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AUTOMATIC SURFACE RECONSTRUCTION OF SIMPLE MECHANICAL OBJECTS BY TRIANGULATION OF STRUCTURED LIGHT

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ABSTRACT

Here the results are presented of a particular type of 3D scanner, set up by the authors, that projects one or more planes of laser light onto the object to be measured, viewed through a CCD camera. The object is placed on a turntable and the profiles are acquired through 360°. The coordinates of the object are determined by means of simple trigonometric operations. A reconstruction algorithm pastes the profiles together and builds up a mesh for displaying the surface on the computer. Then an interactive editor is used to correct any defects produced for example by holes, shadows or highly complex shapes.

1 INTRODUCTION

In many industrial activities (robotics, quality control, machines with numerical control, reverse engineering) the exact surface measurements of an object are required to be known [1]. The control of surfaces of any shape is very difficult, and generally speaking the systems available on the market today have been designed to satisfy a very narrow range of requirements. As a result large companies often develop their own control systems. Many different approaches have been adopted in surface measurements [2] ranging from mechanical ultrasonic profilometers to laser light projection (in the form of dots, lines or grids), time-of-flight-based systems, photogrammetry and a variety of moiré [3] or interferometric techniques [4] for phase measurements. Sensitivity of depth measurements varies depending on the technique used: those based on time-of-flight usually have resolution of more than 1 mm, for triangulation techniques resolution diminishes to less than 1 mm while with interferometric techniques or those using confocal microscopes, resolution goes down to a few nanometres. In recent years, major advances have been achieved in scanning microscopes [5]; Binning and Rohrer [6] (who were awarded the Nobel prize in 1986) developed the first microscope with a tunnel effect obtaining a resolution of nearly 10 Angstrom.

Historically, computer imaging systems for automated control [7] have relied on binary images, which are adequate for identifying objects that can be recognized by their own silhouette. These systems are usually rapid and cheap and are based on simple control schemes such as the sum of pixels or contouring control.

In many applications however the utilization of binary images is not sufficient, especially when controlling the dimensions of objects with complex shape. In this case one can resort to digital imaging in grey levels. These depend on a number of parameters, such as type and number of light sources, their intensity and position, geometry of the object, etc. The features extracted from these images may be affected by a series of factors and interpreting their geometry is not always a simple matter [8].

Because of its enormous potential in terms of rapidity and the low components cost, triangulation of structured light is now used in many imaging systems, its accuracy being adequate in many areas. An active illumination system is used where a light of known shape emitted by a source precisely localized with respect to the viewing system intercepts the object to be measured.

This work is concerned with a special kind of range-sensor designed and built by the authors that works by projecting one or more beams of laser light onto the object viewed through a CCD camera. The coordinates of a point illuminated by the beam and observed by the CCD camera can be determined with simple trigonometric operations. The object is placed on a turntable driven by an automatically controlled stepping motor and 360 deg profiles are obtained. A reconstruction algorithm pastes the profiles together and builds up a grid for computer display of the surface. An interactive editor enables correction of any defects caused for instance by holes, shadows or highly complex shapes. With this system simple objects can be measured if the profiles, illuminated by a plane of light according to the triangulation angle, can be viewed using a CCD camera.

2 DATA ACQUISITION SYSTEM

The basic components of the system are a He-Ne laser (λ = 632 nm, 10mW), a mirror galvanometer quickly rotating back and forth, a CCD camera with a sensor consisting of 640 x 480 pixels, whose signal is digitized in 256 gray levels, a turntable (with smallest step of 1.8°) for moving the object to be analyzed, controlled by a suitable card, and a PC that handles all the acquisition operations.

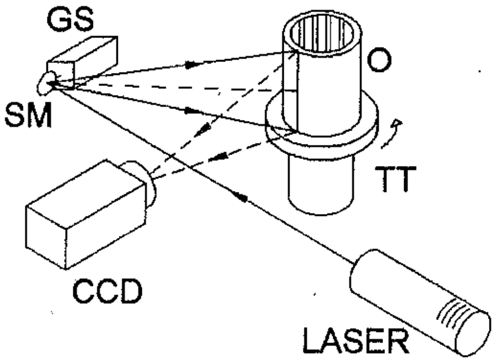

Fig.1 - Global perspective of the sensing device

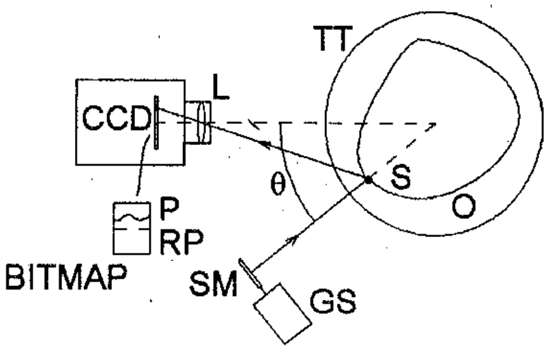

Fig. 2 - Arrangement in the horizontal plane

Fig. 1 shows the laser light source, the galvanometer scanner (GS) for moving the mirror (SM), the CCD camera for recording the object (O) placed on the turntable (TT). The device is a single-line structured light system, based on the principle of active triangulation with coherent light. It is both simple and cheap and its components are readily available on the market and can be controlled by a simple PC. Figure 2 shows the arrangement in the horizontal plane of the different components (for simplicity, the laser is not shown). The angle of triangulation θ is formed by the directions of viewing and illumination. If, instead of the object to be measured, there is a vertical reference plane on the turntable passing through the rotational axis, the CCD camera would record the reference profile (RP), whereas when the object is present, the line P forms on the CCD camera, an image of the profile S.

A laser line impinges on the mirror mounted on the galvanometer and illuminates the surface of the object to be measured. As will become clear from the reconstruction algorithm, it is essential for the laser to be aligned such that the line of laser light coincides with the turntable's axis of rotation. The galvanometer is driven by an impulse with frequency adjustable from 105 to 900 Hz. This rapid alternating motion causes the angle of incidence of the laser line, and consequently of the reflected light line, to vary continuously. This generates a plane of light that impinges on the object, evidencing its profile. Since the grabber frequency of the CCD camera frame is lower than the galvanometer's scanning frequency, it is possible to acquire in a single image all the successive positions illuminated on the object, viewed from the angle of triangulation. The PC acquires the entire image consisting of 640 x 480 pixels and stores only those pixels whose light intensity exceeds a predefined threshold. This operation is very fast and only a small part of the data are thus exported onto disk. If we rotate the turntable by an angle α, the system is ready to acquire another profile. After n steps, we will have recorded that portion of the object subtended by the angle $n \cdot \alpha$. If this is equal to $360° - \alpha$ then acquisition has been completed for the entire surface of the object being examined. Once this procedure has been terminated the PC revisits all the files for further filtering. In fact in general the profiles recorded by the CCD camera have a thickness of a few pixels. This is due in the first place to the fact that the laser beam has its own, be it limited, thickness. Furthermore, the illuminated surface may be positioned in such a way as to reflect the whole signal towards the CCD camera, or it may be nearly parallel either to the viewing direction or to the direction of illumination and in this case the CCD camera will record very weak signals (Fig.3).

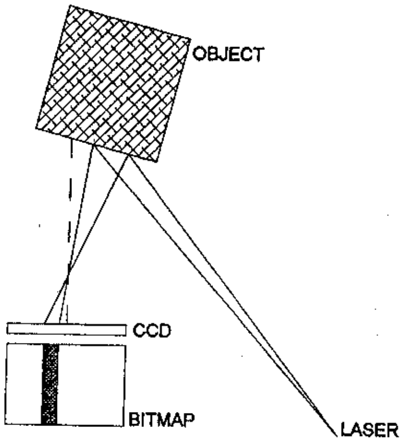

Fig.3 - The profile has a thickness of a few pixels.

Many other disturbances interfere in the process, such as the surfaces' reflectance properties, their colour, their roughness. In particular the latter, with coherent light can generate speckle noise that impairs the quality of the images. Hence the problem arises of establishing the succession of pixels that best represents the line of intersection of the laser line with the surface of the object. A number of different strategies have been proposed in the literature [9]: selecting the pixel with maximum intensity, calculating the centre of gravity of the pixels by weighting their coordinates with their light intensity, selecting the median pixel. It has been reported that in favourable conditions it is possible to achieve sensitivity of 0.5 pixel [9] and 1/8 pixel [11]. In any case with the system proposed here different strategies can be chosen, even though in practice no significant differences have been observed in the measurements. This procedure is repeated for each line of the image, thus obtaining a profile made up of a single pixel per line. This is the basic information for the reconstruction software.

3 RECONSTRUCTION ALGORITHM

The geometry of the system may be depicted, in a simplified form, as follows:

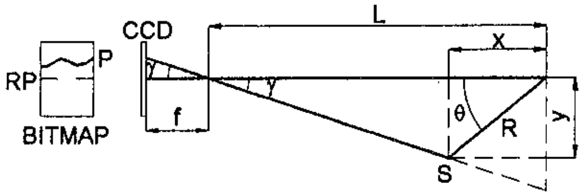

Fig. 4 - Parameters of the triangulation system

The purpose of the sensing device is to localize in space the coordinates of the point S. The viewing angle γ is given by

$$\gamma = \mathrm{atan}\left(\frac{x_{ccd}}{f}\right) \tag{1}$$

where x_{ccd} denotes the coordinate of the profile measured on the CCD camera and f is the focal distance. From the sine theorem we can write:

$$\frac{R}{\sin(\gamma)} = \frac{L}{\sin(\theta+\gamma)} \tag{2}$$

and it follows that

$$R = L \cdot \frac{\sin(\gamma)}{\sin(\theta+\gamma)} \tag{3}$$

and

$$x = R \cdot \cos(\theta) \qquad y = R \cdot \sin(\theta) \tag{4}$$

The resolution of the system, i.e. the smallest dimension of R that the system is able to perceive, relates to the dimension of the pixel ε, to the distance L of the CCD camera from the turntable's axis of rotation and to the focal length f:

$$\Delta R = \left(\frac{\varepsilon \cdot L}{\varepsilon \cdot \cos(\theta) + f \cdot \sin(\theta)}\right) \tag{5}$$

Depthwise resolution Δx is given by:

$$\Delta x = \Delta R \cdot \cos(\theta) = \frac{\varepsilon \cdot L}{\varepsilon + f \cdot \tan(\theta)} \tag{6}$$

Usually $\varepsilon << f \cdot \tan(\theta)$ so we can write:

$$\Delta x \approx \frac{\varepsilon \cdot L}{f \cdot \tan(\theta)} = \frac{\varepsilon}{m \cdot \tan(\theta)} \tag{7}$$

where $m = \frac{f}{L}$ denotes the magnification of the camera lens .

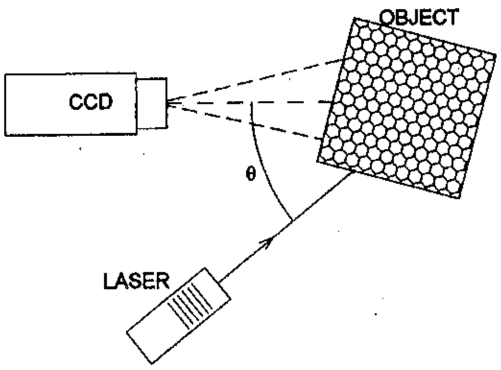

Fig. 5 - Shadow effect

The sensitivity of the system is enhanced when the angle of triangulation θ is increased, together with the magnification m and a CCD camera with a pixel of small dimensions ε is used. In reality a large angle of triangulation increases the probability of shadow formation (see Fig. 5) i.e. part of the profiles may not be visible by the CCD camera, hence in practice angles in the range 10÷30° are used. As already mentioned, the CCD camera used here has a active sensor composed of 640 x 480 rectangular pixels, each measuring 11 μm x 9 μm. As a result, if for example a magnification m of 0.025 is used (L = 500 mm and f = 12.5 mm), then we can write, as a function of θ, the table shown below:

θ	10°	15°	30°	45°	60°
Δx [mm]	2.5	1.64	0.76	0.44	0.25
ΔR [mm]	2.53	1.7	0.88	0.62	0.51
Rmax[mm]	312	265	189	155	140
Hmax[mm]	67	84	116	135	149
ΔR/Rmax	0.008	0.0064	0.0047	0.004	0.0036

Table 1. Ratio of triangulation angles θ and some significant parameters

where

$$R_{max} = L \cdot \frac{\sin(\gamma_{max})}{\sin(\theta + \gamma_{max})}$$ represents the maximum radius visible by the CCD camera and

$$H_{max} = (L - R_{max} \cdot \cos(\theta)) \cdot \tan(\beta_{max})$$ indicates the maximum corresponding height.

If the viewing axis of the CCD camera is positioned exactly along the turntable's rotational axis, then the maximum look angles in the horizontal and depth directions, are respectively:

$$\gamma_{max} = \text{atan}\left(\frac{320 \cdot 0.011}{12.5}\right) \approx 15.7^\circ \qquad \beta_{max} = 2.0 \cdot \text{atan}\left(\frac{240 \cdot 0.009}{12.5}\right) \approx 19^\circ.6 \qquad (8)$$

Under the above conditions, if θ = 10°, it is possible to analyze a cylinder (whose axis coincides with that of the turntable), 67 mm high, with horizontal section having maximum radius of 312 mm obtaining a theoretical resolution of 1/125 (Fig.6b). Because the smallest step angle of the stepping motor used to drive the turntable is 1.8°, the final grid will be composed at the most of 200 x 480 points with circumferential distance of 9.8 mm and vertical distance of 0.14 mm. If, by contrast, θ = 60° it is possible to analyze a cylinder 149 mm high, having horizontal section with maximum radius of 140 mm obtaining a theoretical resolution of 1/278 (Fig.6a). In this case the circumferential distance between the points of the densest grid will be 4.4 mm, while the vertical distance will be 0.31 mm. From the above it clearly emerges that though the theoretical resolution in calculating the single points of the profiles is adequate for many applications, the step angle of the stepping motor is insufficient and restricts the system's overall accuracy. Hence, if one measures a surface that is not continuous, but with rapid variations (as happens when passing from one plane to another), the result will be generally a smooth surface.

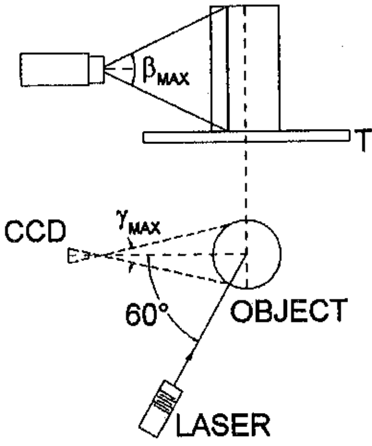

Fig. 6a - Configuration with θ=60°

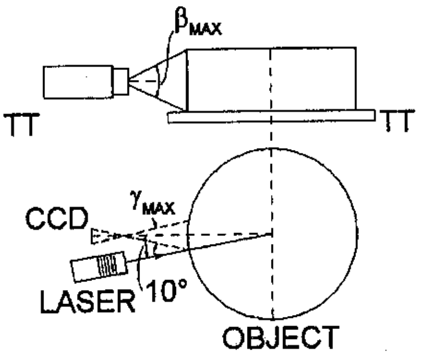

Fig. 6b - Configuration with θ=10°

The viewing axis of the CCD camera does not necessarily have to pass through the turntable's centre of rotation. If the object is positioned on the turntable and its shape is such that the profile intercepted by the laser line always lies between the turntable axis and the projector, then it will be possible to position the CCD camera in such a way as to take full advantage of all its 640 pixels (Fig. 7). By so doing the accuracy of the system can be enhanced.

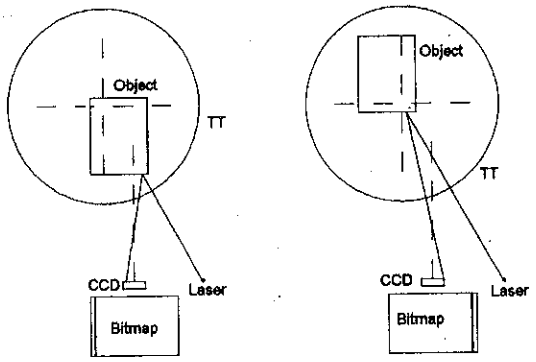

Fig. 7 - Different arrangement of the set up.

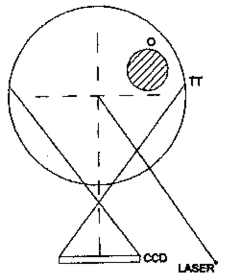

Fig. 8 - Shadow effect.

There is no need to position the object exactly on the turntable, but it is important to acquire the maximum number of profiles, placing it as far as possible in the middle (Fig.8).

As all the parameters involved in the previous calculations are affected by error, the effective resolution of the system is not as good as that reported above. Moreover, any errors in turntable rotation also need to be accounted for. For good results it is important for the system to be accurately calibrated so as to establish automatically and in as accurate and reliable a way as possible the positioning of the different components [10-12]. In addition, in certain circumstances, it is possible to enhance resolution by as much as 50% using appropriate cylindrical lenses [13].

The set up illustrated in Fig.2 is efficient for measuring objects with relatively simple shapes. For those with very complex shapes, added to the problems mentioned above (reflection of metallic or mirror surfaces, colours, speckle noise due to roughness and coherent light, etc.) is the problem of shadows, i.e. the presence of regions illuminated by the beam but not visible by the CCD camera or viceversa visible by the CCD camera but not illuminated (Fig. 5, 8). In certain cases it may be convenient to use a second plane of light, symmetric to the first with respect to the CCD camera (see Fig. 9). In this case the plane of light reflected by the mirror SM mounted on the galvanometer GS is split with a beam-splitter (BS). One beam is directed onto the object (O) while the other falls onto the mirror (M) and then onto the object. If the profile S_1, illuminated by the right beam cannot be viewed, then with the new configuration the probability of acquiring it from the left after rotating the object in a clockwise direction by $\theta_1 + \theta_2$ degrees, increases. On the other hand the existence of a second line of light might well pose a serious problem were the shape of the object to cause the two lines to intersect (Fig. 10).

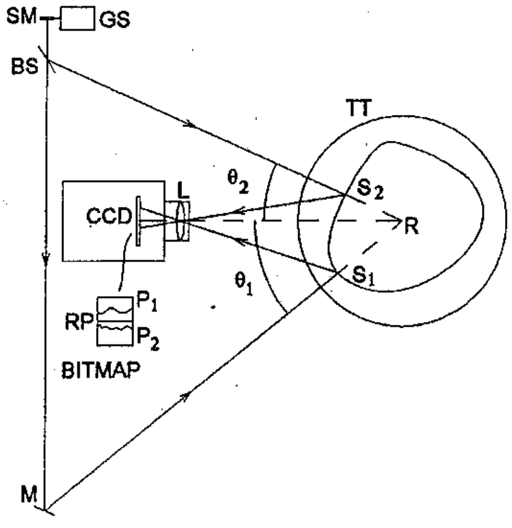

Fig.9 - System with two beams.

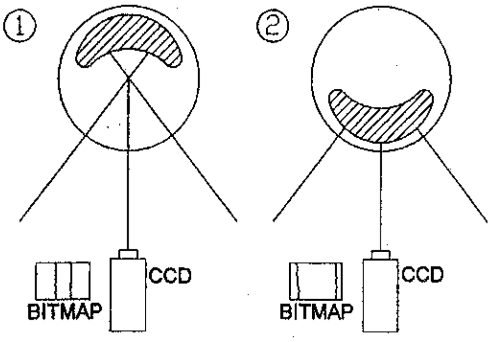

Fig.10 - Profiles intersection.

In fact, it could happen that the line of light coming from the right of the CCD camera intercepts the object to the left of the rotational axis (for a viewer placed on the CCD camera), and conversely, that the line of light coming from the left of the CCD camera intercepts the object to the right of the axis of rotation. In this case the signal acquired by the CCD camera would be misinterpreted. To avoid this inconvenience, two options are available: either a colour CCD camera is used, projecting lines of coloured light, or the acquisition procedure is repeated in time for each line projected individually. The first option involves purchasing a colour CCD camera, which is more expensive and slower than the traditional cameras because three times the amount of data has to be acquired, transferred and processed. Measuring a coloured surface may also create difficulties of interpretation. By contrast, using a colour CCD camera would enable to acquire simultaneously different profiles and the digital restoration of coloured objects. The second solution opted for here is cheaper, more reliable and more versatile, though data acquisition times are longer.

In its current configuration, the system takes a little less than two minutes to record 200 profiles with just one laser line. This slowness relates basically to the CCD camera's frame-grabbing card an Oculus TCX with 1 Mbytes local memory and an ISA bus that transfers the data to a PC in blocks of 64 Kbytes. With a more modern card and a PCI bus acquisition times could be more than halved.

The software code for the acquisition control has been writen in C, the reconstruction program has been written in FORTRAN 77 and can be readily adapted to different types of computers. It reads the starting data, consisting of the series of coordinates of the profiles recorded by the CCD camera. Each profile is regarded as a data vector and is inserted into a matrix whose column index refers to the rotational angle of the turntable. The program examines, two by two, all the sections of successive profiles and generates two triangles with one common side between four points: two on the first and two on the second. Should one of the points be missing, then no triangles converging thereon are generated. To display the results, there is no need to triangulate all the points acquired, but a more regular grid is preferable, in which the triangles have similar size in the vertical and horizontal directions. In fact, while in the vertical direction the number of points is at the most 480 (i.e. the number of pixels of the CCD camera in that direction), in a horizontal section there are at the most 200 data (equal to the maximum number of steps of the motor used to drive the turntable), distributed around the boundary. Thus it is up to the user, when visualizing the results, to choose the step of the points along the profile. The results obtained with the reconstruction program are saved in a file with DXF format and can be examined using commercial software such as AutoCad or Microstation.

4 EXAMPLES AND DISCUSSION OF RESULTS

The range-sensor has been tested on a variety of objects having different shapes and surface features. The type of material is particularly important for the effects it produces on the diffusion and intensity of reflected light. The variation of surface features is thus a severe test for assessing the sensor's effective potential. Concerning variation of the objects' geometries, it should be pointed out that surfaces with marked hollows create a shadow effect.

The first object examined was a small plastic cup normally used for coffee. Its perfectly axysymmetric shape facilitates reconstruction even though this material, semi-transparent and diffusing, yields not very clear cut profiles.

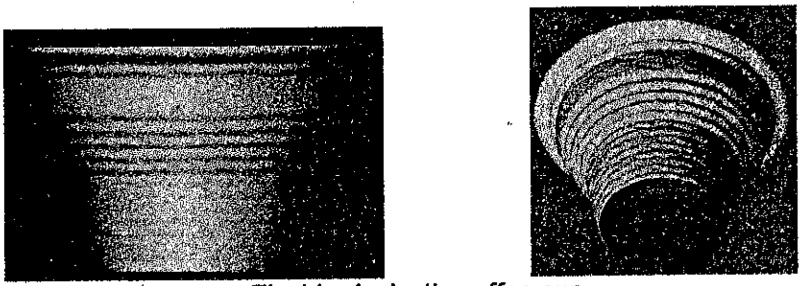

Fig.11 - A plastic coffee cup.

The second object was a mannequin head, of dimensions comparable with a human head, composed of expanded polystyrene but coated with a synthetic red velvety material. Shadows were created around the nose, so we resorted to two lines of light symmetric with respect to the CCD camera.

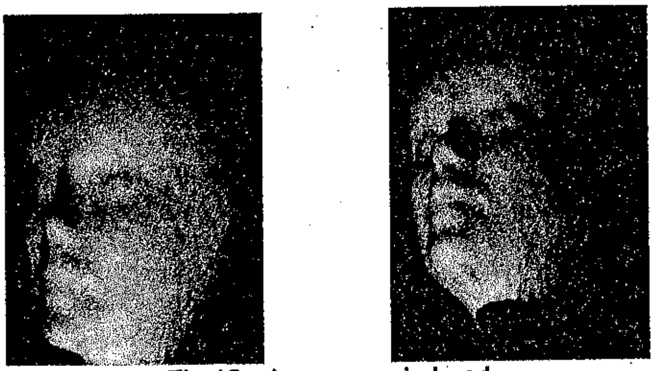

Fig.12 - A mannequin head

A small bust of the poet Giosuè Carducci formed the object of another test. The test on this bust, made of stone, proved to be very interesting for assessing the sensor's efficiency. Its highly polished surface created a zone of diffused light around the illuminated profile, attenuating the contrast. Moreover the complexity of the bust created numerous obstacles to viewing. Profile acquisition was performed with two lines of light having triangulation angles of ±22.4° at a distance of 490 mm using a 50 mm lens with focal distance of 12.5 mm.

Fig.13 - A small bust of the poet Giosuè Carducci

5 CONCLUSIONS

The system set up here enables automated measurement in rapid times of objects of simple shape, i.e. objects whose surface, illuminated from a certain angle, can be viewed by a CCD camera. The system is cheap, its components are readily available on the market and the accuracy achieved is sufficient for many industrial sectors. The output, in DXF format, permits interfacing with many commercial CAD products. The existence of more than one material with very different surface features may impair the measurement, resulting in poor accuracy. Furthermore, a self-calibrating procedure is required [10-12] such that the components may be quickly positioned, best calculating the system's parameters.

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