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PATTERN RECOGNITION IN COMPUTER INTEGRATED MANUFACTURING

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In this paper a new approach to an automatic controlled system of manufactured parts is suggested. Inputs of the system are: an unordered cloud of 3D points of the part and its CAD model in IGES and STL formats. The 3D cloud is obtained from a high resolution 3D range sensor. After registration between the cloud of points and the STL CAD model, the cloud is segmented by computing the minimal distance and compared to some local geometric properties between the 3D points and the NURBS surfaces. Controlled results are displayed in two ways: visually, using a colour map to display the level of discrepancy between the measured points and the CAD model, and a hardcopy report of the evaluation results of the tolerance specifications. The computing times are 2 seconds for a model STL made up of 15000 triangles put in correspondence with an image made up of 20000 points and about 10 seconds for the same image put in register with the same object represented with its model NURBS.

K e y w o r d s: vision system, segmentation, pattern recognition, inspection

1 INTRODUCTION

The increasing number of manufactured objects showing complex surfaces, either for functional reasons or by design, and technological improvement in manufacturing all create a need of automatic inspection of complex parts. This type of apparatus requires a very accurate geometrical definition of the inspected object, accurate data acquisition system, and clearly defined rules for the inspection of these surfaces. The use of three-dimensional coordinate measuring machines and recent advent of laser sensors combining measurement accuracy and fast acquisition allow obtaining a great number of 3D measurement point.

These accurate 3D points permit an explicit description of object surfaces. Inspection is the process of determining if a product (part or object) deviates from a given set of specifications (tolerances).

Coordinate Measuring Machine (CMM) is an industry standard mechanism for part validation, but in spite of its high precision it has some important limitations such as: the need of mechanical fix turing, low measurement speed and the need to be programmed as new part is inspected.

On the other hand, recent advances in non- contact sensors like laser range finder, with significant improvement in speed (about 20 000 points/s) and range precision (about 25 micron), allow them to be used in inspection tasks. It is more useful to use CAD models in inspection because the models contain an exact specification of an industrial part and they provide a well-defined model for inspection.

CAD models provide a mathematical description of the shape of an object, including an explicit parameterization of surface shape and an explicit encoding of inter-surfaces relationships. The database can also be augmented with manufacturing information including geometric tolerance, quality of surface finish, and manufacturing information.

An advantage of using CAD representations for inspection is their high flexibility; it is easier to add a new object to the inspection system even before it is manufactured.

In industry, inspection is usually performed by human controllers, based on a sampling of parts rather than on the total production, because of the reduction in time and cost.

Controlled system is beneficial because the constant of improvement of high-speed production technologies dictates a need of fast inspection techniques. Indeed, the fast development of products (rapid prototyping) is able to produce real parts starting from CAD models and allows the manufacturing of products of great complexity as high speed.

In this paper, we submit a controlled system that uses as input an unordered cloud of 3D points of the part and its CAD model in IGES and STL format. The cloud of 3D samples is digitized by a 3D laser range sensor with a resolution of 25 micron and a depth field of 10 cm. The system registers the cloud of 3D points and the STL CAD model of the part.

Most manufactured parts have to be checked, using specifications on defined surfaces. So in order to be able to control the surfaces of interest, the cloud of points is

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registered with the IGES CAD model and segmented as many times as the number of surfaces in the part.

In inspection process, each surface of interest is checked according to corresponding segmented 3D points. The system then outputs a visual and a hardcopy report.

2 PREVIOUS RELATED WORK

The automatic verification of manufactured object is a fairly recent concern. The main reason is that to carry out this type of task. It is necessary to have contactless sensors. The digitalization of the images from video camera and later from CCD camera gives possibility to obtain information on objects at high speed. Quickly one attains the limits of these sensors for the analysis of 3D parts, at least in industry, because of their limited precision and the difficulty to rebuild up the third dimension.

The appearance of sensors combining a laser beam and a CCD camera allows the rebuilding of the third dimension, without, however, giving the accuracy obtained with a 3D coordinate measuring machine. The laser telemeter sensor permits to attain desired speed and precision. It is at the present time possible to automate the inspection process.

At present, few papers look at the use of depth image for inspection. One reason is the lack, up to now, of powerful systems for the recovery of depth images.

Relating to the inspection process we can quote the article of T.S. Newman and Jain [1], a survey of the question, where the problem is tackled from the point of view of luminance images (grey-level or binary) range images or other sensing modalities. They discuss general benefits and feasibility of automated visual inspection, and present common approach to visual inspection and also consider the specification and analysis of dimensional tolerances and their influence on the inspection task.

The system developed by Newman and Jain [2] permits the detection of defects in range images of castings. This system uses CAD model data for surface classification and inspection. The authors report several advantages for the use of range images in inspection: they are insensitive to ambient light, the objects can usually be extracted from their background more easily, depth measurement is accurate, and most important, the range image is explicitly related to surface information.

The authors show an interest with the use of the CAD database in order to carry out the task of control. Moreover, they show the weakness of the current CAD systems to make automatic check. The authors do not tell about tolerances measurements.

In [3], Tarbox and Gottschlich report a method based on comparing a volumetric model of reference object with a volumetric model of an actual object iteratively created from sensor data. To provide a framework for the evaluation of volumetric inspection, they have developed a system called IVIS (Integrated Volumetric inspection System). They obtain a volumetric image of the defects by using custom comparison operators between the reference model and the model of the analyzed part.

Truco *et al* [4] report an inspection system that involves the location of the part, the optimal planning for the sensor placement, and the measurement of some geometric characteristics based on the CAD model.

Some interesting works that deal with the reconstruction problem are those by Pito [5], [6] and by Papadopoulos and Schmitt [7]. Pito presents a solution for the next best view problem of a depth camera in the process of digitizing unknown parts. The system builds a surface model by incrementally adding range data to a partial model until the entire object has been scanned. Papadopoulos proposes an automatic method for digitizing unknown 3D parts, using an active sensor with a small field of view.

In this work, we expand a new approach for an automated control system.

3 PATTERN RECOGNITION AND DIMENSIONAL CONTROL

Running a vision task brings into operation several types of data and processing: camera and lighting device configuration, image processing sequences and the modelling of recognition patterns and dimensional control. The complete programming of the vision system includes three steps: installing the vision inspection cell, perfecting the image processing of the work scene, and storing the geometrical and optical characteristics of the parts which actually constitute the learning process.

4 THE 3D LASER CAMERA

The basic geometry of 3 laser camera is based on the synchronization of the projection of a laser beam with its return path. The main advantage of this approach is to obtain simultaneously high resolution and large field of view contrary to standard triangulation geometries where a compromise is made between resolution and field of view [8].

The synchronized scanning geometry is based on a doubled-sided mirror that is used to project and detect a focused or collimated laser beam (Fig. 1). The scanning of the target surface by the sensor results in the output of 3D points (x, y, z) and their luminous intensity (I) at the surface. The auto-synchronized sensor explores surface line by line at a rate that can be specified by the user (512 points/ line). The source used in NRCC prototypes is a laser, which is typically coupled to an optical fibber. A scanning mirror and a fixed one are used to project the laser beam on the scene. The scattered light is collected

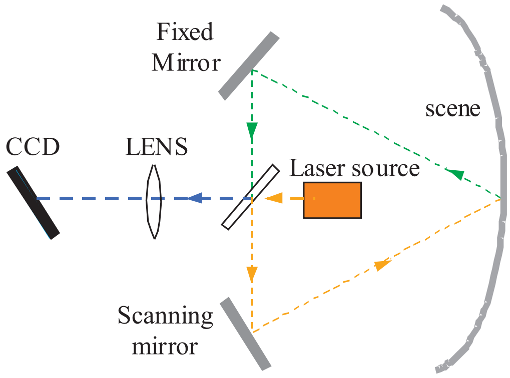

Fig. 1. Optical principle of the NRCC sensor

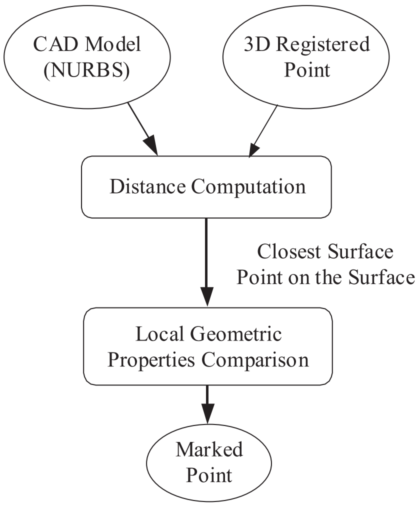

Fig. 2. Block diagram of the point segmentation system

through the same scanning mirror used for the projection and focused to a linear CCD.

Essentially the configuration illustrated on the Figure 1 is a profile measurement device. A second scanning mirror (not shown in the illustration) can be used to deflect orthogonally both the projected and the reflected laser beam. It can be mechanically translated by commercially available gantry positioning device such as coordinate machines (CMM).

5 THE REGISTRATION METHOD

After digitalization of the part, we have two sets of data, the CAD file resulting from the design, and the cloud of 3D points. These data are expressed in their own reference systems. The operation, which consists of superposing these two sets, is called registration.

The registration of two shapes is defined as finding the 3D rigid transformation (rotation + translation) to be applied over one of the shape to bring it with the other one, into one common cartesian coordinates system. The registration process in this paper relies on the well-known work of Besl and McKay [9] who in 1992 developed a general-purpose representation method for the accurate and computationally efficient registration of 3D shapes, including free-form curves and surfaces.

The method is based on the Iterative Closest Point (ICP) algorithm, which requires only finding the closest point from a geometric entity to a given point. The rigid transformation is computed using a unit quaternion. But as the transformation estimation is done by a Mean Square (MS) distance computation, this method is not robust to outliners points, obtained either by noise or by the presence of other parts in the scene. As a solution to this problem, Masuda and Yokoya [10] estimate the rigid motion between two range images in a robust way by fusing the ICP algorithm with random sampling and Least Median of Squares (LMS) estimation. They demonstrated that registration between two images can be achieved by a high level of robustness (up to 50 %) to occlusion and noise.

Moron [11] implemented an algorithm for registration between an unordered cloud of 3D points and a CAD model in STL or IGES format. In the registration process, we use the CAD model in STL format rather than IGES, so that few precision is lost but computation time is largely improved. The registration method can be decomposed into three main steps:

First, the algorithm randomly selects N_s 3D points from the original 3D data set, and then computes a rigid transformation by using an ICP algorithm on the subset. This process is repeated NT times. For finding a solution at this non-linear problem, we take just a sample of N_s points.

The probability of finding a solution increases as N_s decreases or N_T increases. After each ICP execution, the quality of the estimated rigid transformation is evaluated by computing the median square error.

Second, the best estimated rigid transformation corresponding to the least median square error is applied over the whole 3D data, and the original 3D data set is segmented into inliers and outlier point sets.

Finally, a standard mean square ICP algorithm is then applied on the inliers set of points to find the optimal rigid transformation solution.

In order to find a global solution, it may be necessary to apply this method several times, with different initial conditions.

From now, we only consider the solution corresponding to the best estimation.

6 3D DATA SEGMENTATION

In the registration process, we superposed the CAD model with the 3D data of the part. However, for we are interested in inspecting some specific surfaces, we must segment the part into its different surfaces.

The 3D cloud is segmented by computing the distance between every 3D point and all of the surfaces in the

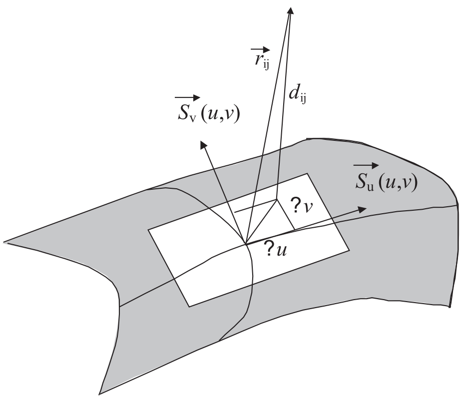

Fig. 3. Point/NURBS surface distance

CAD model (IGES format), and by comparing some local geometric properties between each 3D point in the cloud and its closest point on the surface.

In the IGES CAD model, all the surfaces of the part are defined as a parametric NURBS surfaces. The problem of computing the distance from a 3D point to a NURBS surface can be formulated as finding a point on the parametric surface such as the distance between the 3D point and the point on the surface is minimal in the normal direction to the tangent plane at the point on the surface.

The problem is solved as a minimization problem. The local geometric properties that we estimate are: the normal surface, the Gaussian curvature and the mean curvature.

Concerning the point on the parametric surface, those properties are estimated using the surface parameters (NURBS). Concerning the 3D point, we use a parametric second order polynomial computed across a neighbourhood of points. If the local geometric properties on the 3D point are similar to those on the parametric surface [12], [13], a 3D point is labelled with the name (number) of the closest NURBS surface. A functional block diagram of the segmentation appears in Figure 2.

6.1 3D Point/NURBS surface distance computation

The distance of a point to a NURBS surface can be computed as follows. Find a point on the parametric space of the surface (u_0, v_0) such that the distance between the surface $s(u_0, v_0)$ and the 3D point r is minimum in direction perpendicular to the tangent plane at the point location (Figure 3).

The function to be minimized is the following one:

$$\min_{u_0,v_0} \|\vec{r} - \vec{S}(u,v)\|^2.$$

If one performs the Taylor expansion of the parametric surface $s(u,v)$, we obtain:

$$\vec{S}(u,v) = \vec{S}(u_0,v_0) + \frac{\partial}{\partial u}\vec{S}(u_0-u) + \frac{\partial}{\partial v}\vec{S}(v_0-v)\,.$$

Using this expansion, the minimization problem becomes:

$$\min_{u_0,v_0} = \left\|\vec{r} - \vec{S}(u_0,v_0) - \frac{\partial}{\partial u}\vec{S}(u_0-u) - \frac{\partial}{\partial v}\vec{S}(v_0-v)\right\|^2.$$

This can be expressed in matrix form as:

$$\min_{u_0,v_0} = \|\mathbf{J}\boldsymbol{w} - \boldsymbol{d}\|^2.$$

Where $\mathbf{J}$ is the Jacobean matrix of $s(u,v)$ and is given by:

$$\begin{pmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \\ \frac{\partial z}{\partial u} & \frac{\partial z}{\partial v} \end{pmatrix} \quad \text{and} \quad \boldsymbol{w} = \begin{bmatrix} u_0 - u \\ v_0 - v \end{bmatrix}$$

is equal to the variation of the parameterization.

If $d(u,v)$ is the error for the initial parameterization (u_t, v_t) *ie* the initial closest point to the triangulated CAD format. Let: $d(u,v) = rS(u,v)$, then the solution to the minimization problem is equal to: $w(\mathbf{J}^\top\mathbf{J})^{-1}\mathbf{J}^\top\boldsymbol{d}$.

Using an iterative procedure, one can compute the distance of the point from the surface in less than four to five iterations.

6.2 Geometric properties comparaison

Let P be a point from the 3D range data, and Q the closest point to P on the surface. To finish the segmentation process, we estimate and compare some local geometric properties around of P and Q. Geometric properties of Q are estimated by using the NURBS CAD model.

We estimate the local geometric properties of P by using the method proposed by Boulanger [12]. This method is viewpoint invariant because the surface estimation process minimizes the distance between the NURBS surface S and the 3D data point in a direction perpendicular to the tangent plane of the surface at this point. The surface normal $n(u,v)$, the Gaussian curvature $K(u,v)$ and the mean curvature $H(u,v)$ for the point $P(u,v)$ from the parametric surface $\eta(u,v)$ can be estimate by:

$$\vec{\eta} = \frac{\vec{r}_u(u,v) \times \vec{r}_v(u,v)}{\|\vec{r}_u(u,v) \times \vec{r}_v(u,v)\|}$$

$$K(u,v) = \frac{[\vec{r}_{uu} \cdot \vec{r}_u \cdot \vec{r}_v]\,[\vec{r}_{vv} \cdot \vec{r}_u \cdot \vec{r}_v] - [\vec{r}_{uu} \cdot \vec{r}_u \cdot \vec{r}_v]^2}{[\vec{r}_u \cdot \vec{r}_v]^4}$$

$$H(u,v) = \frac{A + B - 2C}{2D^3} \quad \text{where}$$

$$A = \left(\vec{r}_u \cdot \vec{r}_v\right)\left\lfloor \vec{r}_{uu}\vec{r}_u\vec{r}_v \right\rfloor, \quad B = \left(\vec{r}_u \cdot \vec{r}_v\right)\left\lfloor \vec{r}_{vv}\vec{r}_u\vec{r}_v \right\rfloor,$$

$$C = \left(\vec{r}_u \cdot \vec{r}_v\right)\left\lfloor \vec{r}_{uv}\vec{r}_u\vec{r}_v \right\rfloor, \quad D = \left(\vec{r}_u \cdot \vec{r}_v\right) \quad \text{and}$$

$$\vec{r}_u = \frac{\partial \vec{r}}{\partial u},\ \vec{r}_v = \frac{\partial \vec{r}}{\partial v},\ \vec{r}_{uu} = \frac{\partial^2 \vec{r}}{\partial u},\ \vec{r}_{vv} = \frac{\partial^2 \vec{r}}{\partial v},\ \vec{r}_{uv} = \frac{\partial^2 \vec{r}}{\partial u \partial v}.$$

We need to estimate the first and the second partial derivatives at the point P by using a parametric second

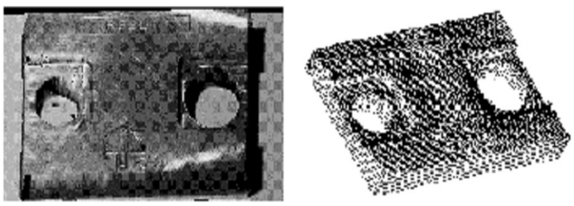

Fig. 4. Picture and 3D data of the part to be controlled

Fig. 5. 3D points cloud resulting from the Digitalization of a mechanical piece

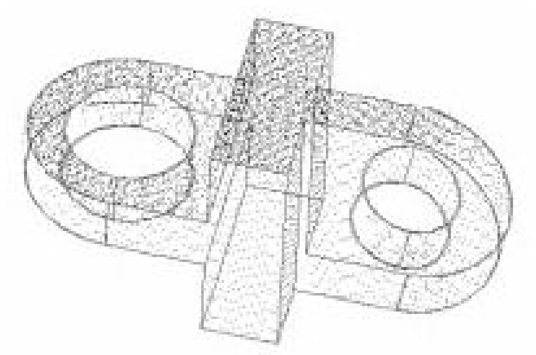

Fig. 6. Registration of a 3D cloud and its CAD model

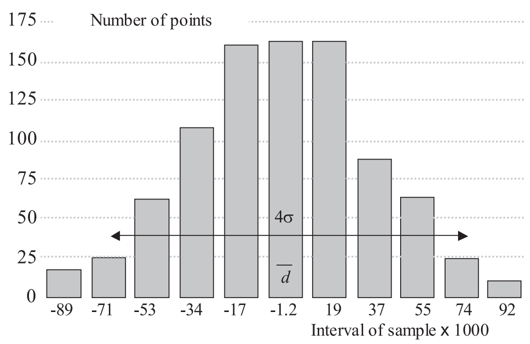

Fig. 7. Distribution of 3D points to CAD model distance

order polynomial. It is obtained by using a $N \times N$ neighbourhood, where $r(u,v) = (x(u,v), y(u,v), z(u,v))^\top$ is the measured point from the range sensor. Let

$$\vec{\eta}(u,v) = \sum_{i=0}^{2}\sum_{j=0}^{2} \vec{a}_{ij} u^i v^j = \big(h_x(u,v), h_y(u,v), h_z(u,v)\big)^\top$$

Where a_{ij} is the coefficient of each component of $n(u,v)$ and equals to zero if $i+j \geq 2$. Using this polynomial the partial derivatives at the point P are:

$$\vec{\eta}_u = \vec{a}_{10} + 2\vec{a}_{20}u_0 + \vec{a}_{11}v_0 \,,$$
$$\vec{\eta}_v = \vec{a}_{01} + \vec{a}_{11}u_0 + 2\vec{a}_{02}v_0 \,,$$
$$\vec{\eta}_{uu} = 2\vec{a}_{20} \,, \ \vec{\eta}_{vv} = 2\vec{a}_{02} \,, \ \ \vec{\eta}_{uv} = \vec{a}_{11}$$

where (u_0, v_0) are the parametric coordinates in the center of the neighbourhood. These parameters are found by using the least-square-method.

Finally we compare the local geometric properties of Q, estimated from the NURBS surface, to P from the 3D range data.

Let α_{tol} be the permissible angle between the surface normal N_S and 3D data normal N_r at point P. Then the condition $|\text{Angle}(N_S, N_r)| < a_{tol}$ has to be respected. Let K_{tol} and H_{tol} be the defined variation of the Gaussian and the mean curvatures, then the conditions: $|K_S - k_r| < K_{tol}$, and $|H_S - H_r| < H_{tol}$ have to be respected.

7 PRACTICAL RESULTS FOR VISUAL INSPECTION

A high speed range sensor is used to digitize the parts. The sensor is mounted on a coordinate measuring machine to allow precise mechanical registration between views.

The result of this digitization is an unordered set of 3D points describing the scanned object as illustrated in Figures 4b and 5.

Our goal is to check the cloud of 3D points against the CAD model of the part. Registration of the cloud with the CAD model is the first step illustrated in Figure 6.

Figure 7 shows the distribution of the 3D point to CAD model distance, for the surface segment with a flatness tolerance. From this figure, a Gaussian distribution can be approximated.

Rigorously, to measure the flatness of the surface we would place the parallel planes to the NURBS surface at the distances: max and min from d (see Fig. 7). After registration, in order to be able to check for geometric tolerance, the cloud of points is segmented as many times as the number of surfaces in the part. Figures 8 and 9 showed two segment surfaces.

We computed the mean distance and the standard deviation of Figure 7, as: $d = -0.000434562$ mm and $\sigma = 0.0365986$ mm. The distance is bigger than the specified tolerance (0.01 mm).

Figure 8 shows a datum surface and a surface with a perpendicular tolerance specification. We have computed the mean distance and the standard deviation as: $d = -0.00242864$ mm and $\sigma = 0.0435986$ mm. For this

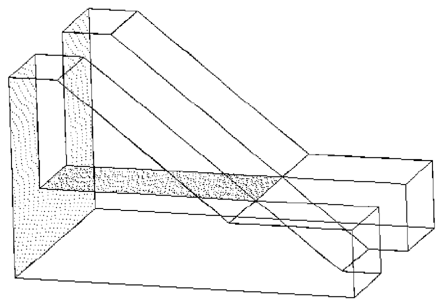

Fig. 8. 3D points of two perpendicular surfaces

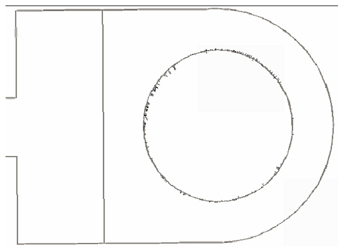

Fig. 9. Visual result for cylindricity checking

Fig. 10. Variance versus incident angle in the direction of the laser sweep

surface, $4\sigma = 0.1743544$ mm is less than the specified tolerance (0.4 mm), so we can say that the surface true to the perpendicular specification.

In the figure 9, we show a visual inspection of a hole (parts viewed in the figure 6). It has a tolerance cylindricity specification of 0.0163 mm, and we computed $4\sigma = 0.118912$ mm.

During the digitalization process, some noise is added to the measured points as a function of the laser camera position. Since we did not take the noise value into account in tolerance conformity computations, an out-of-tolerance result cannot guarantee a lack of conformity for sure. We are presently modelizing the noise formation process in order to enhance tolerance conformity computation.

In Figure 10 we present the variance (in mm2) in the laser propagation axis versus the incident angle (in degrees) the laser beam reaches the surface. The incident angle is measured in the same direction as the laser beam sweep. From Figure 10 we observed that the smaller value of dispersion is produced for an incident angle range 15 and 30 degrees, but not in the vicinity of 0° as expected. This result is due to the inclination between the CCD sensor and the laser head in the camera in order to produce the optical triangulation. A correction in the orientation parameter for our planning strategy had to be applied.

Fig. 11. The main window of the graphic system

For a rapid visualisation of various defects in the part, we have implemented a graphical using interface as shown in Figure 11. It illustrates the different actions that can be executed for a specific surface or for the whole surface. This is the main window of the system.

Figures 13 and 14 represent respectively the objects support and plate using the coloured triangles with a maximum error of 0.21 mm and 0.32 mm (red zone).

8 CONCLUSION

We have submitted a visual control system for manufactured parts. The system first registers a cloud of 3D points with a STL CAD model of the part, and then segments the 3D points in different surfaces by using the IGES CAD model.

The segmentation process is not dependent on the part geometry. It depends basically on the 3D point's precision and in a most important way on the density of points on a segmented surface, in order to obtain a good estimate of the local geometric properties [13].

The inspection methodology presented allows us to verify tolerances, not only on flat surfaces, but also on complex surfaces because we know exactly the description of the part from the CAD model.

The Inspection results are available in two ways: visually, using a colour map to display the level of discrepancy between the measured points and the CAD model, and a hardcopy report of the evaluation results of the tolerance specifications.

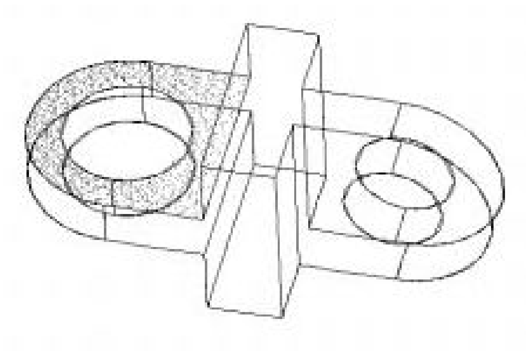

Fig. 12. Superposition of a sample and cloud points

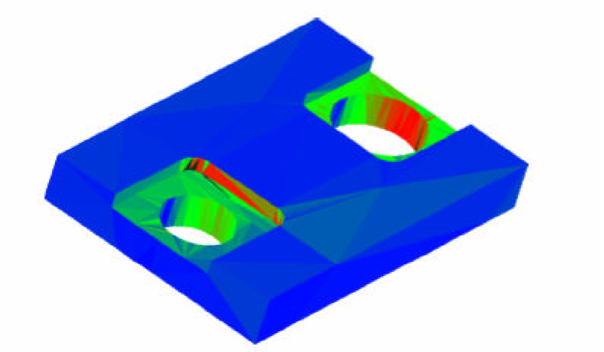

Fig. 13. Object visualisation result Maximum error 0.21 mm

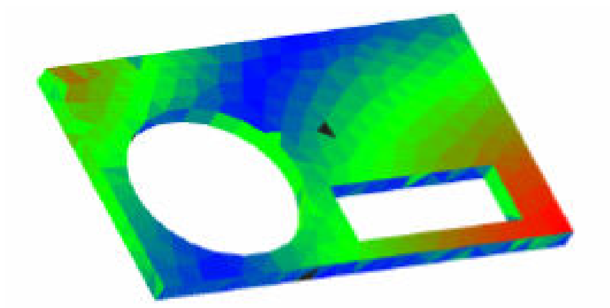

Fig. 14. Object visualisation result Maximum error 0.32 mm

The precision of the inspection results is mainly a function of the precision of the 3D points. At present we find some range sensors with a high precision, but in order to approach the precision of a Coordinate Measuring Machine a lot of work in the digitalization process has to be done.

The algorithms presented in such article programmed in C++ constituted two programmes:

A matching program between the STL CAO model and/or the cut NURBS CAO model of the 3D set of points has been developed. An investigation program from the 3D matched points with the CAO model has been also elaborated.

The method presented in this paper is interesting owing to the fact that we directly use the models of the objects such as they are contained in the data base of system CAD (model NURBS and model STL).The computing times are 2 seconds for a model STL made up of 15000 triangles put in correspondence with an image made up of 20000 points and about 10 seconds for the same image put in register with the same object represented with its model NURBS [14], [15]. Range sensor is very interesting in the inspection task because it provides large number of measurements in a short period of time and without contact with the part.

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