PHI = 2.0 * PHI;
 FUNWRAP = 0.0 * PHI;
 Q = sparse([], [], [], m*n, m*n, (5*m*n)+12);
 Q = 0.0 * Q;
 c = zeros(m*n,1); c = 0.0 * c;
 [m,n] = size(PHI);
 for i=1:1:m
   for j=1:1:n
       if (i>1)
           left=PHI(i-1,j);
           Term=min(PHI(i,j)*PHI(i,j),left*left);
           Q((i-1)*n+j,(i-1+0)*n+j)=Q((i-1)*n+j,(i-1+0)*n+j)-Term;
           Q((i-1)*n+j,(i-1-1)*n+j)=Q((i-1)*n+j,(i-1-1)*n+j)+Term;
           delta=PHI(i,j)-left;
           while (delta>pi)
              delta=delta-2*pi;
           end
           while (delta<=-pi)
              delta=delta+2*pi;
           end
           c((i-1)*n+j)=c((i-1)*n+j)-Term*delta;
       end
       if (i<m)
           right=PHI(i+1,j);
           Term=min(right*right,PHI(i,j)*PHI(i,j));
           Q((i-1)*n+j,(i-1+1)*n+j)=Q((i-1)*n+j,(i-1+1)*n+j)+Term;
           Q((i-1)*n+j,(i-1+0)*n+j)=Q((i-1)*n+j,(i-1+0)*n+j)-Term;
           delta=right-PHI(i,j);
           while (delta>pi)
              delta=delta-2*pi;
           end
           while (delta<=-pi)
              delta=delta+2*pi;
           end
           c((i-1)*n+j)=c((i-1)*n+j)+Term*delta;
       end
       if (j>1)
           bottom=PHI(i,j-1);
           Term=min(PHI(i,j)*PHI(i,j),bottom*bottom);
           Q((i-1)*n+j,(i-1)*n+j+0)=Q((i-1)*n+j,(i-1)*n+j+0)-Term;
           Q((i-1)*n+j,(i-1)*n+j-1)=Q((i-1)*n+j,(i-1)*n+j-1)+Term;
           delta=PHI(i,j)-bottom;
           while (delta>pi)
              delta=delta-2*pi;
           end
           while (delta<=-pi)
              delta=delta+2*pi;
           end
           c((i-1)*n+j)=c((i-1)*n+j)-Term*delta;
       end
       if (j<n)
           top=PHI(i,j+1);
           Term=min(top*top,PHI(i,j)*PHI(i,j));
           Q((i-1)*n+j,(i-1)*n+j+1)=Q((i-1)*n+j,(i-1)*n+j+1)+Term;
           Q((i-1)*n+j,(i-1)*n+j+0)=Q((i-1)*n+j,(i-1)*n+j+0)-Term;
           delta=top-PHI(i,j);
           while (delta>pi)
              delta=delta-2*pi;
           end
           while (delta<=-pi)
              delta=delta+2*pi;
           end
           c((i-1)*n+j)=c((i-1)*n+j)+Term*delta;
       end
    end
 end
FF = Q\c;
for i=1:1:m
   for j=1:1:n
       FUNWRAP(i,j) = FF((i-1)*n+j);
    end
 end
```

Figure 2: Second part of the algorithm in Matlab. (New methods of unwrapped phase).

The modulation phase ψ obtained by unwrapping physically represent the fractional fringe order numbers in the interferogram. The shape can be determined by applying the out-of-plane deformation formula for shadow moiré:

$$Z_{i,j} = \frac{p.\Psi_{i,j}}{(\tan\alpha + \tan\beta)} \quad (10)$$

where:
$Z_{i,j}$ = elevation difference between two points located at body surface to be analyzed
p = frame period
α = light angle
β = observation angle

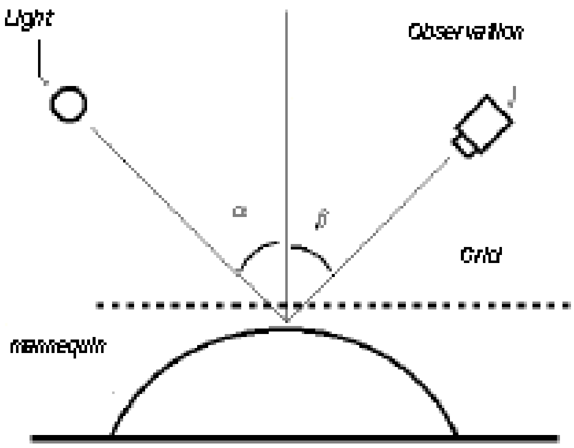

Figure 3:Layout of Experiment.

3. EXPERIMENTS

The shadow moiré technique and processing algorithm were tested and calibrated before it was applied for shape measurement. To validate these techniques they were compared with another digital model using a commercial software Rising Sun.. Results comparing real profile with digitalized images prove the precision and accuracy of results.

It was developed and tested a program successfully dedicated, capable to calculate the profile 3D from the processing of the acquired images. The carried through experiments had in such a way allowed the mapping of contours of parts of the human body how much of other free contours. However, valley to point out that this technique presents limitations in measurements of contours with brusque geometric changes of the profile, with extreme reflection and in which has the possibility of formation of shades, which harm the complete quantification.

The development of a system of measurement without contact and not destructive capable was possible to measure soft free contours three-dimensionally. Soon, this system becomes applicable the measurement 3D of contours in an industrial environment, for example, comparing itself in real time, the profile 3D of an on-line product of production with its respective standard, being able to be applied the industrial processes, as form of inspection and quality control assured of products. Also, for the evaluation of deformities of feet, hands, shunting lines in the vertebral column without the generation measurement uncertainties and injuries in the region measured had to the contact with the feeler, being able to be used in lacerated regions.

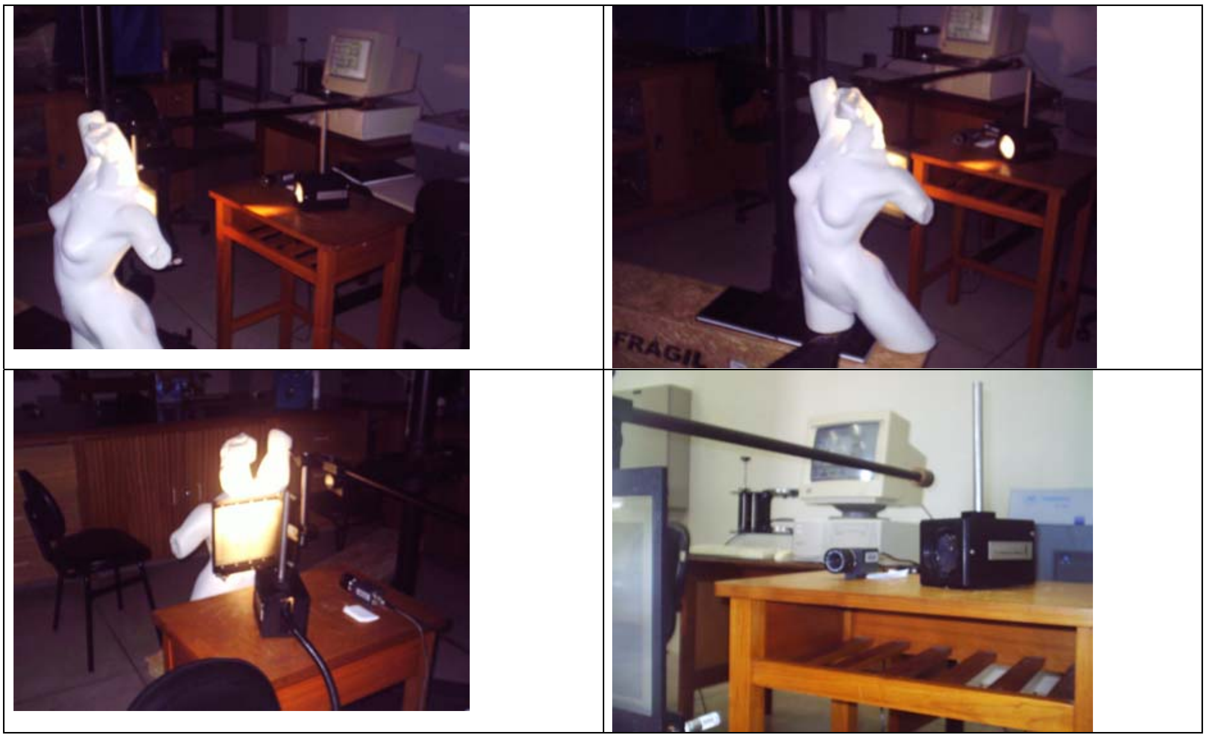

Figure 4: Photos of Experiments. Mannequin of white color and the physical assembly in the laboratory.

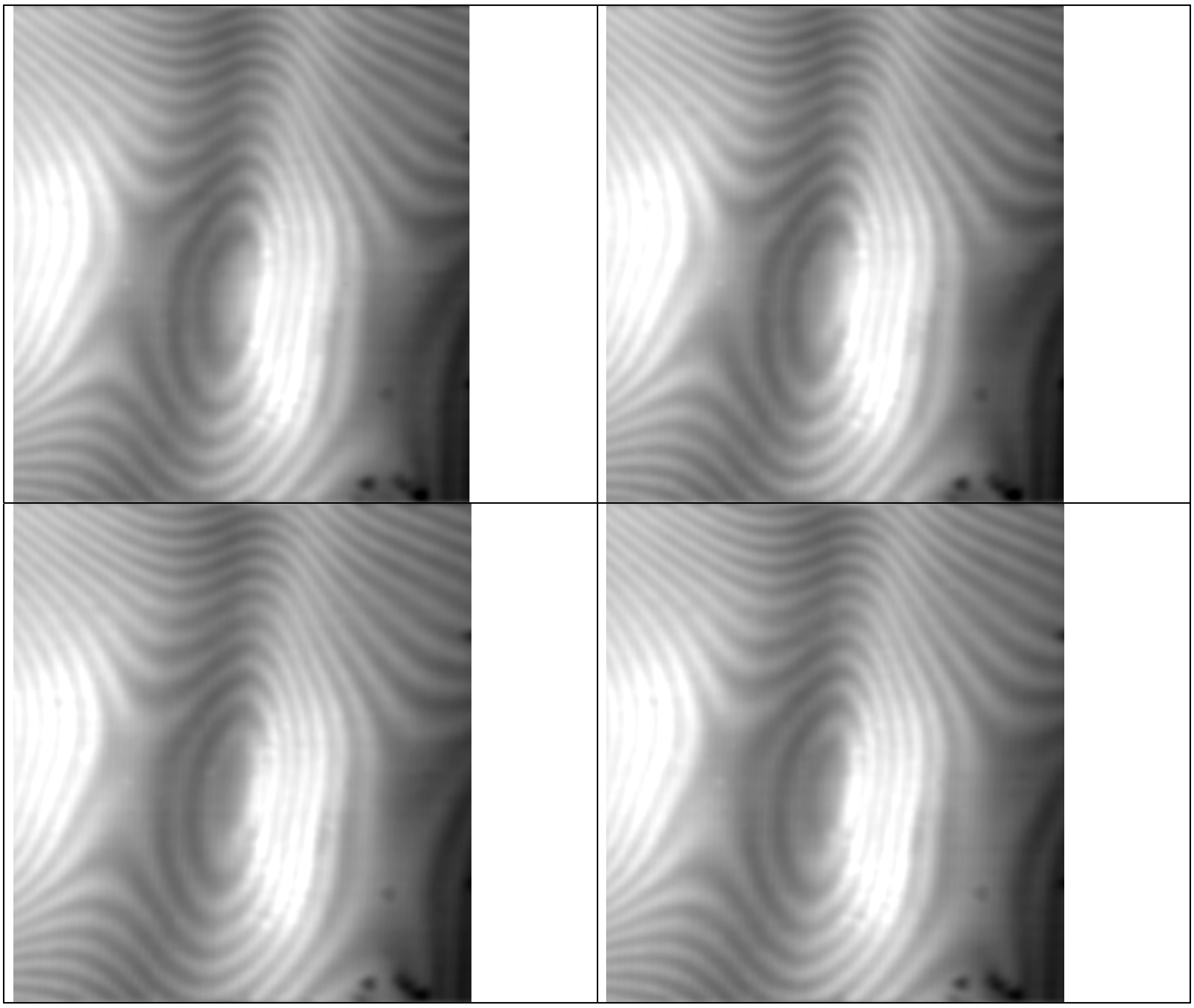

Figure 5: Photos of images. Original Moiré Interferogram. 4-frame Phase-shifting algorithm.

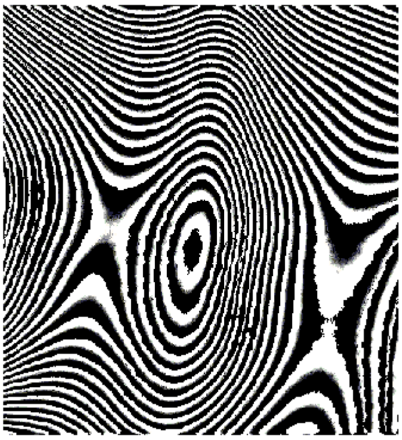

Figure 6: Wrapped phase. After algorithm of figure 1.

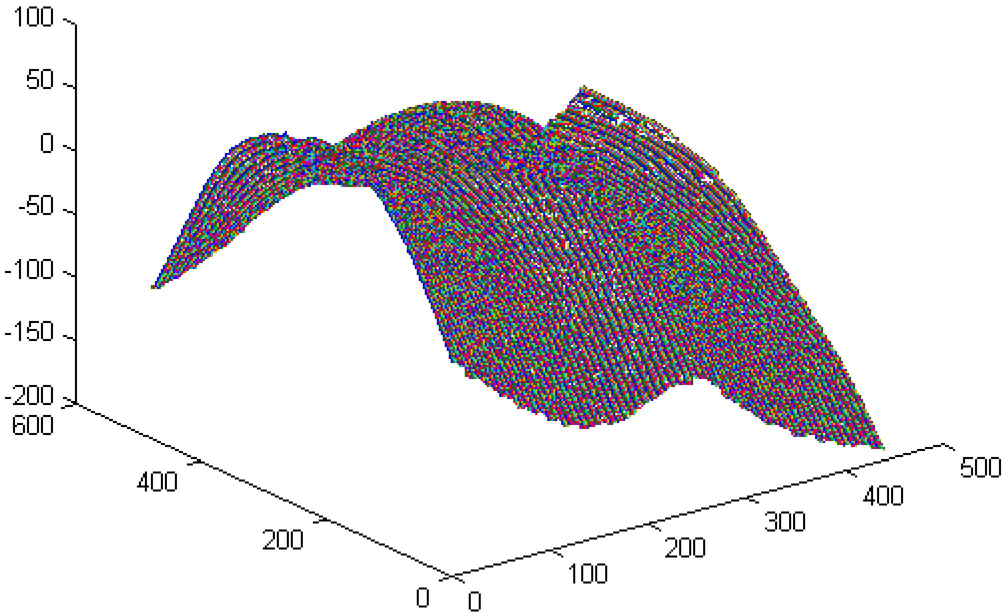

Figure 7: Result in Matlab (3D). After algorithm of figure 2.

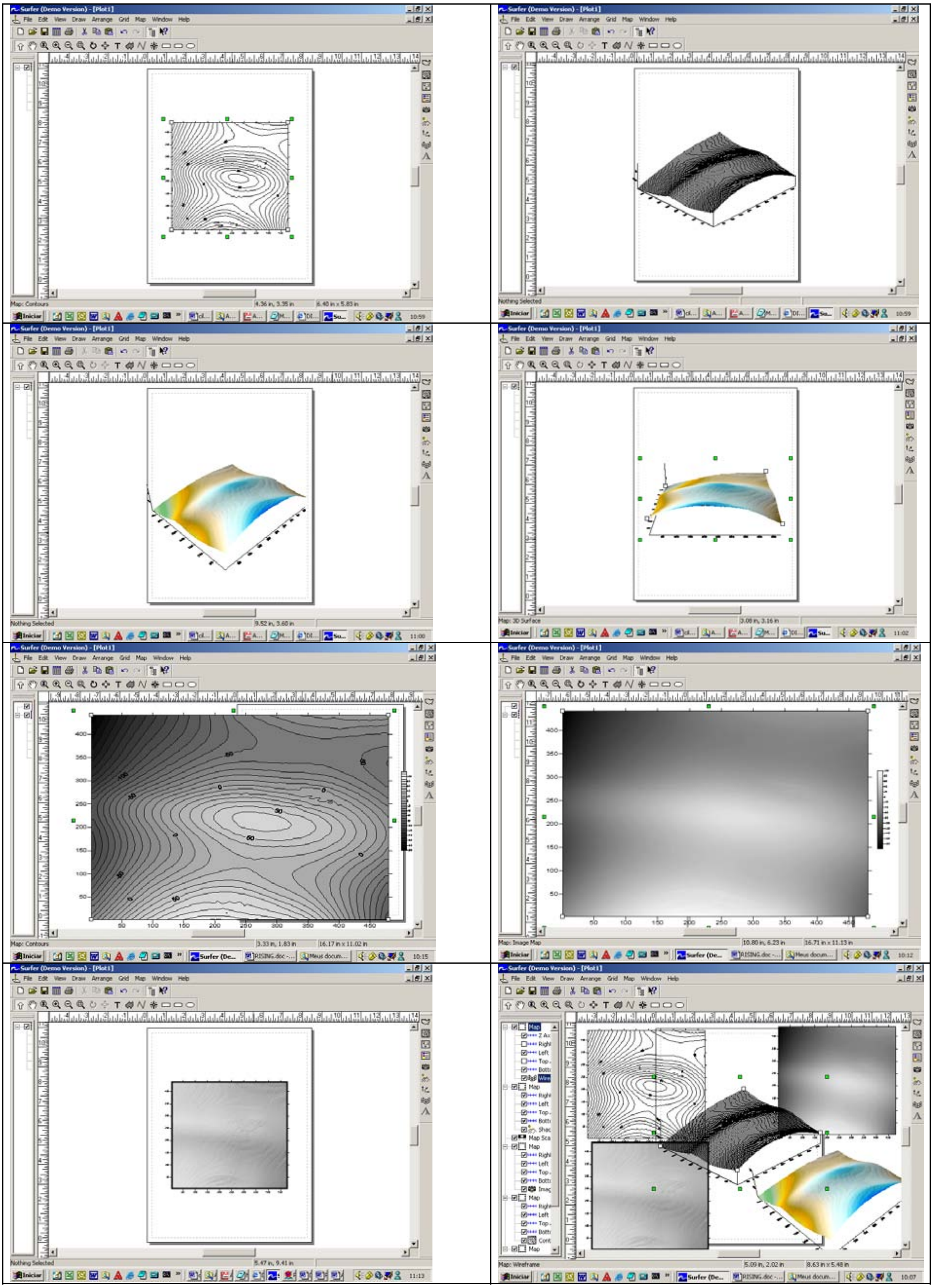

Figure 8: Result of MatLab program export to Sufer. (a) Profile in 2D. (b, c, d) Profile in 3D. (e, f, g) Color Profile. A brief metrological analysis of the possible measurement uncertainties of the optical system was done and also the uncertainty value was estimated.

```
Z = ((1.0*p)/(tan(alfa)+tan(beta))) .* FUNWRAP;
fid = fopen('NameArq.txt','w');
[m,n] = size(Z);
for i=1:1:m
    for j=1:1:n
        fprintf(fid,'%d %d %10.5f\n',i,j,Z(i,j));
    end
end
fclose(fid);
```

Figure 9: Code to export from MatLab to Sufer. Matrix of depth (x, y, z).

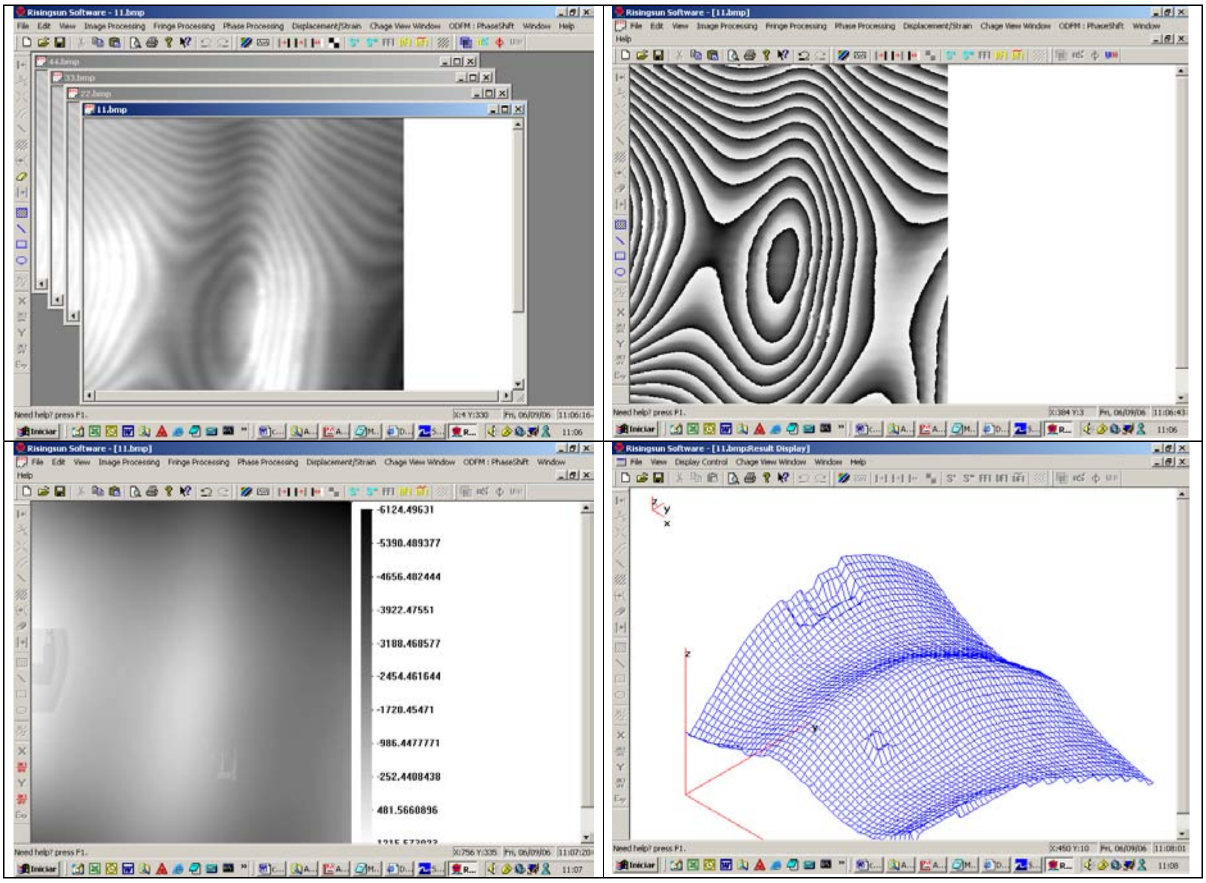

Figure 10: Execution step by step of the program Rising Sun. (a) Photos of images. (b) Wrapped phase. (c) Profile 2D. (d) Profile 3D. Comparison with Rising Sun. Comparing the measures of the program developed in Matlab with the results of Rising Sun programs using the same photographs.

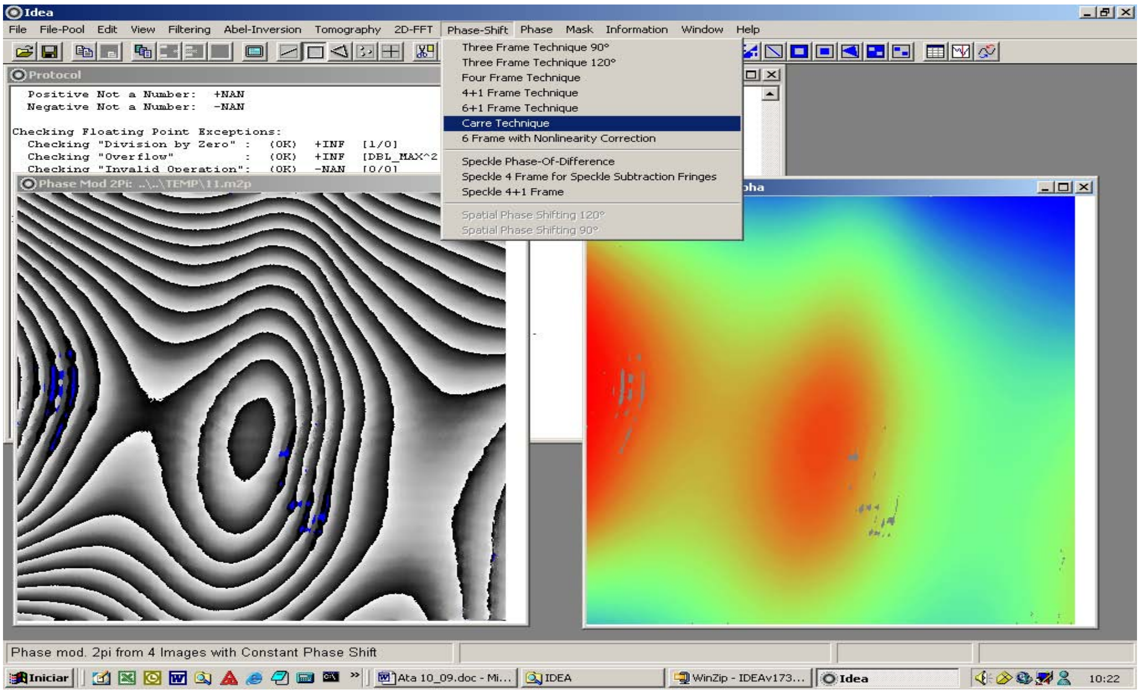

Figure 11: Comparison with IDEA. (a) Wrapped phase. (b) Profile 2D color. Comparing the measures of the program developed in Matlab with the results of IDEA programs using the same photographs. The program in MatLab presented resulted similar if comparative with others commercial software of Moiré.

4. CONCLUSION

The modified algorithm is shown to be capable of processing the optical signal of interferogram. Comparison of results from the Phase-shift Moiré Interferometry and a commercial software Rising Sun showed that it was in agreement. Optical methods, as the *Moiré* Techniques (MT), have been used for investigation of objects topography (perfilometry) with diffuse or irregular surface as human's bodies, or industrial design. Experimental set up with a digital photographic camera, and an illumination system, and grids with period of 1,0 mm. For MT with phase shifting a manual system was used to displace the surface. For classic shadow MT, one image of the surface was taken with the *moiré* fringes that were manual digitalized and generate a digital model of the surface. For MT with phase shifting, 4 images were taken and the surface was moved away a small distance of the grid. The fringes were moved ¼ phase among of each photography. Using these images, after removal of the *moiré* lines, a digital model of the surface was generated. These techniques are easy to use, have high precision and low cost. The results show that MT was precise and accurate. Classic shadow MT of is simple but with hard operation and becomes quite accessible by using common computational programs. MT with phase shifting is fast, however it demands specific computational routines. The metric analysis of the considered system demonstrated that its uncertainties of measurement if find next to 5% of the measured value, longed for in the objectives of this work. However, the uncertainties of measurement of the geometric parameters and the phase still require attention. The measurement results obtained by the optical system demonstrate its industrial and engineering applications.

5. ACKNOWLEDGEMENTS

The authors appreciate the generous support of the Pontíficia Universidade Católica de Minas Gerais – PUCMINAS.

6. REFERENCES

Cloud, G. Optical methods of engineering analysis. Cambridge, Cambridge University Press, 1998.

Gasvik, K. J. Moiré techniques by means of digital image processing. Applied Optics. Washington. v.22, n.23, p.3543-48, set., 1983.

Golden software, inc. Surfer 32 user's guide. Golden, Golden Software, Inc, 1995.

Liao, J. E.A. and Voloshin, A.S. Enhancement of shadow-moiré methods through digital image processing, Esperimental Mechanics, v. 33(1), march 1993.

Post, D.; Han, B.; Ifju, P. High sensitivity moiré: Experimental analysis for mechanics and materials. New York, Spring-Verlag. 1994.

Riley, W.F.; Durelli, A.J. Application of moiré methods to the determinationof transient stress and strain distributions. Journal of Applied Mechanics. v.29, n.4, 1962.

Schiammarella, C. A. The moiré method – A review. Experimental Mechanics. v.44, n.8, p. 418-433, nov., 1982.

Soille, P. Morphological phase unwrapping. Optical and Lasers in Engineering. v.32, p. 339-352, jan., 2000.

Takasaki, H. Moiré topography. Applied Optics. Washington. v.9, n.6, p. 1457-52, out., 1970.

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