A structured lighting for 3D shape measurement of glass surface

Jean-Pierre CHAMBARD, Vincent CHALVIDAN
HOLO3
7 rue du Général Cassagnou
F-68300 SAINT-LOUIS

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Abstract

This paper describes an optical technique that enables 3D measurement of a shiny surface by reflection of a regular pattern. The technique called "deflectometry" has already been used to detect curvature defects. We have developed a calibration procedure in order to quantify the gathered information and enable a 3D reconstruction of the surface.

We give a detailed description of the setup as well as the calibration procedure. Then we present the results of a metrology study that allows an assessment of the global uncertainty of the measurements. Applications in the car industry are then presented.

Introduction – The 3D measurement of shiny surfaces

Optical techniques that enable quick and global 3D measurement of surfaces are more and more accepted and used in industry, in particular because of a better knowledge of their metrological characteristics. Structured lighting is an optical technology based on fringes projection that allows quick 3D digitization of manufactured parts. The technology is today widely used in automotive industry and in aeronautics. In a few minutes an object can be completely digitized and the resulting cloud of 3D points may be used either for dimensional control (direct comparison with CAD file is possible) or for reverse engineering. However, the technology works only on surfaces that are optically diffusing, with no specular reflection.

Optical surfaces like mirror, lenses, glass plate are usually controlled by interferometry techniques [1][2] or wave front measurement systems [3] [4]. These tools are extremely accurate but can only measure small surfaces and are used in well controlled laboratory conditions. Car glasses that exhibit large surfaces are traditionally measured by contact LVDT sensors. Here a mechanical set-up is designed to allow multiple point measurement on a glass that is properly positioned on reference points. Therefore a specific set-up is needed for each glass model.

On the other hand, the principle of deflectometry [5] that is based on the optical reflection of the light on the surface is used to control curvature defects on large area. We have developed a specific equipment based on that principle and a calibration procedure that enable 3D measurement of large optical surfaces with a good accuracy. This paper details the set-up wit its metrological characteristics and gives a few examples of applications in the car industry.

Structured lighting on shiny surfaces

The figure 1 is a schematic drawing of the set-up. It is based on a mechanical structure made of a horizontal ceiling, printed with a regular pattern and supported by four rigid legs. A high resolution camera is placed at the centre of the ceiling. The glass to be measured lies on a table that is placed below the mechanical structure. An image snapped by the camera is shown on figure 2. We see on the surface of the glass the pattern that is deformed by the curvature of the glass. The amount of the pattern deformation that is linked to the local curvature is evaluated by image processing.

From a mathematical point of view, the set-up may be simply modelled by the three following vectorial relationships that describes the optical reflection on the surface :

$$\vec{i} + \vec{j} = k\,\vec{n} \,, \qquad (1)$$

$\vec{i}$, $\vec{j}$, $\vec{n}$ are normalized vectors

$$\vec{i} = \frac{\overrightarrow{OM}}{\left\|OM\right\|} \,, \quad \vec{j} = \frac{\overrightarrow{PM}}{\left\|PM\right\|} \qquad (2 \,\&\, 3)$$

$\vec{n}$ = vector normal to the surface at point M

The calibration of the set-up is done in two steps. First, pictures of a reference plate that is placed at several heights of the measurement space (the area where the glasses to be measured will be placed) are recorded. This phase

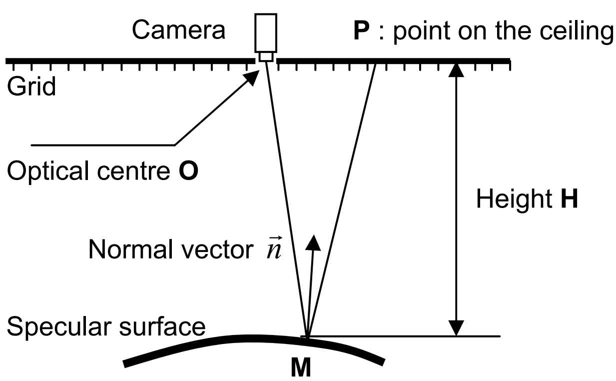


Figure 1 :
Schematic view of the set-up

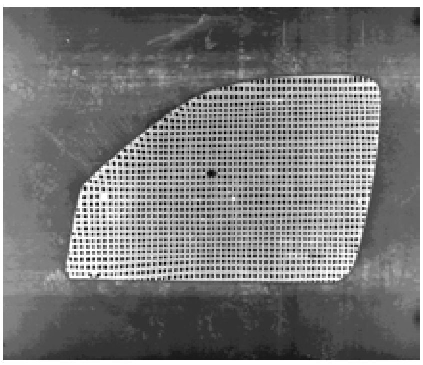


Figure 2 :
Typical recorded picture

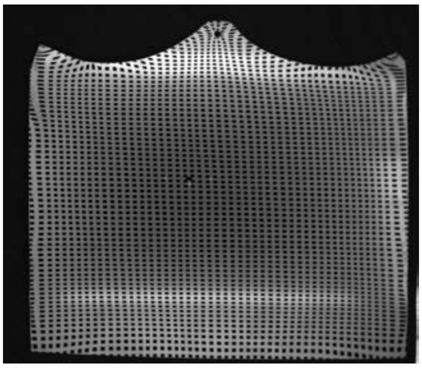


Figure 3:
Recorded side glass

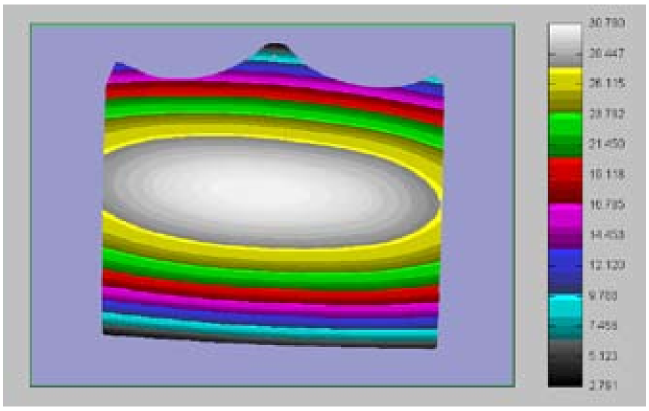


Figure 4:
Resulting 3D shape

allows establishing a correspondence between each pixel (i,j) of the camera and the XYZ position of the point in space, and to determine the position of the optical centre O.

Then in a second phase, we take pictures of a flat mirror also placed at several heights within the measurement space.

At the end of these two steps we have the position of the optical centre O, and the coordinates of the incident $\vec{i}$ vector for each pixel of the camera. All that values are given in a common frame linked to the marked ceiling.

Calculation of the 3D shape based on one picture

Starting on an initial picture like the one on figure 2, an image processing based on optical phase calculation allows determining very accurately the position of the point P (of the rel. 3), for each pixel of the camera. Then assuming that we know the height of a first M point on the glass and that we have the calibration data, it is possible to determine the normal vector $\vec{n}$ simply by using the relation 1.

From the parameters of that first point (M, $\vec{n}$), we can calculate by numerical integration the coordinates of the neighbouring point. Then again, once we know the position of that second point, we can calculate the normal vector of the surface at that point. By an iterative process, all the points of the surface are calculated, as well as the associated normal vectors.

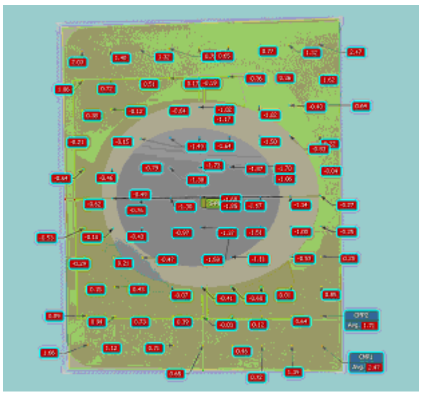


Figure 5:
The 99 control points

The whole process takes less than 5 seconds for 30 000 points calculated. The figure 3 and 4 give the example of an initial picture of a car side glass and the resulting height map of the glass.

A metrological study

As it is a new measurement system, we have carried out an extensive metrological study in order first to identify the parameters that introduce errors in the 3D reconstruction and then to evaluate the global uncertainty of a typical measurement. The study has been done on equipment that has the following features:

- Ceiling size : 4 m x 4m
- Distance table-ceiling : 1.80 m
- Measurement space : 1.30m x 1.30m x 0.10m
- Camera resolution : 1000 x1000 pixels

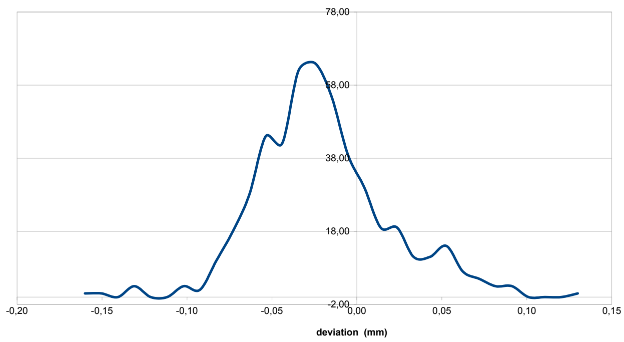
One major factor of uncertainty is the process of calibration itself. During that calibration some parameters of the set-up have to be given: geometry of the grid on the ceiling, distance between ceiling and glass support table. Furthermore, in the mathematical model of the set-up, we have made the assumption that the grid is regular and flat which is not the case practically. We have then estimated the influence of several kind of grid defect (grid spacing, ceiling flatness) on the measurement uncertainty by numerical simulation. As an example, the measurement error on a glass when the grid spacing value is misevaluated from 5%. This clearly indicates that the calibration process must be very carefully worked out in order to avoid systematic errors in the measurement.

Another factor that has an influence on the uncertainty is the ambient temperature. We have carried out experiments in order to evaluate the impact of 15 °C of temperature variation. The result is a maximum deviation is 0.3 mm for 30 measured points. This deviation is due either to the thermal dilatation of part of the measurement set-up or to the deformation of the glass itself, due to the temperature variation.

Other parameters listed below have been evaluated either experimentally or by simulation, and have a moderate effect on the uncertainty:

- Mechanical stability of the set-up: The whole set-up is mounted on a floor that can be deformed by heavy vehicle passing nearby or subjected to vibration induced by the production equipment
- Ambient light: As it is an optical system, the variation of ambient light may have an influence on the results
- Influence of the operator: The equipment may be operated in an automatic mode or in a manual mode. In that second case, some parameters that are fixed by the operator may influence slightly the results (glass positioning, camera exposure, ..)
- Mechanical stability of the glass: For the measurement the glass is

Figure 6:
Deviation for the 99 measured points when measuring the glass in 5 positions



lying in a horizontal position on the table and this can generate flexural deformation due to the own weight of the glass. For car side glasses, the normal position of the glass in the car is vertical. In that case, the measured values have to be compensated for this deformation.

Assessment of the uncertainty

The uncertainty has been evaluated on a car glass by repeatability and reproducibility tests (type A evaluation). We have defined 99 control points on a car glass (roof glass) that has been measured at 5 different positions on the table of the set-up. Each measurement is compared to the actual value that has been obtained with a measuring arm that has an expanded uncertainty of 80 µm. Figure 5 shows the selected 99 control points and we see on figure 6 the result of the statistical analysis of the deviation.

We obtain an expanded uncertainty of 112 µm. In the uncertainty budget table (figure 7), we observe that the uncertainty of the actual values of the glass (given by the measuring arm) is of the same order of magnitude than the standard deviation of the reproducibility tests. This means that by using a more accurate mean to get the actual values of the glass we would reach a better final expanded uncertainty.

Examples of applications

We have developed two versions of the measuring system. One version is a manually operated (the measurement is manually triggered and then processed), the other is fully automatic and is dedicated to on line control.

The manual version, dedicated to design office, R&D department or metrology services is integrated in the METROLOG™ software that allows standard metrological post-processing of the data. The glass to be measured is placed on a set of standardized positioning stops. The software detects automatically the position and type of

	Value (µm)	Comment
Uncertainty of glass actual values (1σ)	40	Data from equipment supplier
Repeatability	1.3	
Reproducibility	40	
Combined standard deviatio u_c	56	
Expanded standard uncertainty U	112	

Figure 7:

Uncertainty budget

the different stops and this enable to realize registration operation between the actual glass and the CAD definition. The output of the measurement is either a complete dense cloud of up to one million points or a direct comparison of the actual shape with the CAD definition. Once the configuration of the software is done, the measurement of one glass takes less than one minute. This opens the possibility to quickly realize capabilities tests on sets of 30 or 50 samples.

The on-line version allows 100% control of produced glasses. The glass has to be placed on a table during about one second to record the picture and then has to be taken away. There is no need of accurate positioning because an automatic registration is done, based on the glass contour. The measurement is completely automatic. The operator has only to create, for a given glass model, a configuration file that contains all the information needed for the control: definition of control points, tolerances, CAD definition. Then the measurements are done and stored in 5 seconds. In that on-line version, only the control points (up to 50 points) are recorded.

The same measurement principle can be used to measure curvatures on surface or to detect curvature defects. As we get as additional data a dense map of the normal vector, it is possible to obtained by numerical derivation, any curvature map (see figure 8). Very tiny defects can be detected by analysing curvature map: figure 9 shows an example of small defects detected on a plastic cover.

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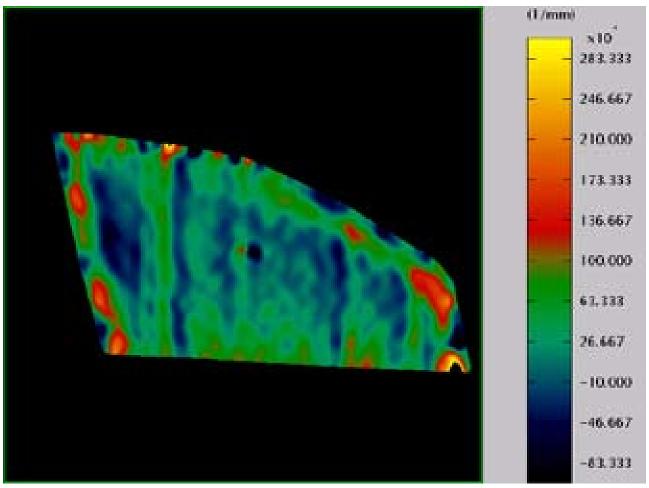
Figure 8:

Curvature map on a glass



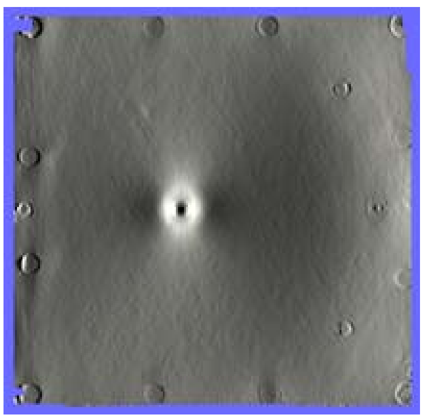


Figure 9:

Example of defect detection