The use of optical sensors to evaluate three-dimensional shapes plays an increasingly important role in a number of applications. One important advantage of optical sensors is that no contact is required with the object being measured; another is that they are significantly faster than contact probes. Typical industrial applications for optical sensors are production quality control, both in the micro and the macro ranges,1 the digitization of free-shape surfaces in reverse engineering,2 and a number of 3-D computer vision problems.3 Examples of the latter are object manipulation by means of robots4 and obstacle detection for robotic vehicles.5 New areas in which optical sensors have been successfully introduced include the measurement and preservation of antiquities, and 3-D virtual reality entertainment products.7

A number of recent publications have described the optical techniques developed for both active and passive 3-D measurement. In passive methods, no controlled source of light is necessary. Surface reflectance, stereo disparity and camera motion are examples of techniques based on the passive approach. The main drawback associated with these techniques is the intense computational effort required to obtain information on depth.8 In active methods, use of a pattern of radiation simplifies the problem of depth measurement. Interferometric and moiré techniques yield very accurate measurements over small depth ranges.9 Time of flight methods are suitable for medium and long distances.10 Triangulation-based methods match the short distance interval: in this context, systems based on coherent light scanning are widely used,11 as are whole field profilometers, based on the projection of structured light. In this final category are a number of pattern projection schemes, which differ from each other in the coding used to express the direction of light.12-16

Since its inception, the Optoelectronics Laboratory at the University of Brescia has been active in the field of optical sensing, especially in the context of distance measurements6; the Imaging Group at the Lab has been involved in the design and implementation of techniques and systems for 3-D vision since 1992. The Group has recently developed an optical instrument for 3-D based on the projection of structured light. The basic components of the system are a liquid crystal projector, which projects fringe patterns on the target, and a video camera for the acquisition of the patterns. The measurement technique designed to elaborate the patterns and obtain the depth information is based on a combination of the Gray Code and the Phase Shift methods.17,18 It produces an extended measuring range and high resolution, and allows for measurement of a wide variety of targets characterized by shape discontinuities and fine surface details.

A great deal of work has been done at the Lab to
The height of the object point \( P_o \) is \( z_M = K \cdot z_{P_o} \). It is evaluated by considering that two different light rays are viewed along the same direction of acquisition (\( \overrightarrow{AC} \) in the figure): these are ray \( \overrightarrow{PA} \) and ray \( \overrightarrow{PP_o} \). They are both imaged at pixel \((j, k)\) on CSP, the former in the presence of the reference plane, the latter in the presence of the object, and are univocally identified by light codings \( l_1 \) and \( l_2 \), respectively. Thus, \( VPM(j, k) = l_1 \) and \( OBPS(j, k) = l_2 \). Depth \( z_M \) is easily obtained by considering that triangles \( \overrightarrow{AP_B} \) and \( \overrightarrow{CP_o} \) are similar, and that the following equation holds:

\[
z_M = \frac{L \cdot d}{|\overrightarrow{AB}| + d}
\]

In Equation (1), distance \( |\overrightarrow{AB}| \) is the base of triangle \( \overrightarrow{AP_B} \). It is computed as the difference between the coordinates along \( X_M \) of points A and B. As detailed in reference 16, these are derived as a nonlinear function of parameters \( L, d, \alpha \) and of light codings \( l_1 \) and \( l_2 \), respectively.

Coordinates \( x_M \) and \( y_M \) of \( P_o \) are determined using
the following equations, which implement the 2-D to 3-D mapping with the correction of the error introduced by the parallax effect:

\[ \frac{2L}{J-1} \quad \frac{2L}{K-1} \]

In Equations (2) and (3), \( J \) and \( K \) are the resolution of the CCD matrix, and \( FW \) and \( FH \) represent the width of the field of view along \( XM \) and \( YM \), respectively.

This procedure yields an extended measurement range, due to the high number of different codings, as well as high resolution, due to the fact that they are real numbers. The procedure yields point clouds corresponding to fields of view of up to 400 by 400 mm\(^2\) and depth range up to 150 mm, with an overall mean value of measurement error of 40 \( \mu m \), and a variability of about \( \pm 35 \mu m \). Suitable sampling and smoothing procedures, aimed at reducing the size of the data files, are provided by a tool for the visualization and processing of range data. The software, developed in collaboration with the VIT Group (IIT, NRC, Canada), is fully compatible with the Lab's 3-D digitizer as well as with the more common file formats available for the 3-D data (rotate, PIF, NRC, VRML and ASCII). The working environment is user friendly and interactive; OpenGL is the graphic library under Windows 98 and NT. The use of OpenGL allows fast manipulation and visualization of the point clouds, and a compact structure of the source code.

Performance has been tested on a number of objects, selected with an eye to evaluating the system's ability to detect free-form surfaces characterized by both an extended measuring range and a high level of shape complexity. As an example, Figure 4 depicts the measurement of the flower pot shown in Figure 2. The digitized surface is visualized as a point cloud at reduced density (4a), as triangles (4b), and as synthetic rendering at maximum density (4c), corresponding to about 200,000 points. The illuminated area is 300 by 400 mm\(^2\) and the depth resolution is equal to 70 microns, which allows for detection of the fine decorations on the object's surface. Another example is the digitization of a wheel rim, shown in Figure 5; here, the deformation induced by the object on one of the projected fringe patterns is clearly visible. A single view is sufficient to measure the top surface of this object; the illumination area is equal to 400 mm x 400 mm, with a depth range of 150 mm. The range image is presented in Figure 6: here, the system has evaluated a 70 \( \mu m \) measurement resolution. The time required to perform the measurement, including the
The time necessary for the projection of the patterns, is about 30 seconds on a Pentium II PC.

Characteristics of the optical head
The geometry of the optical head can be varied as a function of the resolution required: the projector's orientation and the distance from the video camera can be shifted inside a 20°–50° rotation interval and a 400mm to 1m translation interval. A number of different video cameras may be used for acquisition. The Lab uses a Sony XC-77CE for high quality measurements: it yields low distortion and resolution of 756 x 581 pixels, but only the intensity information can be acquired. When color needs to be added to the range data, a Robosoft EVI-371D video camera is used. It yields lower quality images, but both the zoom and the focus can be automatically adjusted.

Two devices have been used for projection. The first is from Automatisierung & Bildverarbeitung Dr. Wolf GmbH (LCD-320) (ABW*); the second, 3D-PRO, developed by the Lab, is characterized by superior performance in terms of resolution, flexibility of the patterns which can be projected, projection time, and reduced weight and dimension. Two different setups of the optical head are depicted in Figure 7. The first mounts projector ABW LCD-320 and two video cameras, for color and gray level acquisition (7a); the second mounts the 3D-PRO device. This is a “light” version of the optical head, particularly useful for on-site measurements (7b).

Acquisition of whole objects
Application of the technique to more complex objects often requires multiview acquisition. To this end, the optical head can be mounted on the moving stage outlined in Figure 8. Stepped motors are used to fully control the translation of the optical head. In this way, areas as large as 2 m² can be scanned and measured by acquiring and aligning a number of separate patches. Symmetrical circular objects can be placed on a rotation stage to acquire views at different values of the rotation angle, denoted by \( \phi \) in the figure. During the setup, the projector and the video camera can be repositioned automatically.

The calibration master is the plane shown in the fig-
ure: the optical head is rotated 90° and gradually moved in a vertical direction; for each shift in rotation, a calibration algorithm is activated to accurately determine the measurement parameters. The calibration of the rotation stage is also calculated to determine its position with respect to the optical head; this data, together with information on the mechanical characteristics of the translation stages, allows each point cloud to be expressed in a global reference system, centered in the rotation stage (\(X_R, Y_R, Z_R\) in Figure 8).

The sequence of range image acquisition is determined based on the size and shape of the object. For objects characterized by predominant shapes along the X and Y axes, the object is in a fixed position, and the optical head is moved by steps along X and Y, depending on the field of view. In this case, translation matrices alone are used to align the range images. In general, however, with objects that can be completely measured by rotation and by moving the optical head, alignment is performed using a combination of rotation and translation matrices.

A good example is the digitization of the car door shown in Figure 9. The size of this object (1.2 m high by 1.6 m wide), requires acquisition of the patches shown in the figure, each about 400 mm x 300 mm. In this case, translation along X and Y has been used and the patches are partially overlapped. The entire point cloud is shown from different perspectives in Figures 10a, 10b and 10c. Figure 10d depicts the rendered surface.

**Digitization of sculptures**

Complex objects such as sculptures and statues can be digitized by using a reduced number of separate views: these are then aligned automatically and merged into an entire point cloud, from which a model of the object can be visualized and built. Besides accuracy of measurement, this application requires integration of information on color and texture. This can be obtained without increasing either the complexity of the device or its cost, since the video camera automatically acquires the color and texture information along with the fringe patterns used to code the light directions.

A good example is shown in Figure 11, which also depicts the effect of the projection of a fringe pattern. The target is a handmade sculpture: its surface presents both fine details and smooth parts, and is glazed, partially reflective and variably colored. The acquisition of a single view of this object leads to the measurement in Figure 12a: here, the point cloud has been sampled and then tessellated by means of triangles, taking into account the information on color. The rendered surface is presented in Figure 12b. The resolution is 70 µm, with a range of error of within 0.1 mm, over a field of view of 400 x 400 mm² and depth range of 150 mm. Note that this data has not been subjected to further elaboration. The time needed to acquire the data in the form shown is a maximum of one minute, considering both the projection time and the time necessary for data elaboration, storage and visualization, all performed using Windows 98 on a Pentium II PC system. Typical values of the data files are 5 megabytes (MB) (480 kilo points) for the range information, and 7 MB when the color information is added.

Use of this technique to evaluate statues is shown in Figure 13, which shows both the prototype developed at the Lab and the marble statue used as a target for measurement. The statue occupies a working volume of 1,200 mm by 400 mm by 400 mm. It was com-

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**Figure 10.** Digitized point cloud of the car’s back door.

**Figure 11.** The handmade sculpture used to test the system’s color integration performance.

**Figure 12.** Integration of range and color. (a) Tessellated point cloud of the sculpture in Figure 11. (b) Rendered surface.
completely acquired in 16 views, through a combination of object rotation and vertical translation of the optical head. To save time, the sequence of acquisition and storage of the views was pre-programmed using a command batch file. This operation took an hour and a half, mostly due to the limited speed of motion of the mechanical translation axes. The point clouds of the whole statue are presented in Figure 14, along with the surface model (the model was produced using Wrap software from Geomagic).

**Reverse engineering of free-form surfaces**

The optical digitizer has been combined with a coordinate measuring machine (CMM) for the reverse engineering of complex, free-form surfaces. This application was developed in collaboration with the Dipartimento di Innovazione Meccanica e Gestionale (DIMEG) of the University of Padova, Italy. The aim is to rapidly and accurately reconstruct the computer-aided design (CAD) model of objects of complex geometry, exploiting the benefits of both optical and mechanical sensors, with a minimum of human intervention. The combination of the sensors is performed at the level of measurement information, in the context of a module for the intelligent aggregation of information from optical and mechanical instruments. The methodology can be summarized as follows. A suitable number of point clouds of the object are optically acquired, in order to completely capture its shape. For the ordering and the adaptive sampling of the point clouds, these are then pre-processed based on the surface curvature, and imported into a commercial CAD system (PRO/E from PCT) for the definition of curves and surfaces over the point clouds.

An initial CAD model represents the starting point for the digitization process on the CMM, and simplifies the solution of common problems related to unpredictable changes of curvature, direction and shape of the object. An accuracy of 0.5 mm is sufficient to generate a collision-free inspection probe path; moreover, for more precise detection of interference and collisions of the probe, a suitable distance before and after probing and a clearance plane can be set. Using this approach, the desired level of accuracy is obtained in one digitization step or two steps at maximum, in case of very complex surfaces.

An example is the reverse engineering of the door handle shown in Figure 15. Non-contact digitization of the entire object has been carried out by acquiring four partial views, in correspondence with a rotation of the target of 0°, 90°, 180° and 270°. The acquisition/elaboration time for each view is less than one minute. The views are then ordered and aligned; the scan curves are automatically defined; the results are shown in Figure 16. At this point, style curves are reconstructed within the CAD system. Using the curves defined in the previous step, the functional surfaces are reconstructed. The resulting rough CAD model is used as an initial approximation of the surface to drive the CMM contact probe. Based on the comparison of the digitized points and the surface defined by the CAD model, new exploration surfaces are implemented (Figure 17). The final shading of the handle CAD model is depicted in Figure 18. For the entire upper part of the handle, following the second mechanical digitization, a maximum digitizing error of 0.0321 mm and an average error deviation of 0.0075 mm have been estimated; by the third digitization, these are reduced, respectively, to 0.0109 mm and to 0.005 mm. Using this technique, the time required to complete the reverse engineering of the handle is dramatically reduced: from several days to a few hours.

**Conclusions**

The article has described the main characteristics of a 3-D digitizer developed at the Optoelectronics Lab at the
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