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Context Dependent Automatic View Planning: The Inspection of Mechanical Components

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ABSTRACT

Literature shows how 3D CAD product models can be used as reference in order to manage the verification process by 3D optical scanning systems and the computation of the optimal viewpoints. However, in the mechanical field, a variety of inspection tasks is experienced by engineers involved in the quality control process: GD&T verification, production phases control such as sheet metal cutting, evaluation of aesthetic appearance of parts, global shape deformation measurement and specific point deviations assessment. This leads to the necessity of flexible view planning approaches which adapt to the specificity of the required inspection task.

The present work targets the development of a comprehensive view planning approach in which several algorithmic options are triggered by the product features to be inspected. Algorithms have been implemented in a prototypal software system which has been experimented as an off-line application to provide inputs to a multi-axis Degree of Freedom (DoF) robot arm mounting an optical 3D scanner.

Two test cases from die casting and automotive fields are presented. They show the computation of acquisition poses in a suitable sequence and efficiency in the obtained results.

Keywords: GD&T, 3D scanning, inspection, view planning, quality control.
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1 INTRODUCTION

Over the last years, methods have been proposed to provide designers with effective tools in order to simulate the whole verification process [1]. Such approaches are promising, especially in the field of automatic parts inspection by optical digitizers mounted on articulated robot arms. In [2] and [3] system architectures are proposed for industry shop floor applications. A first off-line software module allows tolerance prescription and geometries from the 3D CAD product model to be identified. Then, acquisition poses are elaborated and the sensor path is optimized. Control cell behavior is also simulated. A second on-line software module manages the hardware tools (3D scanner and robot) and performs the virtual inspection by comparing the acquired cloud of points and the 3D CAD geometry.

In this context, the off-line view planning stage is crucial. Even if several solutions have been proposed in literature, it is not possible to consider the problem completely solved. In fact, the application in the industrial mechanical field requires coping with the following peculiar aspects, which are neglected by the current state of the art:

- geometries are generally defined by NURBS surfaces rather than tessellated representations and tolerance attributes are normally referred to such entities;
- several geometries are recurrent such as holes, slots, cylinders, ribs, etc**é** and require specific acquisition rules in order to assess assigned dimensional and geometrical tolerances;
- toleranced surfaces and datums (see terminology in [4]) should be covered as much as possible since the inspection results could be unreliable if entities are partially measured;
- global shape recovery with a minimum number of views is not necessarily the main goal, unless required for a correct view alignment;
- view sequence and alignment must be carefully assessed in order to guarantee the best global process accuracy performance;
- the object to be acquired must be localized and referred to the robot coordinate system since it is usually simply placed on a working plane by operators;
- acquisition strategy based on reflective markers may be employed for aligning view when the Iterative Closest Point (ICP) algorithm fails (for instance surfaces with scarce curvature). Such alignment is usually known as Reference Point Matching (RPM).

After a brief review of the state of art on inspection planning approaches, the paper investigates acquisition strategies based on view planning methods in order to take into account the cited aspects. Algorithms are proposed to automatically plan and refine views on the basis of typical mechanical inspection targets. The elaborated solutions have been implemented in a software system which can provide data for piloting a robotic inspection cell. Examples from automotive fields are reported to show functionalities and performance.

2 RELATED WORK

CAD-based tolerance inspection has been extended from Coordinate Measuring Machine (CMM) [5] to 6 DOF (Degree Of Freedom) robotic arms coupled with 3D optical scanners. A comprehensive literature review of methodologies, techniques, metrological issues and systems can be found in [6-8]. Through the use of optical 3D digitizing systems it is possible to inspect complex shapes in a short time. One of the main critical stages is how to determine the sensor position in order to achieve the best measurement accuracy adopting a small number of views. The challenge of automatic viewpoint determination has been widely studied in robotics, computer vision and photogrammetry. Proposed methods can be classified in two main categories: model-based methods (or based on *Known* objects) and non-model based methods (or based on *Unknown* objects).

From the very beginning, most view planning methods were non-model based and were formulated as the search of the Next Best View (NBV) given previous scans of the object [9]. They have been carried out by many researchers and examples are reported in [10-13]. Non model-based method applications range from robotic environment exploration [14-15] to large indoor-outdoor sites [16] and cultural heritage artifacts acquisition and reconstruction [17].

However, given the focus of this paper on the inspection process of mechanical products, the 3D CAD model is certainly available and can be used for automating the determination of sensor localizations.

Tarbox et al [18] proposed three algorithms to plan poses on a fixed sphere cantered on the object. Trucco et al. [19], Cowan and Kovesi [20], Xi and Shu [21] proposed similar approaches based on the satisfaction of sensor pose requirements. Sometimes, an initial off-line phase is followed by an on-line poses refinement to augment the coverage ratio.

Prieto et al. [22] show a more robust framework which takes in account the inspection automation starting from the CAD model. More recently another model-based method application in the industrial context has been reported in [23]. A volumetric model implemented through a 3D voxel map is generated from the object CAD model and used to define a sensing plan composed of a set of viewpoints and the respective scanning trajectories. Ellenrieder and Komoto [24] determine the necessary number of camera positions given a certain inspection task and an objective function to be minimized. In [25] an automatic 3D digitizing system for inspection purposes is reported. Using an approach based on the Minkovsky operations to calculate the visibility of the different faces of the part B-Rep model, the minimum set of directions required to entirely digitize the part is computed. Finally, Shi et al. [2] use a two-stage approach. Firstly, off-line planning is performed, then on line feedback of scanning process is analyzed. Areas not acquired during the first phase due to reflection and shadows drive the second acquisition.

The wide range of applications, the variety of object features being inspected and the differences among numerous contact and non contact sensors and positioning systems, make it hard to identify which approach overcomes the view planning problem better. The main outcome of the state of the art analysis is the necessity to develop specific applications in context. In particular, the mechanical field requires an analysis of the inspection tasks, a classification of products in homogeneous families and optimized algorithms on the inspection target.

3 3D VIEWS PLANNING ALGORITHMS IN THE MECHANICAL FIELD

The inspection process is divided into an off-line stage carried out in the design department and an on-line one performed on the production shop floor. Figure 1 shows a generalization of such process, highlighting the several aspects to be taken into account. The main steps are composed of: the localization of the toleranced 3D CAD model in a reproducible coordinate system; the generation of a set of acquisition poses using alternative algorithms; the viewpoint sets simulation and coverage ratio assessment; the iterative generation of additional poses; the computation of an optimized pose path. The depicted process can be subsequently repeated changing object orientation. Simulation results are merged with the previous cycles in order to come to an overall assessment.

The flowchart in figure 1 shows a very general approach which needs to be focused on specific application domains. In particular, this paper targets the Views Planning phase. The analysis of typical mechanical inspection procedures has revealed five classes of tasks, which lead to different choices for the view planning algorithms to be employed.

In a previous work inspected objects were only divided into two main categories [26]. The first one contains those whose volume is roughly contained in the scanner field of view. In this case the sensor approximately moves on a spherical surface cantered in the object. The second class contains objects whose extension is wider than the scanning volume. Rather than moving around the part, the scanner follows its shape and covers the surface in the same way as if it were painting. This strategy is generally referred to as *Sweep Positioning (SP)*.

The extended classification of inspection tasks which is here proposed includes (see figure 2):

a) Standard GD&T inspection (planarity, parallelism, perpendicularity, …): the focus is on target faces (usually planes, cylinders, cones, …) which represent tolerance entities or datums. They require complete coverage in order to correctly assess the tolerance prescription, for instance the complete inclusion of the acquired points in a virtual volume;

b) Trims and cutouts in sheet metal parts: the aim is to evaluate trim border profiles. Pose direction must be determined as perfectly aligned to surface mean normal. This allows reaching higher quality results by the combination of 3D acquisition with border detection algorithms from the 2D camera image;

c) Large multi-face surfaces, such as large object portions characterized by scarce curvature and many NURBS patches. Examples are represented by aesthetic surfaces such as car or boat silhouettes. The aim is the analysis of the global curvature trend of the surface, its appearance and how it reflects the light;

d) Global shape recovery for assessing plastic deformations caused by thermal effects or shrinkage. Typical examples include metal casted parts, sheet metal parts, plastic components.

e) Necessity of assessing specific target points in order to verify their localization. Applications refer to the assemblability of parts, i.e. coincidence of fixing points or alignment of adjacent profiles.

3.1 View Planning Approach

Figure 3 reports a flowchart highlighting the six sub-steps adopted to compute acquisition viewpoints on the basis of the input geometry and the required inspection task.

The method is based on the initial definition of a cloud of sampled points used for driving the poses computation process. Specific sampling rules have been defined according to the typology of inspection task to be accomplished. The choice of basing view planning on a set of sampled points is motivated by:

- A harmonization of the approach among the set of possible inspection tasks described above;
- The possibility of computing global surfaces' visibility properties, i.e. optical accessibility, from the combination of those of the discrete sampled points.

The classes of the identified mechanical inspection tasks lead to variants in the point sampling strategy and view planning algorithm, as shown by the Table 1.

Point sampling rules include surface, global and border sampling or direct input by the user in case should specific points be measured. From the pose computing point of view, three approaches are defined: the normal positioning, the sweep positioning and the iterative pose adding. The selected inspection task drives the choice for these options accordingly to table 1 and the geometric characteristics of the object to be acquired.

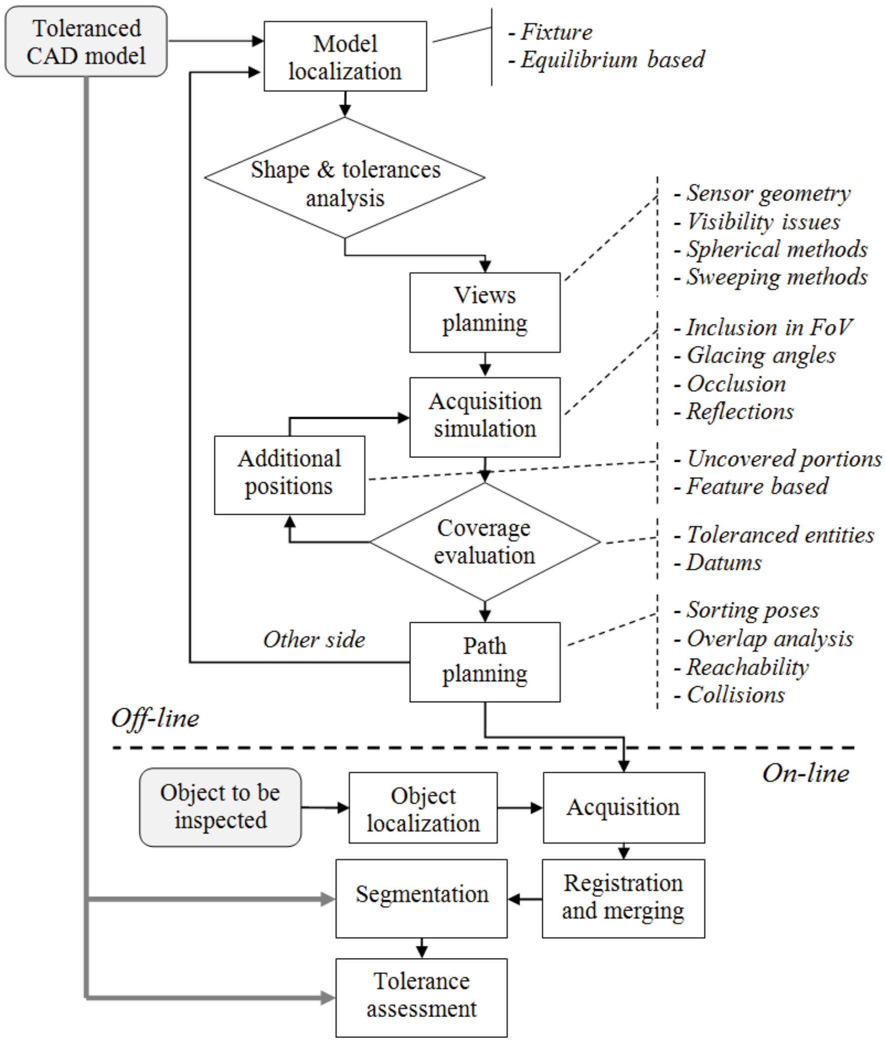


Fig. 1: General steps of inspection process by optical systems for industrial applications.

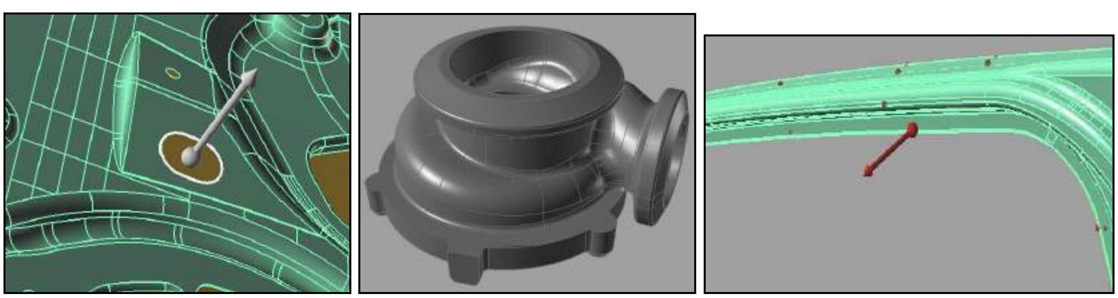


Fig. 2: Examples of inspection tasks: sheet metal cutout border acquisition (left, task of type b), global shape inspection (in the middle, task of type d), and specific target point assessment marked with red dot and arrow (on the right, task of type e).

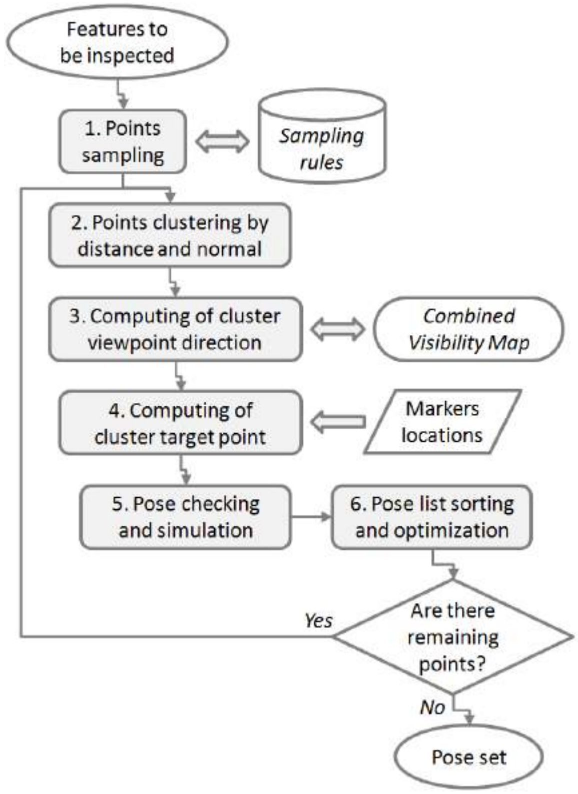


Fig. 3: Flow chart of main steps of pose set elaboration.

Iterative pose adding refers to the algorithm which searches for uncovered points and adds poses to maximize the ratio of acquired points. On the contrary, sweep positioning is used when the sampled points cloud extension at least doubles the field of view of the scanner. In this case the face parameterization or the parameterization of an interpolated patch is used to subdivide the cloud in acquirable portions.

Inspection task	*Points sampling rule*	*Pose computing approach*	*Industrial example*
a) GD&T	Surface sampling	Iterative pose adding Sweep positioning if the object is wider than the scanner field of view	Face parallelism of a milled part
b) Trims	Border sampling	Normal positioning	Slot in a sheet metal part
c) Large multi-faces surfaces	Surface sampling	Sweep positioning on an interpolated patch	Car door external surface
d) Global coverage	Global sampling	Iterative pose adding	Cast pump body
e) Specific target points	User defined points	Iterative pose adding	Plastic cover with clips

Tab. 1: Classes of inspection tasks and approach for points sampling and pose computing.

3.2 Model Geometry Representation

CAD geometry is generally formulated as a Boundary Representation (B-Rep) of NURBS faces. In the proposed view planning methods, object bodies are exploded in boundary faces, which are taken as the basic geometric unit used for views computation. The model must guarantee that the faces are consistently positively oriented to the actual external side of the object.

The choice of NURBS representation is motivated by the fact that standard mechanical prescriptions target faces. Additionally, they can be marked as normal, priority or fixture. Normal and priority express two different levels of importance for the surfaces to be scanned. Priority is given to toleranced faces or datums. The distinction avoids useless efforts in acquiring non significant details. Fixture surfaces are also taken into account for occlusions. They include the scanning plane where the object is laid and any equipment necessary to hold it.

A triangulated mesh of each face is computed and used in the pose simulation step. Cordal tolerance is balanced to avoid too numerous triangles but to preserve geometry details. Each mesh facet represents the discrete unit for the computation of the face visibility. In the online phase, a volumetric voxel model is used to assess collisions between model, sensor and other parts of the robotic cell.

3.3 Point Sampling and Point Clustering

The first step of the approach is the *Point sampling*. This phase varies accordingly to the chosen approach options.

In the case of *user defined samples* the input is given by the user and corresponds to specific points to be examined. For the *Border sampling*, an edge is sampled under a certain cordal tolerance and a maximum subdivision step. On the contrary, surface and global sampling refer to point clouds respectively drawn from the geometry of a specific surface or the whole boundary of the model.

In case of *Surface Sampling*, at first a face is subdivided into portions which are contained in the scanner field of view and whose variation of the normal directions does not exceed an angular limit. Portions are generated in order to allow a suitable overlapping area between adjacent patches. To this aim, the surface is analyzed and split along isocurves. For each subdivision, samples are chosen as surface Greville points which are contained in non-trimmed portions (Fig.4).

This procedure is based on the consideration that control vertices basically determine shape and differential properties of a NURBS surface. The more a face is shaped, the more numerous control vertices will be. In case of very simple geometries like cylinders or planes, the low number of samples is increased to a minimum amount. Six-eight samples for each of the two parameters have been experimented as sufficient while a normal angular variation has been fixed at 90°.

In the case of *Global Sampling* option, the previous approach may lead to an excessive number of points. Starting from the set given by the sampled points of the faces, decimation is accomplished considering both points distance and normal orientation. This leads to a reduced curvature based point cloud.

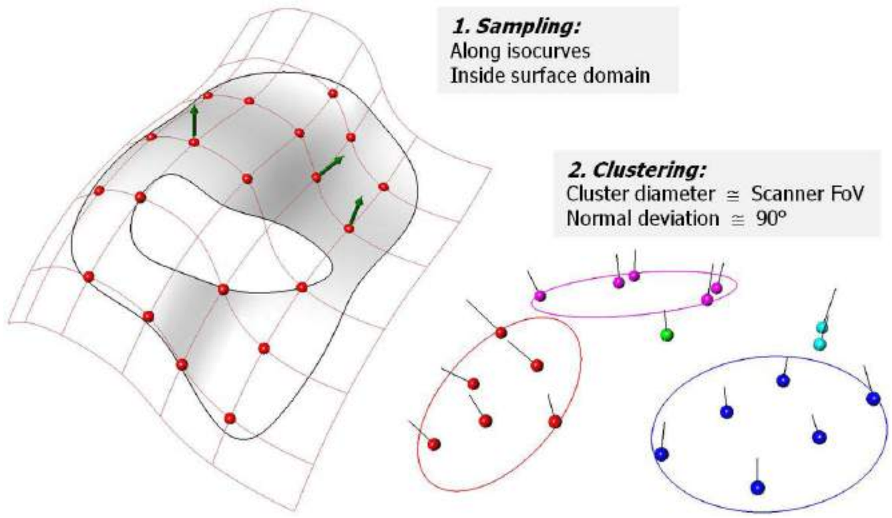


Fig. 4: Surface sampling is accomplished along surface isocurves and inside non-trimmed portions. Samples are then clustered by distance and normal orientation.

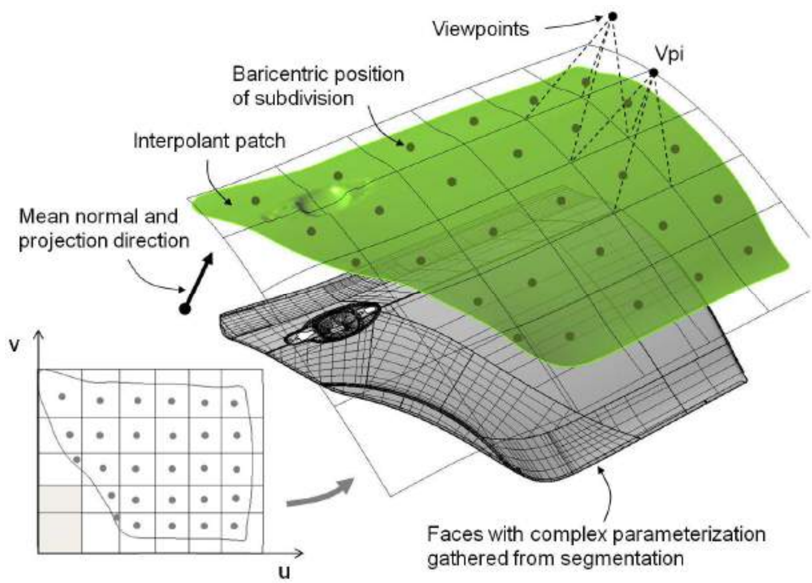


Fig. 5: Sweeping strategy: a NURBS patch is interpolated to the object faces in order to drive acquisition along its simplified parameterization (inspection task of type c).

Finally, when the object extension is much wider than the scanning volume, surfaces must be treated as a whole, since no feasible path can be drawn considering each face a time (large multi-faces surfaces, Fig.5). Object surface is firstly segmented in face subsets which contain homogeneous normal orientation under a certain angular tolerance. A NURBS interpolating patch is then projected to the faces along the clustering direction. Angular tolerance should be less than 90 degrees, so faces do not overlap during projection. The interpolating patch is defined with a sufficiently dense control vertices number. Interpolation is obtained projecting CVs to the face cluster. The patch is then trimmed eliminating unused external and internal portions. This process leads to a smooth surface which is suitable to drive scanner sweeping as in the Surface Sampling rule.

As the second step of the process, obtained sampled points are clustered. Relative distances among points and the orientations of the surface normals are used to obtain clusters which are likely to be acquired from a single point of view. Two conditions have been fixed: the maximum distance between two points of the same cluster must be less than the scanner field of view, and the maximum angle between the normals must not be higher than 90°. Clusters are then refined using the *k-means* algorithm.

3.4 Pose Computation

View computation moves from sampled point clusters. The computation starts from the cluster with the highest number of points.

In its most trivial form, a viewpoint is drawn from a cluster mean point P*m* and a cluster mean normal N*m*:

$$P_m = \sum_{i=1}^{S} P_i \;\; ; \;\; N_m = \sum_{i=1}^{S} N_i \tag{1}$$

where *Pi* is the *i*-th sampled point, *Ni* surface normal at *Pi* and *S* the number of cluster points. The scanner position is the point along *Nm* at focal distance from *Pm*. Such pose computation option is used only in the *Normal Positioning* to guarantee perfect alignment between the camera plane and the surface.

In the other cases, experience shows that by using optical scanners, 30-50° tilted positions are preferred. This allows a good quality on the read coordinates to be maintained and information from adjacent faces to be added in order to correctly perform ICP alignment.

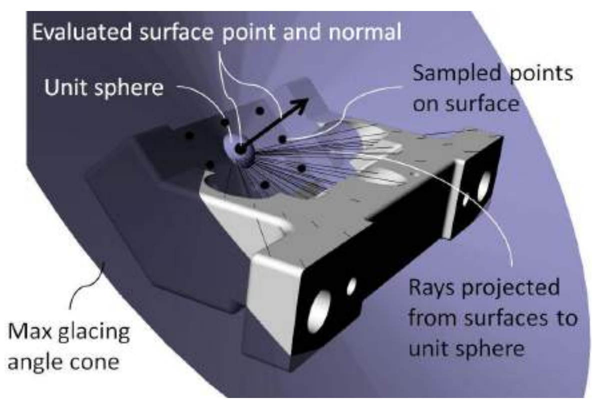


Fig. 6: Determination of the Visibility Map. For a generic point, occlusion produced by other surfaces is evaluated in the cone corresponding to the max glacing angle.

The Visibility Map (VM) is then used to determine tilted occlusion-free directions [1]. VM is calculated for each cluster point by projecting the inspected faces onto a unit sphere cantered at the point (Fig.6). The unit sphere is then sampled at constant azimuth / elevation intervals (5°) and the

Boolean information whether something has been projected onto the sphere or not is transcribed into a matrix which forms the VM itself. The great advantage of the VM is that it only needs to be calculated once and then the availability of scan directions for a certain point is stored in terms of azimuth / elevation pairs.

VM computation is efficiently performed on GPU using the standard graphic library OpenGL. The viewing camera is repeatedly located in the points of the cluster and pointed as the normal to the surface. The scene is drawn, and the depth buffer coordinates are read and transformed in a global absolute spherical coordinates system. The VMs obtained for the points of the cluster are overlapped producing a grey level image, namely the Combined Visibility Map (CVM). Each pixel encodes the number of sampled points which are visible for the selected azimuth/elevation pair. Such procedure is based on the assumption that the distance of a certain viewpoint is sufficiently larger than the scanned surface dimensions [24].

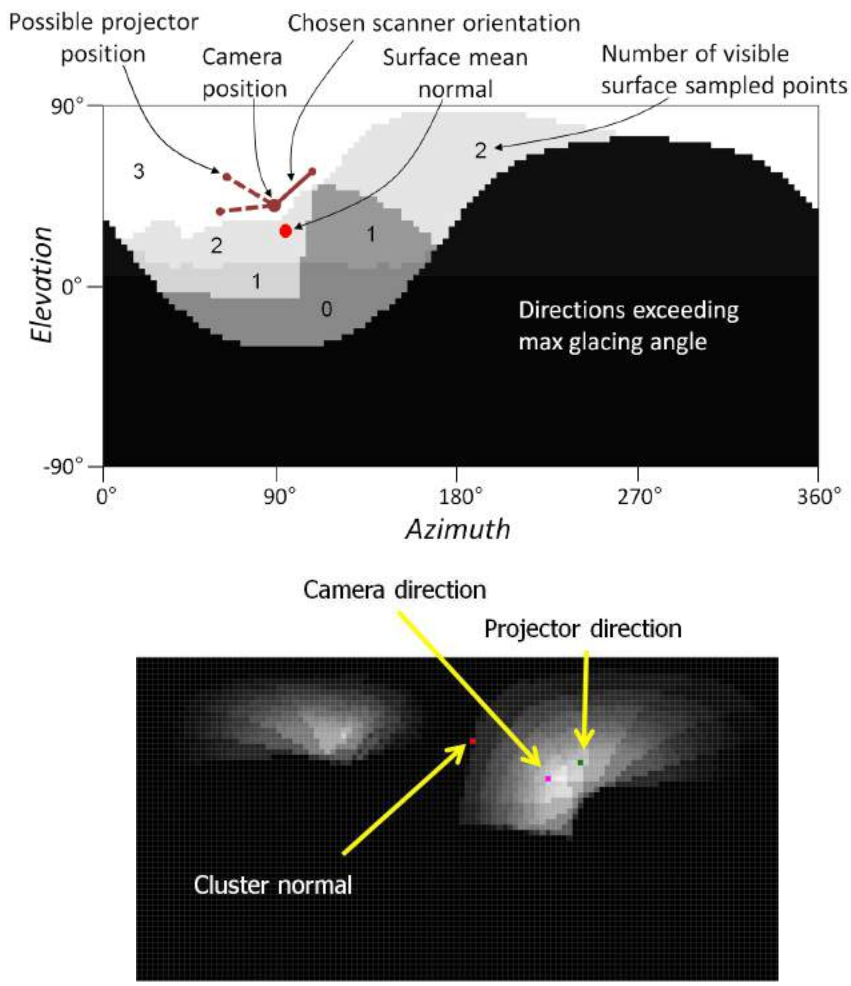


Fig. 7: Examples of Combined Visibility Map obtained from the intersection of tree fictitious points (upper) and a real one (lower). The red dot represents the mean surface normal while the different tones of gray show the regions with different levels of occlusion. Scanner orientation is searched in the most white area.

Scanner pointing direction is searched in the CVM portions with higher numbers of visible points in order to maximize cluster coverage (Fig.7). The optimal pointing direction is chosen as the one minimizing the angular distance from the cluster mean normal Nm. A second point for the projector location is searched at a fixed angular distance determined by the sensor hardware, i.e. the angle between the projector and the camera axes. Among the possibilities, the one forming the smaller absolute angle with the horizontal one is preferred.

To determine actual scanner position a target point is finally needed. Pm is the initial choice that is then improved by considering other points or markers which are sufficiently close to it. Markers and sampled points that have normals compatible with the viewing direction are firstly selected. Then, they are ordered by distance. In the case original point cloud extension is smaller than the scanner field of view, the target point is translated in order to include additional points or markers. Such displacement is guaranteed not to cause the original cluster points to fall outside the scanner field of view.

At the end, computed pose validity is preliminary checked against possible collisions and spatial reachability.

3.5 Pose Simulation and Path Elaboration

The simulation algorithm works on the triangulated mesh, which approximates the NURBS surfaces to be digitized. The simulation is a sub set of such facets, which fulfill the following well-known conditions [1-3]: inclusion in the sensor field of view, value of camera glacing angle, value of projector glacing angle, visibility from the camera, visibility from the projector, absence of laser or projected pattern reflections towards the camera. Significant performance in computing is reached taking advantage of the Graphics Processing Unit (GPU) of 3D computer cards. In particular, the GPU Depth-Buffer is useful again to quickly detect occluded areas.

Simulation aims to verify the possibility to actually digitalize the whole point cluster from the computed viewpoint. In fact the view planning algorithms do not deterministically guarantee the complete points coverage due to the number of assumptions and tuning parameters which have been introduced. For this reason view planning is iterative, and at each step the process moves from the remaining uncovered points. Remaining uncovered points are merged with the initial excluded set, clustered again, and the iteration goes on. The process is repeated until it is not possible to add more poses.

A termination condition is also introduced to prevent infinite iterations. If a point fails more than three times in generating a pose, it is excluded from clustering. A point fails if it belongs to a cluster that cannot produce a valid pose or if the point cannot be acquired from the calculated pose.

Poses are sorted on the basis of the marginal number of points which are covered in addition to the ones in a higher position on the list. A pose at the end of such list is discarded if it does not add any new covered point. For any iteration this operation is repeated. The list of poses is continuously optimized as more efficient poses are added and useless ones removed.

Path elaboration finally targets the correctness of the registration process as a valid sequence of the obtained poses. In the case of using reflective markers, their identification leads to straightforward alignment in a global reference system by RPM. Otherwise, it is necessary to analyze couples of adjacent simulated point clouds in order to assess if the ICP method can be performed. Two aspects are assessed: the extension of overlap area and the quality of the overlap in terms of the absence of directions with low curvature which could cause sliding and incorrect position during alignment [3]. Finally, starting from RPM alignable poses, the shortest path connecting 3D viewpoints is determined using the Dijkstra algorithm.

4 TOLERANCE INSPECTION SYSTEM

The proposed tolerance inspection system is based on the architecture which has been illustrated in other papers [3, 28]. It is divided into an off-line software system for view planning and simulation and an on-line system composed of the scanner, the robot, a rotary table, the robot controller and a software application (Fig 8).

A software system has been developed to test the proposed approach and algorithms for view planning. The off-line inspection application has been developed as a Plug-In of a commercial 3D CAD system, Rhinoceros 4.0 (by McNeel Inc.). The application has been written using Microsoft VisualBasic.NET language and libraries such as Rhinoceros SDK, OpenNURBS and OpenGL.

Two test cases are here briefly reported. The first one concerns a standard tolerance control for a die cast part (Fig.9). Poses are generated from toleranced faces through the surface sampling method and iterative pose adding. Off line planning is accomplished on possible standing orientations which are virtually found from the local minima of the z coordinate of the object centre of mass (CoM) computed from the CAD model.

The die cast part example has allowed view planning algorithm to be analysed in case of GD&T inspection tasks. Shape (cylindricity), orientation (parallelism, perpendicularity) and localization tolerances have being prescribed to the model.

The software initially elaborates 8 poses which are necessary to cover faces that are the target of tolerances or datum. Such poses were too far from each other and do not form a unique scanning path. Then two additional poses (pose number 2 and 9 in fig. 9) have been manually added in order to bridge distant poses. The simulation of the acquisition and then matching process has virtually confirmed that the elaborated sequence allow the ICP algorithm to work properly.

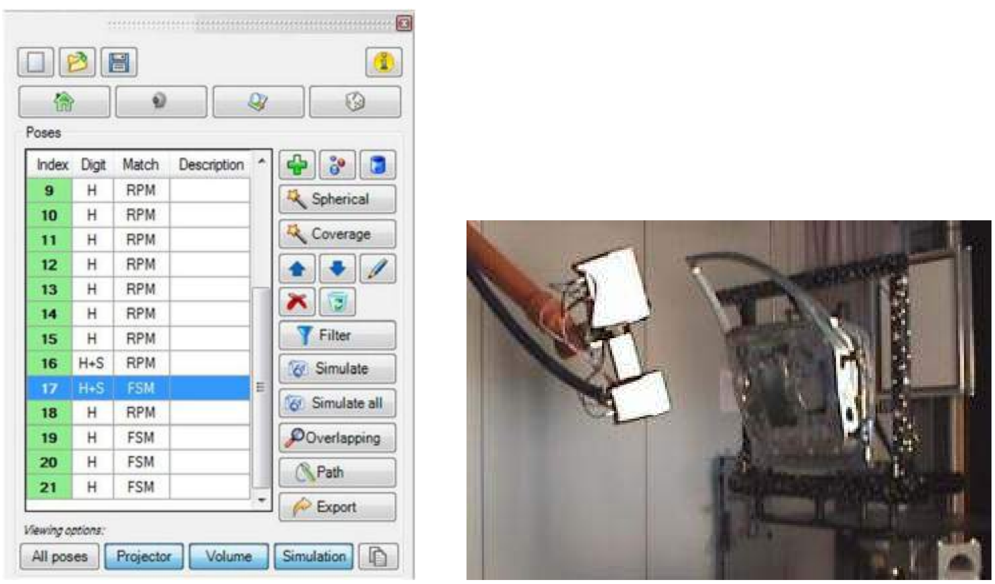


Fig. 8: On the left, off-line inspection application user interface. The list of elaborated poses and available functionality are shown. On the right, example of robotic cell used to test the system: Kuka robot, Steinbichler COMET V optical scanner, a rotary table and frame with markers (courtesy of Steinbichler Optotechnik GmbH).

This application example was then physically tested by using a laser scanner (Minolta Range 7) mounted on a robot arm. Inspection poses have been reproduced by the on-line software module thanks to robot head localization matrices exported by the off-line software system.

The 10 point clouds gathered by the scanning process have been successfully aligned using a standard reverse engineering software (RapidForm by Inus Technology) confirming the simulated results.

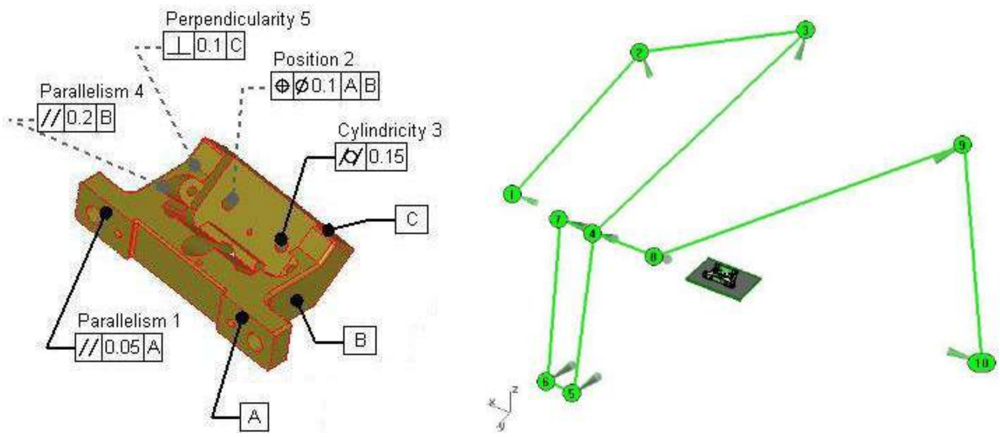


Fig. 9: On the left side tolerance prescription on a die cast component. Target surface and datum will be identified as priorities. On the right the elaborated viewpoints path.

The second case refers to automotive sheet metal parts (doors and hoods) to be inspected to verify the location of points of interest (Fig.10). Such points are introduced in the system by coordinates provided in a specific control document coming from the quality department. The application has been validated on several test cases. Three of them are reported in table 2. In this case, the aim of the experimentation was to assess the robustness of position planning algorithms and the efficiency of the whole application.

Such test cases have been more challenging due to the modelsÕ dimension and complexity (5 to 7 thousand surfaces). Due to the complexity of the shapes, tolerance prescriptions are mostly represented by specific control point localizations used to evaluate profiles correctness. Planarity and parallelism are just limited to hinge surfaces.

Table 2 shows that physical limitations do not allow a full coverage of such points to be reached. Experimentation with a physical setup has confirmed the virtual analysis. The main reason is represented by occlusions caused by the marker frame which is needed to align views. In fact ICP alignment is not applicable due to the extension of the product compared to the scanner field of view. However, point coverage can be improved by a careful design of the frame. The possibility of virtually test acquisition results dramatically shorten the time to come to an optimal solution.

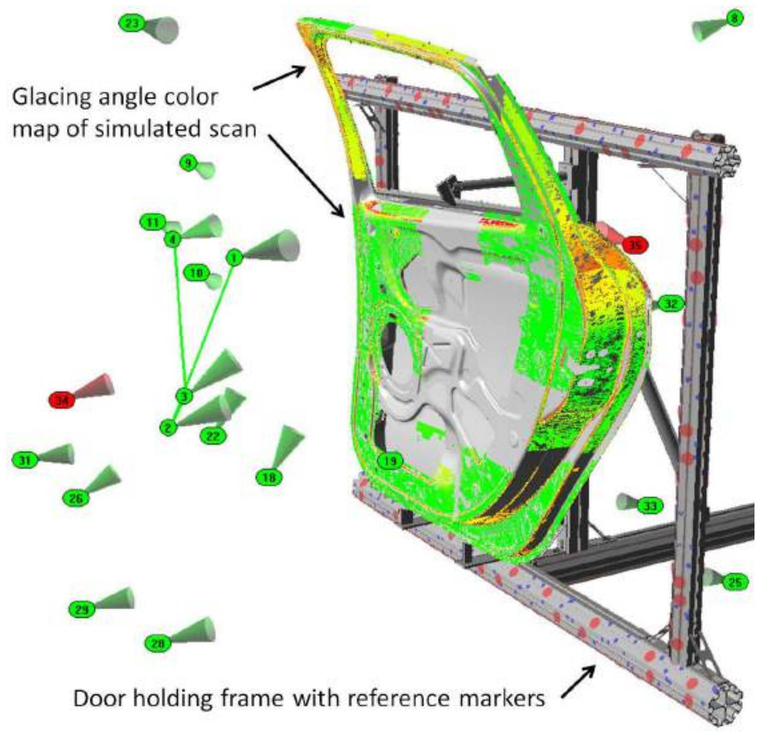
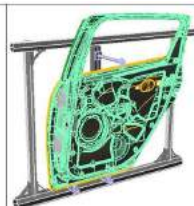
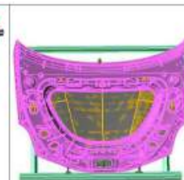
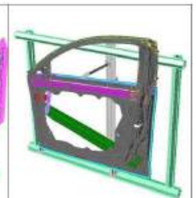


Fig. 10: Rear car door test case. Views are aligned thanks to frame with markers. Poses 1, 2, 3 and 4 align through ICP. Non-alignable poses are shown by red cones. The colours of the simulated acquisitions represent the glacing angles.

	 REAR DOOR	 HOOD	 FRONT DOOR
Model faces	6111	6057	5683
Fixture faces	306	306	306
Control points	107	44	59
Acquired control points	98 (91.6%)	33 (75%)	37 (62.7%)
Computed views	32	19	17
Alignable views	93.7%	79%	82.3%

Tab. 2: Results obtained by using of the iterative pose adding algorithm. Thanks to manual intervention performance can be further increased.

5 CONCLUSIONS AND FUTURE OUTLOOKS

This paper is situated in the context of industrial inspection applications based on an offline planning phase followed by a robotic autonomous on-line inspection system. In particular it focuses on algorithms for planning the 3D views acquisition on the basis of tolerance attributed NURBS representation taking into consideration the specificity of mechanical parts.

The proposed approach bases view planning on sampled point clusters. Cluster forming rules are determined accordingly to the typology of inspection process to be accomplished: GD&T, cutout, global coverage, large multi-face surfaces, specific target points. An iterative procedure has been elaborated to come to an optimized list of view. Finally, simulation algorithms allow an investigation of the acquisition coverage and the feasibility of scans alignment.

The experimentation of the approach has permitted object localization issues to be targeted, both in the case of using reference markers and free matching strategy. The capability of producing a valid set of poses has been investigated for automotive sheet metal parts.

Both implementing and testing activities on real cases have revealed some critical aspects. The first regards the choice of many parameters which are required by the proposed algorithms. This refers to distance and angular thresholds which can be enhanced by experimenting on a large set of test cases. The second regards the assessment of the system robustness compared to other existing model based view planning approaches. The variety of possible geometrical shapes requires an extended testing campaign on some fixed products and different view planning algorithms.

The third strictly refers to the inspection application. The elaborated method and implemented prototypal tool has shown that it is possible to plan views and simulate acquisition cell behavior. However, the quality of simulation must be systematically assessed towards real data. More importantly, the whole process accuracy must be analyzed from a metrological point of view. In fact, many sources of errors can affect the final results: the scanner intrinsic accuracy, view alignment errors, errors in deviations measured by inspection software and, finally, incorrect GD&T standards interpretation in the virtual measurement procedures.

REFERENCES

[1] Stößel, D.; Hanheide, M.; Sagerer, G.; Krüger, L.; Ellenrieder, M.: Feature and Viewpoint Selection for Industrial Car Assembly, Springer Lecture Notes on Computer Science 3175 ð Proceedings of 26th DAGM Symposium, 2004, 528ð535.

[2] Shi, Q.; Xi, N.; Spagnuolo, C.: A Feedback Design to a CAD-Guided Area Sensor Planning System for Automated 3D Shape Inspection, Computer-Aided Design & Applications, 4(1-4), 2007, 209-218.

[3] Germani, M.; Mengoni, M.; Raffaeli, R.: Automation of 3D View Acquisition for Geometric Tolerances Verification, Proceedings of the 2009 3-D Digital Imaging and Modeling Workshop, 2009, Kyoto (Japan). DOI:10.1109/ICCVW.2009.5457489

[4] Geometric Dimensioning and Tolerances GD&T standards, ASME Y14.5, 2009.

[5] Lin, Y.J.; Mahabaleshwarkar, R.; Massina, E.: CAD-based CMM dimensional inspection path planning ð a generic algorithm, Robotica, 19(2), 2001, 137-148. DOI:10.1017/S0263574700003076

[6] Li, Y.; Gu, P.: Free-form surface inspection techniques state of the art review, Computer Aided Design, 36(13), 2004, 1395-1417. DOI:10.1016/j.cad.2004.02.009

[7] Li, Y., Gu, P.: Automatic localization and comparison for free-form surface inspection, Journal of Manufacturing Systems, 25(4), 2006, 251-268. DOI:10.1016/S0278-6125(08)00007-1

[8] Gao, J.; Gindy, N.; Chen, X.: An automated GD&T inspection system based on non-contact 3D digitization, International Journal of Production Research, 44(1), 2006, 117-134. DOI:10.1080/09638280500219737

[9] Connolly, C.I.: The determination of Next Best Views, Proceedings of IEEE International Conference on Robotics and Automation, 1985, 432-435. DOI:10.1109/ROBOT.1985.1087372

[10] Banta, J.; Wong, L.; Dumont, C.; Abidi, M.: A Next-Best-View system for autonomous 3-D object reconstruction, IEEE Transactions on Systems, Man and Cybernetics, 3(5), 2000, 589-598. DOI:10.1109/3468.867866

[11] Scott, W.R.; Roth, G.; Rivest J-F: View planning for automated three-dimensional object reconstruction and inspection, ACM Computing Surveys (CSUR), 35(1), 2005, 64ð96. DOI:10.1145/641865.641868

[12] Impoco, G.; Cignoni, P.; Scopigno, R.: A six-degrees-of-freedom planning algorithm for the acquisition of complex surfaces, International Journal of Shape Modeling, 2005. DOI:10.1142/S0218654305000700

[13] Charyar, M.S.; Thiebaut, F.; Lartigue, C.: Scan planning strategy for a general digitized surface, Journal of Comput. Inf. Sci. Eng., 6(4), 2006, 331-340.

[14] Scott, W. R.; Roth, G.; Rivest, J-F.: View planning with a registration constraint, Proceedings of Third International Conference on 3-D Digital Imaging and Modeling, 2001, 127-134. DOI:10.1109/IM.2001.924419

[15] Torabi, L.; Kazemi, M.; Gupta, K.: Configuration space based Efficient View Planning and Exploration with Occupancy Grids, Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007. DOI:10.1109/IROS.2007.4399451

[16] Blaer, P.S.; Allen, P.K.: Data acquisition and view planning for 3-D modeling tasks, International Conference on Intelligent Robots and Systems, 2007, 417-422. DOI:10.1109/IROS.2007.4399581

[17] Loriot, B.; Seulin, R.; Gorria, P.: Non-model based method for an automation of 3D acquisition and post-processing, Electronic Letters on Computer Vision and Image Analysis, 7(3), 2008, 67-82.

[18] Tarbox, G. H.; Gottschlich, S. N.: Planning for complete sensor coverage in inspection, Computer Vision and Image Understanding, 61(1), 1995, 84-111. DOI:10.1006/cviu.1995.1007

[19] Trucco, E.; Umasuthan, M.; Wallace, A.M.; Roberto, A.M.: Model-based planning of optimal sensor placements for inspection, IEEE Trans. on RA, 13(2), 1997, 182-194. DOI:10.1109/70.563641

[20] Cowan, C.K.; Kovesi, P.D.: Automatic sensor placement from vision task requirements, IEEE Trans. PAMI, 10(3), 1998, 407-416. DOI:10.1109/34.3905

[21] Xi, F.; Shu, C.: CAD-based path planning for 3-D line laser scanning, Computer Aided Design, 31, 1999, 474-479.

[22] Prieto, F.; Lepage, R.; Boulanger, P.; Redarce, T.: A CAD-based 3D data acquisition strategy for inspection, Machine Vision and Applications, 15, 2003, 76ð91. DOI:10.1007/s00138-003-0131-4

[23] Rodrigues Martins, F.A.; Garcia-Bermejo, J.G.; Zalama Casanova, E.; Peran Gonzales, J.R.: Automated 3D surface scanning based on CAD model, Mechatronics, 15(7), 2005, 837-857. DOI:10.1016/j.mechatronics.2005.01.004

[24] Ellenrieder, M. M.; Komoto, H.: Model-based automatic calculation and evaluation of camera positions for industrial machine vision, Proceedings of SPIE the international society for optical engineering, 5674(48), 2005, 467-478. DOI:10.1117/12.585427

[25] Derigent, W.; Chapotot, E.; Ris, G.; Remy, S.; Bernard, A.: 3D digitizing strategy planning approach based on a CAD model, Journal of Comput. Inf. Sci. Eng., 7(1), 2007, 10-20. DOI:10.1115/1.2410023

[26] Germani, M.; Mandorli, F.; Mengoni, M.; Raffaeli, R.: CAD-based environment to bridge the gap between product design and tolerance control, Precision Engineering, 34, 2010, 7-15. DOI:10.1016/j.precisioneng.2008.10.002