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AUTOMATIC SURFACE RECONSTRUCTION OF SIMPLE MECHANICAL OBJECTS USING GRID PROJECTION AND PHASE SHIFTING

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ABSTRACT

The paper is concerned with the results obtained for a particular type of 3D scanner set up by the authors for surface measurements of simple mechanical objects. A grating of laser light, generated by a Michelson interferometer, is projected onto the object to be measured and a television camera is used to capture the images. The phase of this grating is calculated using the phase shifting technique. The object is positioned on a turntable and full field images are acquired through 360°. Its coordinates are determined by means of simple trigonometric operations. A reconstruction algorithm pastes together the images recorded from a variety of angles and builds up a mesh for computer vision of the surface. An interactive editor then allows to correct any defects caused for example by holes, shadows or very complicated forms.

1 INTRODUCTION

Shape measurement of different objects is an important step not only in industrial manufacturing but in many other activities, ranging from handicrafts to medicine [1-6]. Often the need for reliable and accurate information clashes with the necessity not to interrupt or interfere with the production process and hence with the need for rapid, low-cost measuring systems. These often conflicting requirements and the dimensional and topographical features of the variety of objects to be measured have stimulated the development of numerous techniques and the design of a great deal of measurement tools. Consequently it is not easy to classify them exhaustively.

A first distinction can be made between scanners that measure just the outer surfaces and scanners capable of detecting the complex shape and inner form of an opaque object. The latter use energy vectors (ultrasound, X-ray, γ-ray, etc) and special sensors and rely on sophisticated tomographic reconstruction algorithms that, generally speaking, require a great deal of data, memory and computational effort [7,8]. Among the scanners for outer surfaces, mention should be made of the so-called 2 1\2 D scanners for measuring roughness, that have registered major progress in latter years:

- the classical mechanical profilometers with micrometric probe, now supported by optical instruments for measuring surface irregularities using Mireau's white light interferometers [9] that yield lateral resolutions of 0.1 μm and depth resolution of a few nanometres;
- confocal microscopes [10] widely used in biology in that they allow to measure semi-transparent objects in laser light;
- tunnel effect microscopes and their derivatives with which resolutions of a few Angstroms can be achieved [11,12].

3-D scanners can be divided into those that rely on contact (mechanical profilometers) and those that do not (optical or acoustic). Techniques that resort to light as the information vector include triangulation - passive in stereogrammetry, active in light projection - and time of flight measurements [1]. Active non-structured light triangulation [13] (shape from shading) relies on maps of the luminous intensity reflected by the object to detect its shape. In this case the law of surface reflection (e.g. Lambert's law) is assumed to be known which, as a function of certain known parameters (position and intensity of the light source, position of the viewer, optical properties of the material being examined, etc.) allows to reconstruct, point by point, the vectors normal to the surface to be measured and hence its shape.

Active structured light triangulation consists in projecting a luminous figure of known shape onto the object to be measured and in interpreting distortions so as to reconstruct its topographical features [1-3, 14-17]. The luminous figure most commonly used is the plane of light generated by a laser beam passing through a cylindrical lens or deflected by a mirror rotating rapidly around its fulcrum. To enhance data acquisition rates several planes of light can be projected simultaneously onto the object. However, since this procedure may give rise to misinterpretations, the planes of light need to be coded according to their colour, thickness or distance.

When a sinusoidal grating is projected onto a flat surface a series of light and dark fringes is created. If the projected grid is modulated by non-plane surface, these fringes become distorted and their pattern contains information about the shape of the object. The mathematical representation of the distorted grid image is a sinusoidal function similar to that observed in the interference between two rays of coherent light. Thus it can be analysed using the same techniques adopted in interferometry for phase measurements. In particular, the phase shifting technique, besides being rapid and fully automatic, usually yields accuracy of around 1/100 wavelength. It consists in acquiring with a CCD camera at least three interferograms, varying after each acquisition the phase of the reference beam with respect to the object. Once the procedure is terminated, we have at least three images shifted by known quantities, that by means of numerical processing will allow to determine the phase in every point of the image [18-20].

Usually moiré techniques [21-25] are not as sensitive as interferometry and are better suited for inspecting large objects in the manufacturing industry. A number of measuring systems have been proposed that use phase-shifting for automatic analysis of fringes generated by shadow moiré or projecting moiré [26-30]. To solve the problem of vibrations and enhance data acquisition rates another method has been developed [31] whereby the grating projected onto the object is made to interfere with an undeformed numerical reference grating. By so doing just one image is acquired and the three interferences required for the phase shifting algorithm are generated at a later stage by the computer.

In [32] a special configuration is proposed that uses the speckle technique for measuring in and out-of-plane deformations, as well as the geometry of the mechanical parts.

Here the results are presented of a 3D scanner built by the authors, based on active triangulation with structured light where a Michelson interferometer generates the grating to be projected onto the object. A mirror is positioned on the reference ray of the interferometer driven by a computer controlled piezoelectric transducer that introduces phase shifts with respect to the object ray. This allows to generate the images necessary for applying the phase shifting algorithm for automatic fringe analysis. Once the phase has been calculated, it is possible, by means of simple trigonometric operations described further on, to reconstruct the shape of the surface illuminated by the projector and viewed by the CCD camera. To reconstruct the entire surface, the object is placed on a computer controlled turntable so that surface information can be acquired from different angles. The data thus collected are then built up into a mesh and saved on disk in DXF format for further handling by commercial CAD programs such as AutoCad or MicroStation.

2 DATA ACQUISITION DEVICE

The system consists basically of a laser, a Michelson interferometer, a CCD camera, a turntable and a PC that manages the entire acquisition process (Fig. 1):

- the light source is a Spectra-Physics 35mW He-Ne laser (λ = 632.8 nm): the laser beam is focused, through a series of mirrors, onto the Michelson interferometer;
- one of the two mirrors of the interferometer is mounted on a precision sliding table, connected to a Newport Electro-Strictive Actuator, Mod. Esa 1330 piezoelectric transducer that performs linear translations, controlled with micrometric precision, by means of a Newport-μ Mod.ESA-C drive controller, interfaced to the PC with an HP-82340B GPIB card.
- the turntable is driven by a Sanyo 103-7 electric stepping motor controlled by a SAC series RTA card, that is contained, along with the supply transformer, in a custom rack. A serial cable connects the latter with the card that controls the stepping motor (S&h Picasso S), inserted in a slot of the PC;
- the television camera (b/w Video Standard CCD), with a Lenzar lens (t = 12,5 mm, F = 1.3), is connected to the PC by means of an 8-bit Oculus TCX and ISA bus acquisition card and to an auxiliary monitor;
- an IBM compatible personal computer equipped with a 120 Mhz, 40 Mb Ram Intel Pentium processor and Microsoft Windows 95 executive system is used in the acquisition and reconstruction and for displaying the results. The program for handling the acquisition procedures was written in LabVIEW (National Instruments, ver. 3.1.1); the absence of drivers for the CCD camera and for the GPIB card meant that suitable routines had to be developed in C linked to a dynamic library recognizable by LabVIEW. The reconstruction program (written in FORTRAN 77) creates a data file in DXF format compatible with many commercial CAD products.

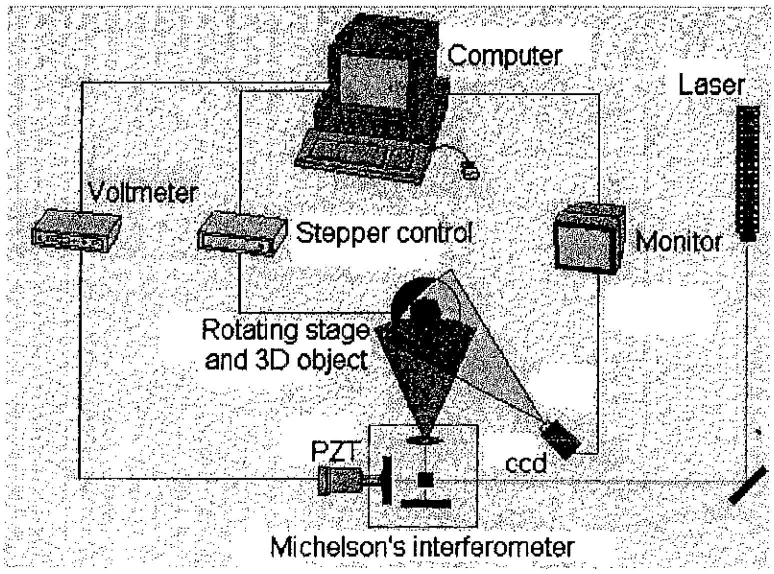


Fig. 1 - System set up.

For simplicity the procedure for reconstructing the object's surface is described for a generic horizontal section. Let us denote with P the centre of the light projector lens and with K the centre of the CCD camera lens. Assume that the reference system is localized in the centre I of the CCD camera with the x-axis in the viewing direction, the y-axis horizontal and the z-axis normal to the picture. The triangulation angle formed by the viewing direction and the direction of projection is θ_o. The projection axis crosses the viewing axis at point O, at a distance x_o from the CCD camera. It is assumed that the reference plane passes through O and that it is normal to the viewing direction. Let us denote with p the angular pitch of the projected fringes, expressed in fringe/degree (Fig. 2).

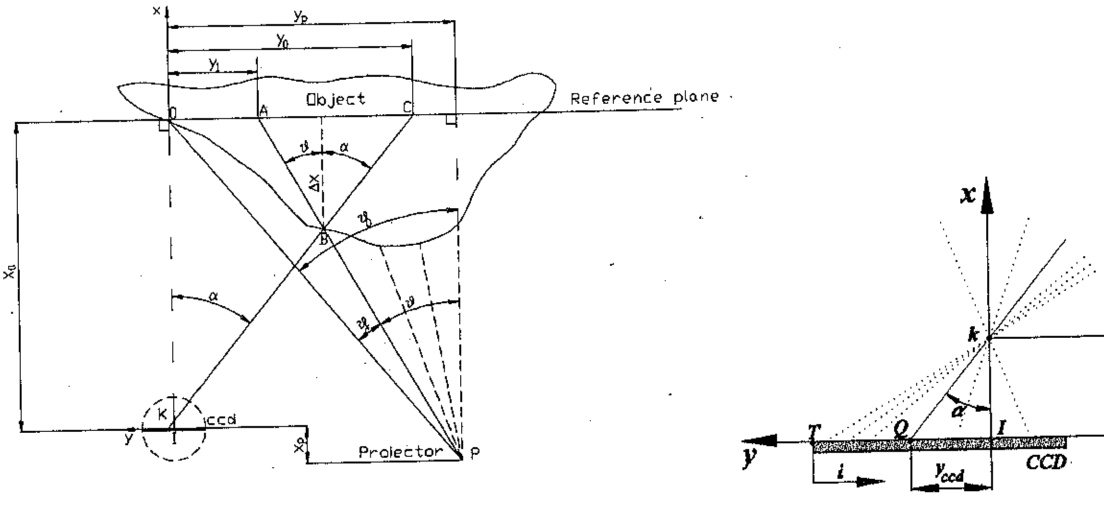
The equation describing the variation of luminous intensity produced by the grating on the reference plane can be written:

$$I_i(y) = I_0(y)\cdot\left\{1+\gamma_0(y)\cdot\cos\left[\phi(y)+\sigma_i\right]\right\} \qquad \text{with } i = 1, 2, 3, 4 \tag{1}$$

The phase $\phi(y)$ is a non linear function of y owing to the diverging nature of the projected rays. σ_i indicates the i-th angular shift that the piezoelectric transducer imparts to the mirror placed on the reference ray of the interferometer. The phase-shifting algorithm allows to calculate the phase in every pixel of the CCD camera. Denoting with i a generic pixel, its distance with respect to the origin I on the centre of the CCD camera is:

$$y_{ccd} = y_{pxl}\cdot\left(\frac{ncol}{2}-i\right) \tag{2}$$

where ncol indicates the number of columns of the CCD (512 in the case at hand) and y_{pxl} is the size of the pixel.



(A) (B)

Fig. 2 - Geometric approach.

The corresponding viewing angle at the i-th pixel is:

$$\alpha = \tan^{-1}\left(\frac{y_{ccd}}{f}\right) \tag{3}$$

where f is the focal length of the lens used. In absence of the object or in the presence of the reference plane alone, the pixel i would be the image of the point C, whose distance from O is:

$$y_0 = x_0\cdot\tan(\alpha) \tag{4}$$

Since in the i^{th} pixel the phase σ_i has been calculated, this means that we can visualize therein a point of the object illuminated by a fringe rotated by:

$$\phi_x = \frac{\phi_i}{360^\circ\cdot p} \tag{5}$$

with respect to the reference fringe passing through O. In absence of the object, this fringe would illuminate the point A on the reference plane at a distance of

$$y_1 = (x_0 - x_p) \cdot \tan(\phi_0 - \phi_x) - y_p \quad (6)$$

from the point O, where x_p and y_p indicate the coordinates of the light projector. At this point we can calculate the coordinates of point B of the object as follows:

$$x_B = x_0 - \Delta x \quad (7.1)$$

$$y_B = y_1 + \Delta x \cdot \tan(\phi_0 - \phi_x) \quad (7.2)$$

where

$$\Delta x = \frac{y_1 + y_0}{\tan(\phi_0 - \phi_x) + \tan(\alpha)} \quad (8)$$

The points of the object are calculated as the intersection of two straight lines departing respectively from the CCD camera and the light projector. The resolution Δx of the system depends therefore on the distance x_o of the object from the CCD camera and from the light projector x_p, on triangulation angle θ_o, on angular resolution α of the CCD camera (a function of pixel dimensions y_{px} and focal distance of the lens f) and of the projector. The latter depends on the angular pitch p of the grating and on the accuracy of the phase shifting which, under normal working conditions, ensures a resolution of $1/(100 \cdot p)$.

A number of phase shifting algorithms have been reported in the literature [20] with 3, 4, 5 and more frames. Some of these have been implemented in the program set up here, but it seems that the best results are achieved with 4 images phase-shifted by 90° proposed in [33]. Since data acquisition takes a few seconds, it is essential that the scene to be examined is stationary and that the system is adequately isolated from vibrations. When the phase-shifting algorithm terminates, we have three pieces of information per pixel, namely luminous intensity (I_0), modulation (γ_0) and phase modulo $2 \cdot \pi$ (ϕ). To find the absolute value of the phase it is necessary to execute a so called "phase unwrapping" algorithm. The success of this procedure depends on a number of conditions. The first is that the images should not be too noisy, a problem that might be caused by speckle interference generated by rough surfaces illuminated by coherent light. The second is that the function of the phase should be continuous; the phase difference between one pixel and the next should be less than $2 \cdot \pi$. In practice, however, due to the presence of noise, it should be less than π and each fringe should have minimum thickness of 3 pixels. This means that it is not possible to analyse situations where more than one object is present and that the step of the grating should be chosen as a function of the object being examined. Because the sensitivity of the system depends on the number of fringes, objects with rapid shape variation should be measured by means of grids which have low frequency and thus are not very sensitive. The phase unwrapping algorithm used here is the spiral scanning one [20] though some controls and modifications have been introduced. First of all the algorithm discards all those pixels with zero modulation that are regarded as background images and not images of the object itself. Pixels that have attained maximum luminous intensity of 255 in one of the four images acquired for the phase shifting are also rejected insofar as they are considered saturated and hence unreliable. Next all the subsets composed of 2x2 pixels are controlled to check the congruity of the phase jumps whose arithmetic sum with sign in a closed loop should be zero. Those pixels not satisfying this condition are discarded [34]. While in the original version the spiral scanning connected the pixels with the smallest phase jump, in the case at hand the choice falls on pixels for which the product of the modulation is largest [35]. Once the unwrapping procedure has been completed, the phase is calculated in the pixels discarded previously, by interpolating it from the adjacent pixels. To measure objects whose shape varies rapidly, the unwrapping problem can be overcome as follows. A grating with a very small number of fringes, chosen such as to avoid phase jumps greater than π, is projected onto the object. The phase is calculated and the phase shifting is then repeated using a grating with a step twice that of the previous one. This time the unwrapping algorithm has more information to go on, provided by the previous calculation. One proceeds in this way until the desired accuracy has been achieved [36].

Compared to systems based on active triangulation where a plane of light is projected, the system proposed here acquires a much larger number of points: each point is measured with accuracy comparable with that provided by the other but their density on the measured surface is such that high accuracy is ensured even in the case of rapid shape variations (with the limits imposed by the unwrapping algorithm, which can be partly overcome as described above).

Once each view of the object has been reconstructed, they are pasted together to form a single surface. Since the distance x_o of the reference plane from the CCD camera is difficult to evaluate, the approach followed here consists in associating to each image a profile of the object acquired with the active triangulation method projecting a single plane of light. To reconstruct the entire surface over the full field of 360°, it is normally sufficient to acquire less than 10 views (the number depends on the triangulation angle) and the pasting operation is fairly rapid.

3 EXAMPLES AND DISCUSSION OF RESULTS

The scanner system was tested for a variety of objects having different shape and surface features, namely size and type of material. The material is particularly important owing to the effects it might have on the diffusion and intensity of reflected light. The variation of surface characteristics is therefore a severe test for evaluating the effective potential of the system.

The first object examined was a mannequin head of dimensions comparable with the human head, composed of expanded polystyrene but covered with a synthetic red velvety material. The particular surface features create a great deal of speckle noise that impairs the quality of the images and consequently the results of phase-shifting. In spite of this drawback, the measurement can be considered satisfactory. Figure 3 shows the mannequin head illuminated by the grating. In Fig. 4 the function of the phase modulo 2π can be seen with the typical saw-tooth phase jump, together with the noise. Figure 5 is the reconstruction of the model using Gouraud's shading technique.

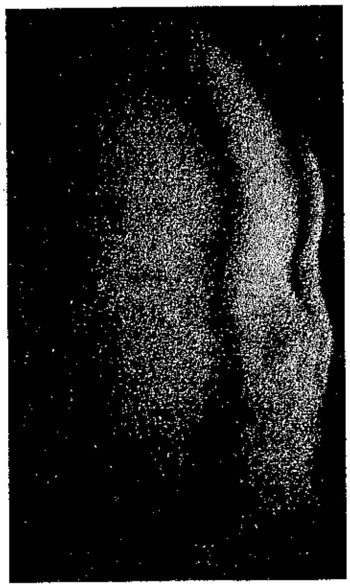


Fig. 3 - Model with the fringes.

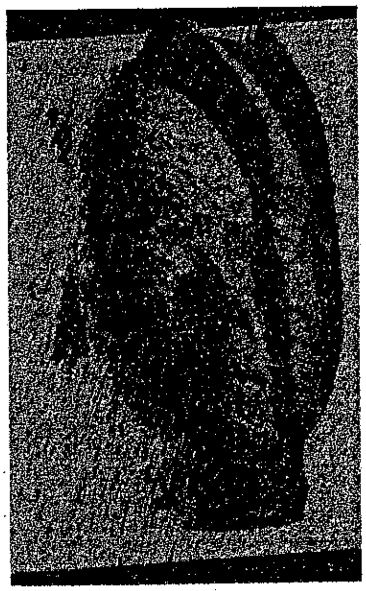


Fig. 4 - Phase modulo 2π.

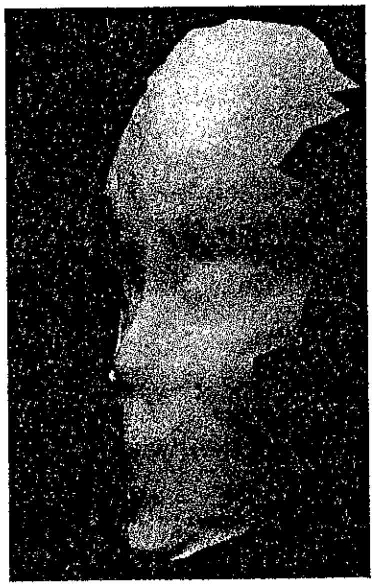


Fig. 5 - Reconstruction of the model.

Another test was performed on a small bust of the poet Giosuè Carducci, made out of stone. This proved to be a very intereresting test for assessing the efficiency of the system in the presence of polished, highly irregular surfaces. For data acquisition a 50 mm lens was used with focal distance of 12.5 mm, a triangulation angle of 20° at a distance of 490 mm for the CCD camera and 1000 mm for the light projector with a 1 per degree fringe grating. Fig. 6 shows the model with the fringes, while Fig. 7 shows the reconstruction.

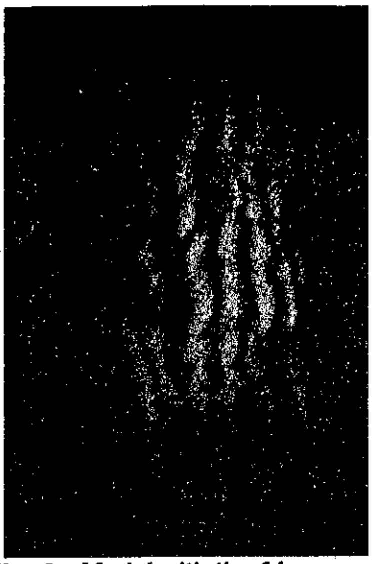


Fig. 6 - Model with the fringes.

Fig. 7 - Reconstruction of the Giosuè Carducci's bust.

The last example concerns surface profiling of a turbine blade (Fig. 8-A) with a highly polished surface that created some problems in acquiring surface information. The reconstruction is shown in Fig. 8-B and C.

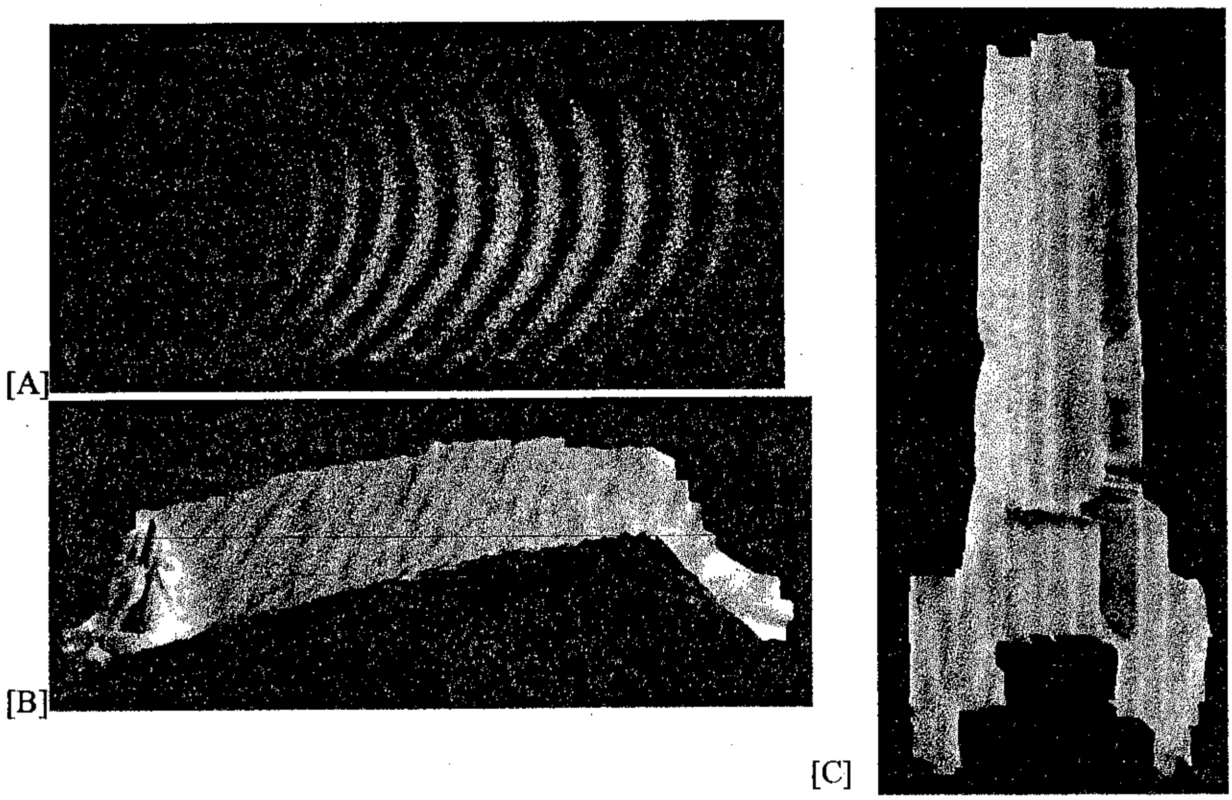


Fig. 8 - (A) Turbine blade with the fringes. (B,C) Reconstruction of the surface turbine blade.

4 CONCLUSIONS

With the system devised here the surfaces of objects with simple shape, illuminated from a certain angle and viewed by a CCD camera, can be rapidly measured. However the system is not suitable in situations where it is required to measure more than one object. A PC controls all the operations, synchronizing the turntable motor, image capturing by the CCD camera and movement of the piezoelectric transducer for the phase shifting algorithm. The operator can intervene by means of a graphic interface developed in LabView (Fig. 9) for selecting certain parameters, such as range and offset of the CCD camera, number of steps of the turntable motor, phase-shifting algorithm, etc.

An accurate knowledge of the system's geometrical parameters is basic to the success of the reconstruction algorithm. For this reason a self-calibration procedure is essential so that the operator is not required to carry out long and complex measurements and can easily change the position of the components to adapt them to the objects being measured [15, 16, 30]. It is important that the interferometer is well isolated from vibrations and real-time active control is also desirable [37]. The output in DXF format enables interfacing with many commercial CAD products.

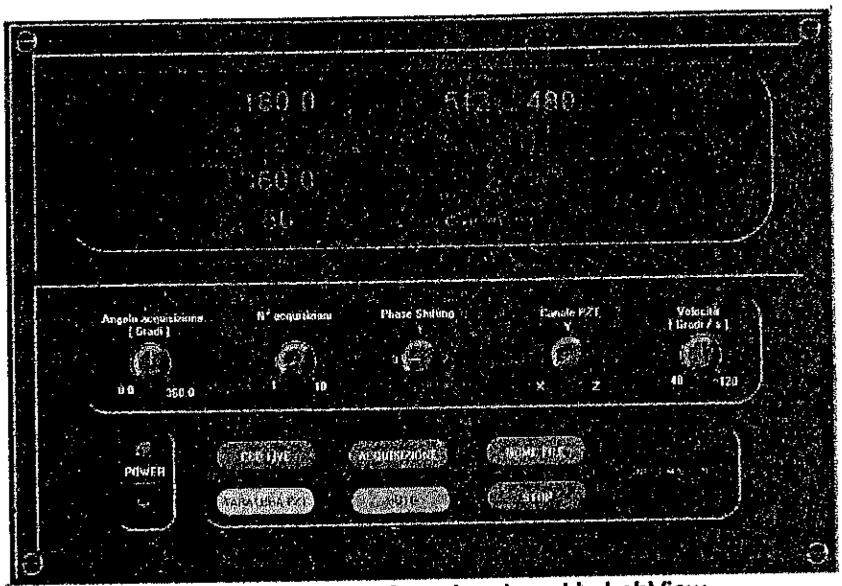


Fig. 9 - Graphic interface developed in LabView.

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