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Abstract Full Paper

INTEGRATION OF A 3D VISION SENSOR AND A CMM FOR REVERSE ENGINEERING APPLICATIONS

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ABSTRACT

This paper describes a novel methodology for the reverse engineering of complex, free-form surfaces, based on the integration of the measurement information from a 3D vision sensor and a coordinate measuring machine (CMM). The aim is to reconstruct the CAD model of objects of complex geometry with high accuracy and at the same time rapidly, exploiting the advantages deriving from the use of both the optical and the mechanical sensors, with a minimum of human intervention. The combination is performed at the level of measurement information, within a module for the intelligent aggregation of the information coming from optical and mechanical sensors. Tools are developed for decimating, filtering, grouping and surface-fitting the 3D images of the vision sensor and the point clouds from digitisation of the CMM. In the paper, the combined system is described, and an industrial application is presented.

1. INTRODUCTION

In the last years, extensive attention has been given to different methodologies of reverse engineering (RE) aiming at producing the computer aided design (CAD) model from digitisation of a given object on a coordinate measuring machine (CMM) (Motovalli, 1998). In the traditional RE approach, manual individuation and segmentation of the surfaces on the physical object represent the first operation. The most important boundaries of the individual surface entities are reconstructed to define a rough model that is used as nominal surfaces to drive the probe in the next phase. It is then generated a CMM part program for the automatic digitisation by means of the touch probe which, in an iterative way, acquires points on the physical model. A problem that is often met in RE is related to the fact that CMMs, especially those with a touch probe, are generally slow in acquiring points: the digitisation process is very time consuming in the acquisition of the first set of points on complex, free-form surfaces. However, use of CMMs is mandatory in the RE process, when high accuracy is required in the reconstruction of functional surfaces.

An alternative approach is represented by the non contact digitisation of surfaces, based on optical techniques: in fact, it is much more efficient in term of speed and reduces the human labour. Moreover, the absence of contact and the fact that no probe compensation is required makes this approach particularly interesting in the RE process. In this frame, a number of systems based on optical methods has been developed. Among them, lasers scanners and vision systems are widely used. Laser scanners have very high data rate (up to 2500 data points per second), and good resolution, of the order of 10 micrometers (Chan, 1997). Vision systems have less resolution (about 100 micrometers); however, they can simultaneously acquire thousands of data points over a large spatial range, without moving the optical head (Sansoni, 2000).

In the last years, a large amount of research has been performed to develop methods for the mathematical modelling of optical 3D points, in order to allow an easy handling of them on existing CAD/CAM systems (Soucy, 1996), (Beraldin, 1997), (Ma, 1995). However, the large amount of data produced as output from these sensors, and the fact that usually the generated data are unordered and present fixed density, independently on the surface curvature, make this integration not trivial. Furthermore, the measurement performances often do not match with the application requirements.

On the other hand, the reduction of the lead time in RE, and the increasing requirements in terms of flexibility and level of automation of the whole digitisation process have resulted in a great deal of research efforts aimed at developing and implementing combined systems for RE based on the integration of mechanical probes with optical systems (Alrashdan, 1998). Many approaches that present combined types of digitisers have been presented in recent literature in a wide range of applications. The vision system can be a simple video-camera, which performs like a human eye, and provides the CMM with the exploration paths of the touch-triggered probe (Chen, 1997a). Systems based on passive stereo vision (two or more video-cameras), as well as laser scanners and whole-field triangulators are part of the state of the art (Cheng, 1995), (Chen, 1997b). In the proposed systems, the integration of the vision system with the CMM is generally limited at the physical and at the facility automation level. The intelligent aggregation of the information from the optical and the contact sensors is not yet investigated, even though it is mandatory to achieve full integration.

This paper describes a novel approach to the integration of a 3D vision sensor and a CMM to perform the reverse engineering of free-form surfaces. The proposed methodology does not foresee the physical integration of the two sensors but their combination at the level of the measurement information. The aim is to reconstruct the CAD model of objects of complex geometry with high accuracy and at the same time rapidly in order to have the advantages deriving from the use of both the optical and the mechanical sensors, with a minimum human intervention. The main characteristics of the methodology are detailed in the following sections.

2 OVERVIEW OF THE METHOD

The outline of the method is schematically shown in Figure 1. The starting point is the acquisition of a number of clouds of points using the 3D vision system. Each one provides initial dimensional information of the object. They are then pre-processed by means of suitably developed procedures for the ordering and the adaptive sampling of the point clouds, in dependence of the surface curvature. Curves and surfaces are defined over the point clouds, by using specialised tools of the CAD system. A 'rough' CAD model of the surface is determined, to be used as start point for the digitisation step in the CMM environment. The a-priori knowledge of a 'rough' surface model allows an efficient programming of the scanning and digitizing path of the CMM mechanical probe, with a reduction of the number of touch points and of the iterations needed to achieve the complete digitization of the object. Then, the measured data are imported back to the CAD environment and used to produce the final, accurate CAD model.

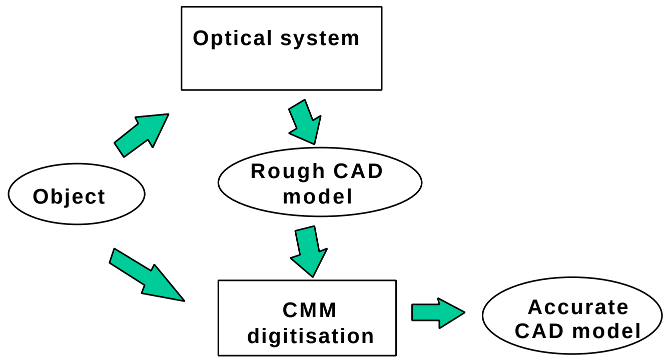


Figure 1. Overview of the method

The two digitizers integrated in the current environment are (i) a whole-field profilometer for 3D vision, specifically developed to perform fast acquisition of even large surfaces with accuracy within 100 micron; (ii) a coordinate measuring machine having a scanning contact probe. It is equipped with a software package dedicated to digitise and measure free-form surfaces. The measurement information is combined within a commercially available 3D CAD system equipped with a specific module dedicated to the reverse engineering process. The pre-processing of the point clouds from the 3D optical sensor and their interfacing/importing into both the CAD and the CMM environments is carried out by means of procedures implemented in the C language.

3 THE CONTACTLESS DIGITISATION OF FREE FORM SURFACES

Figure 2 shows the basic layout of the optical head. It exploits active stereo vision: an LCD projector projects suitable patterns of structured light on the target object, these are acquired, along a different direction with respect to that of projection, by a video camera. The deformation induced on the patterns by the object shape allows suitable light coding: this coding solves in an easy way the well-known correspondence problem. The measurement technique developed to retrieve the depth information is based on the combination of the Gray Code and the Phase Shift methods (Sansoni, 1999). The measurement procedure allows the achievement of dense point clouds, expressed in the video camera internal reference system. The practical usability of the system has been thought strategic, especially in view of using it in the industrial production field. As a result, the processes of determining the geometrical set-up required by input resolution and working volumes, and of implementing the necessary image preprocessing in the presence of non-cooperative reflectance of the surface, are performed automatically.

Two different prototypes have been developed to enlarge the typology of measurable objects. These are shown in Figure 3. In the system of Figure 3.a, the projection and vision devices can be repositioned by means of stepped motors, in order to adjust the working area from tens of millimeters to about two meters. The optical head is mounted on a moving stage, allowing its translation along the vertical and the horizontal directions; in this way, areas large up to 2 m^2

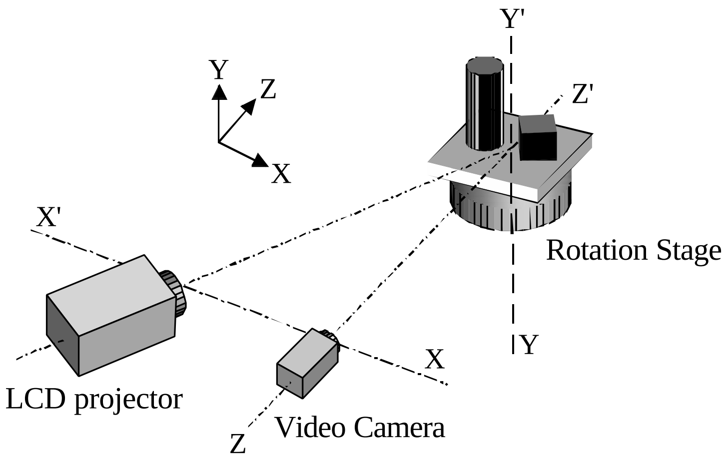


Figure 2. Optical geometry of the 3D vision system

can be scanned and large surfaces can be measured by acquiring and aligning a number of separate patches. Those objects presenting circular symmetry can be placed on a rotation stage. The sequence of acquisition of the range images is decided on the basis of the dimension and the shape of the object. Image registration is performed by using a combination of rotation and translation matrices, determined from the knowledge of the amount of rotation and of translation of the optical head and by suitable calibration.

The system shown in Figure 3.b is the portable release of the digitizer. Calibration is performed in situ, and the multi-view registration exploits both a photogrammetric approach and a matching method based on the ICP algorithm (Chen, 1992). Single views, ranging from (50 by 50) mm^2 to (350 by 400) mm^2 are acquired in 5 seconds. The point clouds can then be edited, visualized and merged to reconstruct the whole shape.

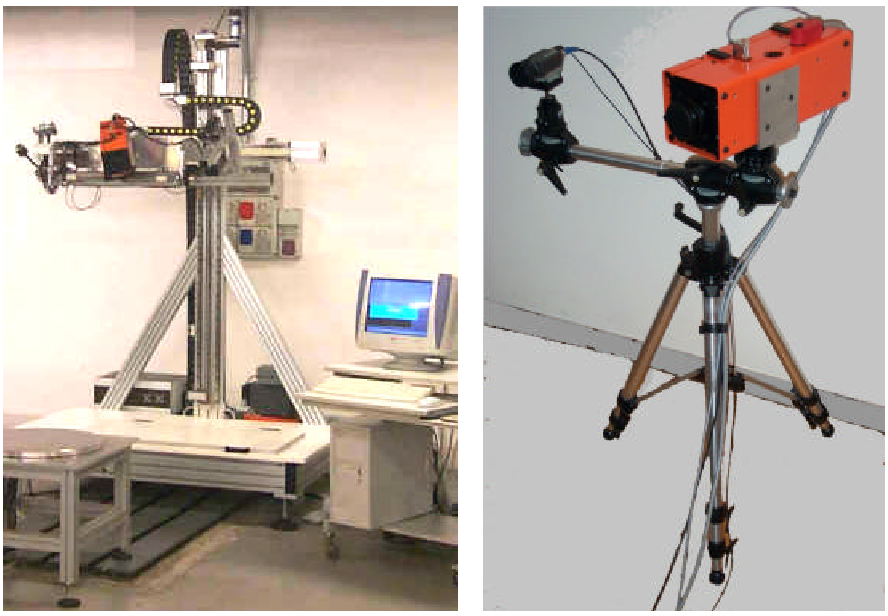


Figure 3. Prototypes used for the contactless digitization of the surfaces

An example of the performance of the system in Figure 3.a is the acquisition of the wheel rim shown in Figure 4. A single view is sufficient to perform the measurement of the top surface of the object; correspondingly, the illumination area is (350 by 400) mm^2, with a depth range of 150 mm. The deformation induced on one of the projected fringe patterns by the object is well visible in the figure. The corresponding range image is presented in Figure 5: here a resolution of the measurement of 70 micron has been evaluated.

4. ORDERING AND FILTERING THE DATA

After the rough data have been acquired by means of the vision system, they have to be *massaged* and converted into organized data before being imported in CAD environment and other manufacturing software. The following features should be available: (i) an interface for visualizing and decomposing/composing the set of points in subsets, that can be manipulated and assembled, (ii) algorithms for reconstructing automatically curves in 3D CAD environment in the case of unstructured sets, and (iii) different filters in dependence of the typologies of the point sets. These tasks are performed by a suitably developed program, called *Visual Point*, which allows the manipulation of cloud of points during the pre-processing phase and becomes particularly useful in the presence of points from random and/or manual sampling, when the data are not structured in a sequence of scan lines. As an example, Figure 6 shows the interface used to decomposing the initial, whole point cloud of Figure 5.

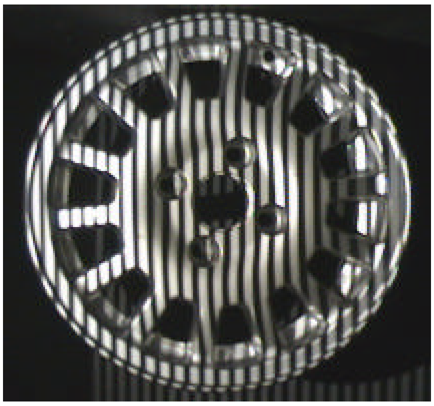


Figure 4. Image of a wheel rim

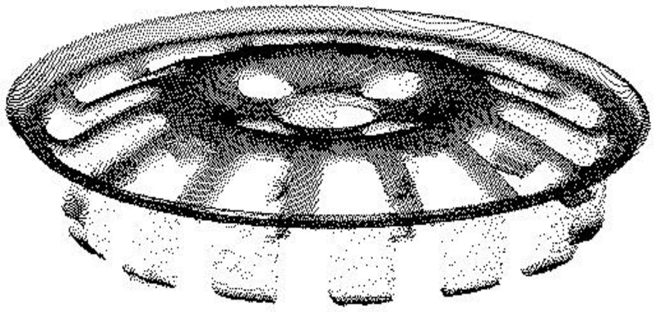


Figure 5. Range image of the top side of the wheel rim

A non trivial problem in the reconstruction of surfaces is that some CAD algorithms need ordered point sets to reconstruct scan curves. In fact, digitised point clouds can be very far from data structures for representing shapes. To overcome this difficulty, Visual Piont implements an algorithm for the ordering of the points. It requires as input parameters a reference plane and an ordering direction and divides the cloud in a set of bands. In this way, the data from the optical system are automatically assigned to bands and ordered along different directions. After that, the versus of adjacent curves is alternatively changed. This allows to decrease the human intervention in the curves reconstruction. Moreover, a filtering function has been developed to adapt the density of the data to the curvature of the surface. A set of interpolating cubic splines is reconstructed connecting the points that belong to each band. Then, the implemented function removes the data characterized by a curvature or a tangent greater than a predefined range (Carbone, 2001). The formats supported by the software are *.ibl*, *.vda*, *.iges*. The system is Windows-based and has an interface with PRO/Engineer and its module Pro/Scan Tools. After the described pre-processing, the organised points can be imported in the CAD system (PRO/Engineer by PTC) and used for creating automatically a set of approximately parallel isoparametric scan curves, the basis for reconstructing "style curves". Figure 7 shows the scan curves and the boundary curves automatically defined by PRO/E over the organised points.

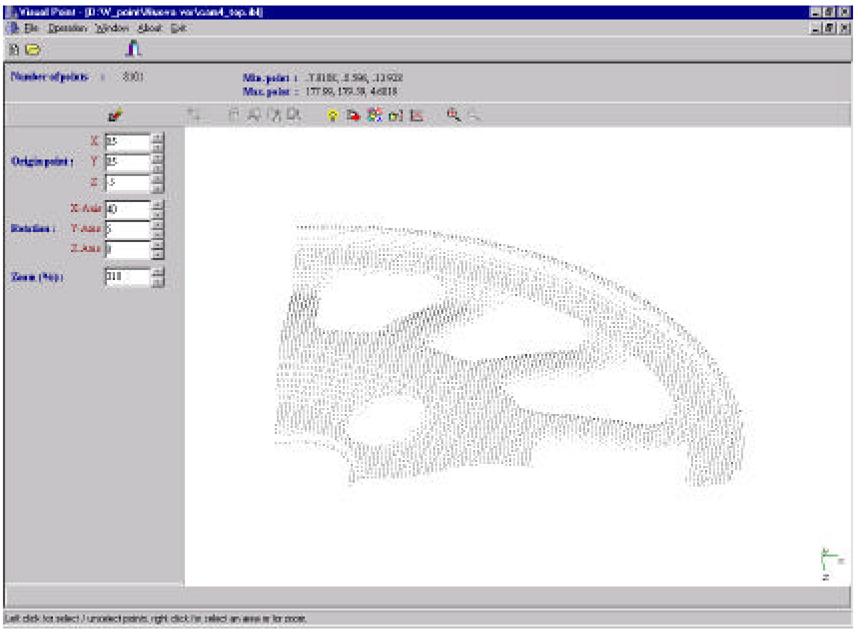


Figure 6. The user interface containing the cloud of points.

5. THE 'ROUGH' CAD MODEL

Once the style curves have been defined, the first rough surfaces can be reconstructed. The surfaces are defined by selecting the Style Surface option in the CAD system: parametric surfaces are created by blending curves along the chosen ordering direction. The curvature surface information available in the CAD system is used to divide the object in

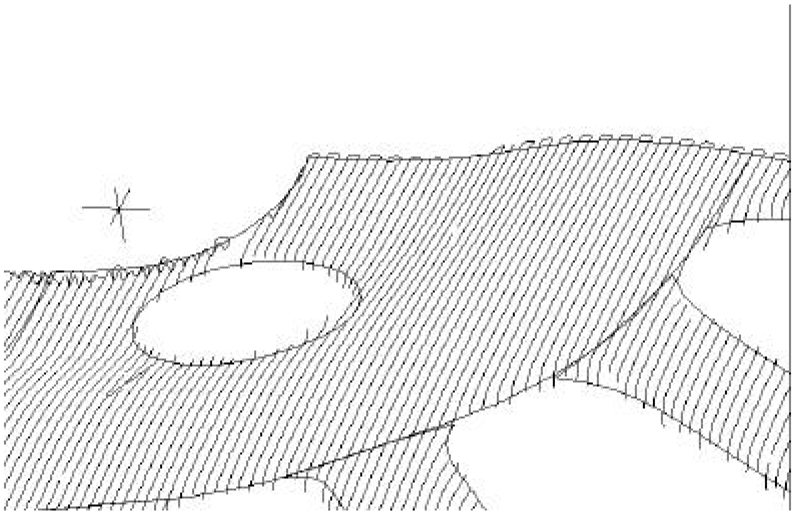


Figure 7. Scan curves and boundary curves defined by PRO/E

surfaces that are composed of patches on the basis of changes in curvature. The usually long time spent to define small patches is not required, because the optimisation in the next step by means of the CMM does not need high accuracy in the rough model. In fact, it is more important that surfaces are not distorted, than they interpolate many curves. In the same way, small gaps between the elements do not matter, assuming that the aim of the proposed approach is to reconstruct the functional surfaces. Figure 8 shows the NURBS surfaces (surfaces A, B, 3a, 3b, 3c, and 3d) defined by the CAD software. The deviations between the CAD surfaces and the points optically measured are very small: the 90% of the points are within a tolerance interval from –0.1mm to 0.1mm with respect to the corresponding CAD surface. The extracted surface geometry is then exported into the CMM environment, and used in the contact digitisation phase.

6. DIGITISATION USING THE CMM

The availability of a first CAD model represents the starting point for the digitisation process on the CMM, and intrinsically simplifies the solution of typical problems, related to unpredictable changes of curvature, normal 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. The inspection process, which includes the definition of the measurement sequence, of the number of measurement points, of the number of probes and their configuration, is planned using predefined inspection plan functions available in the CMM software. By selecting for each view of the component a different probe, and specifying the grid of points or the parameters of the scanning area, it translates the user command into the detailed steps necessary to drive the CMM in a grid structured cycle. Surfaces are then digitised using the mechanical probe and the measurements are carried out until the fixed target tolerance is obtained.

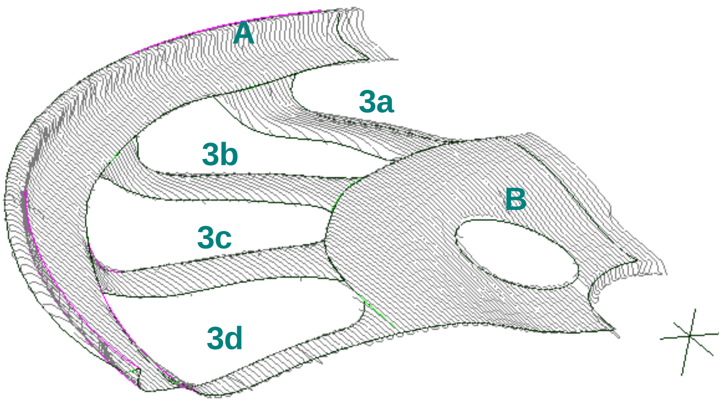
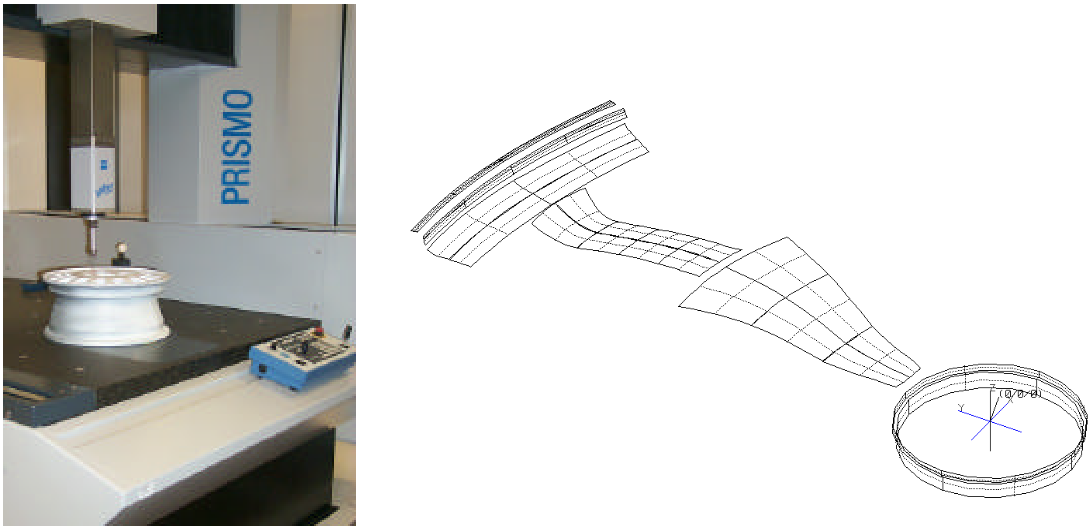


Figure 8: NURBS surfaces of the 'rough' CAD model

Figure 9.a shows the wheel rim during the contact measurement and Figure 9.b presents a partial reconstruction of the wheel rim after the first digitisation cycle performed by the CMM. After the first initial digitisation, Bezier surfaces are automatically created in the CMM software using the acquired points. By analysing the deviations between nominal points (those on the reconstructed free-form surface) and actual points (those acquired by the CMM), further refinement of the CAD model can be performed in order to obtain the required reconstruction accuracy.

The co-ordinate system adopted in the optical digitisation is not used directly in the CMM system, thus there is no influence of the errors due to the 3D vision system in the co-ordinate system definition. The CAD co-ordinate system is set up and matched with the CMMs co-ordinate system before starting the automatic cycles. The manual alignment is automatically improved with a 3D best fit and no perpendicular or planar relationship is necessary.



(a) (b)

Figure 9. Digitisation performed by the CMM. 9.a: the object under measurement; 9.b: partial reconstruction of the object

7. FINAL CAD MODEL

The CMM software supports the IGES format files: thus the file is imported into the CAD environment, where the secondary surfaces need to be reconstructed. In order to have a smooth continuos model, the number of patches has to be optimised and the surfaces have to be extended by joining the adjacent boundaries and by adjusting the intersections. In the final CAD solid model, it is necessary to provide smooth transitions between functional surfaces and to regenerate a little number of secondary surface patches, without enforcing connectivity between neighbouring elements. By following the proposed approach, very high accuracy is obtained in one step or two steps maximum, in case of very complex surfaces. As an example, the final model of the wheel rim is shown in Figure 10: the deviations between the CAD surfaces and the points measured by the CMM are less than 20 micron.

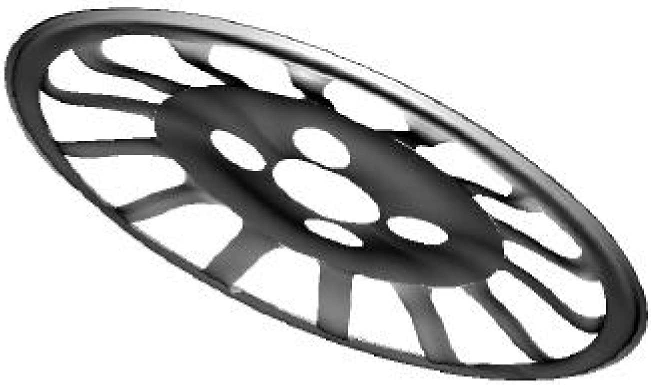


Figure 9. The accurate CAD model

8. CONCLUSIONS

Capturing shape and translating it into a mathematical model is a difficult task in the reverse engineering process, particularly when complex surfaces are involved. Moreover, huge point sets are quite common when working with scanners and vision systems, and most CAD environments cannot handle the data that have to be manipulated prior to the CAD modelling. The developed system facilitates the reconstruction of the CAD model using the advantages deriving from both the vision and the mechanical systems. After the data have been digitised, scanlines are automatically defined. They represent the basis for NURBS curves and surfaces reconstruction in the CAD environment. In this way, the number of iterations and the long time usually required by the manual digitalisation and points manipulation can be effectively reduced.

The proposed system is unique in that it integrates the vision system and the CMM at the level of intelligent aggregation of the information. The absence of the physical integration of the two sensors is a strength of the methodology, as it results into a good level of reconfigurability of the optical head, and increases the typology of measurable objects. Moreover, the measurement characteristics of the CMM are not modified by the integration of the vision system, and, in principle, the use of a single vision system in conjunction with different CMMs is realistic, provided that the sensor has the characteristics of portability and easy calibration.

The development of the procedures for the processing and the modelling of the point clouds within a commercial CAD/CAM system is another aspect of the method. The effective exploitation of systems for reverse engineering based on this integrated approach could have great impact on the industrial practice owing to the possibility of implementing them on commercial, easily available CAD/CAM systems, instead of using specialised and strictly system-dependent tools.

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