Computation of optimal acquisition viewpoints for the 3D optical inspection of mechanical components

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1 Introduction

In the mechanical field, companies are asked to manufacture components with specific constraints in terms of shape and dimensions requirements. Geometrical Dimensioning and Tolerances (GD&T) [1] regulate the acceptable errors that can be made during the manufacturing process. They affect functions, assemblability and cost of a product. Decisions about tolerances are mostly made by product designers that usually not are experts in manufacturing and control. In [2] a method is proposed for providing designers with effective tools in order to simulate the whole verification process. Such approach finds an interesting application in the emerging field of automatic parts inspection by optical digitizers mounted on articulated robot arms.

Nowadays, 3D optical shape acquisition systems, laser scanners and fringe projection-based, have evolved in terms of accuracy, resolution and measurement time and they can be successfully applied in quality control. Many classes of mechanical components are compatible with the achievable accuracy. It refers to foundry casted components, injection moulded plastics, bent sheet metals. In these cases, geometry usually varies much more than scanner accuracy due to shrinkage, spring back or die imperfections. In [3] and [4] system architectures are proposed for industry shop floor application. In these cases a first off-line software module allows identifying tolerance prescription and geometries from the 3D CAD product model. Then, acquisition poses are elaborated and sensor path optimized. Control cell behaviour 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 peculiar aspects:
- 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... and require specific acquisition rules in order to assess assigned dimensional and geometrical tolerances;
- tolerated surfaces and datums (see terminology in [1]) 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 views alignment; view sequence and alignment must be carefully assessed in order to guarantee the best global process accuracy performance; 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).

In this context, after a brief review of the state of the art on inspection planning approaches, the paper investigates new acquisition strategies based on view planning methods in order to take into account the cited aspects. Algorithms are proposed in order to automatically plan and refine views on the basis of typical mechanical shapes and tolerances prescriptions. The elaborated solutions have been implemented in a software system that 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 [6-9]. 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 by 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).

Most view planning methods are non-model based and are formulated as the search of the Next Best View (NBV) given previous scans of the object [10]. They have been carried out by many researchers and examples are reported in [11-15]. Non model-based methods applications range from robotic environment exploration [16-17] to large indoor-outdoor sites [18] and cultural heritage artefacts acquisition and reconstruction [19]. However, since the focus of this paper is on the tolerance inspection process of mechanical products, the 3D CAD model is given and can be used for automating the determination of sensor localizations.

From the very beginning, Tarbox et al. [20] propose three algorithms to plan poses on a fixed sphere centered on the object. Trucco et al. [21], Cowan and Kovesi [22], Xi and Shu [23] propose 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. [24] show a more robust framework that takes into account the inspection automation starting from the CAD model. More recently another model-based method application in the industrial context is reported in [25]. 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 [26] determine the necessary number of camera position given a certain inspection task and object model. In [27] 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 Known objects, the minimum set of directions required to entirely digitize the part is computed. Finally, Shi et al. [3] use a two-stages approach. Firstly an 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 hard the identification of which approach better overcome view planning problem. The main outcome of the state of the art analysis is the necessity of developing application context specific approaches in order to optimize algorithms and result on the basis of the system goals.

3 3D views planning algorithms

In the proposed approach, the component inspection task is split in an off-line stage carried out in the design department and an on-line one performed in the production shop floor. Figure 1 shows the main steps of process, highlighting several aspects to be considered.

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

The input to the off-line stage is the tolerated (dimensions, shape, orientation) 3D CAD model of the part that is conveniently located in a reproducible coordinate system. Its shape, dimensions and GD&T attributes are analyzed [28] and generate a set of
acquisition poses. Data acquired from such viewpoints set is simulated. In particular, the coverage ratio, i.e. the ratio between the acquired portion area and the whole face area, is assessed for each tolerated face or datum. Then, if necessary, uncovered zones drive the definition of additional poses. Specific tolerance feature-based strategies are used to identify additional viewpoints. The process is iterated until the set of positions is satisfactory. A path, i.e. an ordered sequence of poses, is computed assessing robot head reachability, collisions and feasibility of registration/matching process in the desired sequence.

The depicted process can be subsequently repeated changing object orientation in order to view additional portions of interest. Simulation results are merged with the previous one in order to assess the whole object coverage. The set of paths for each side is the input to the on-line phase. Object to be inspected is laid on the inspection plane and located. Acquisitions are registered and merged thanks to robot head positioning matrix and ICP method. Also tolerated model is registered in the same coordinate system. The acquired cloud of points is segmented on the basis of the tolerated features to be checked. Each sub cloud is finally evaluated towards the respective nominal geometry (3D CAD model) in order to verify the prescribed tolerances.

3.1 Model geometry representation and physical localization

CAD geometry is likely to be a Boundary Representation (B-Rep) of NURBS faces [29]. In the proposed view planning approach, volumetric shells are exploded in distinct boundary faces, taken as the basic geometric unit used for views computation. Model must guarantee consistent face positive orientation with 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 differently marked as normal, priority or fixture. Normal and priority express two different levels of importance of scanned surfaces. Priority is usually given to tolerated faces or datums. The distinction avoids useless efforts in acquiring non significant details. Fixture surfaces are taken into account for occlusions and may include scanning plane where object is laid or any equipment to hold it. A triangulated mesh of each face is computed and used in the pose simulation step. Each mesh facet represents the unit for the computation of visibility properties. Finally, a volumetric voxel model is used to assess collisions between model and sensor.

3.2 View planning approach

Figure 1 outlines a general workflow that has emerged from previous works review. In particular, this paper focuses on the Views Planning phase. Figure 2 reports a flowchart highlighting the main sub-steps adopted to compute acquisition viewpoints on the basis of an input geometry and features to be inspected.

The proposed approach is based on six main steps that are here outlined.

At first, a cloud of sampled points is defined for driving poses computation. Specific sampling rules have been defined according to the typology of features being inspected. The choice of basing view planning on a set of sampled points is motivated by:

- An harmonization of the approach among the set of possible inspection tasks described hereafter;
- The possibility of computing global surfaces visibility properties from the combination of those of each sampled point.

Sampled clouds are clustered on the basis of relative points distance and surface normal orientations. This guarantees that obtained clusters are likely to be acquired from a single point of view.

![Flow chart of main steps of pose set elaboration.](image)

The cluster with the higher number of points provides input to compute a pose. Viewing direction and target point on inspected object are separately determined.

Computed pose validity is checked against possible collisions and spatial reachability.

Then, acquisition process is simulated to verify cluster points actual coverage. Remaining uncovered points are merged with the initial excluded set, clustered again and iteration goes on. The process is repeated until it is not possible to add more poses.

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

The analysis of typical mechanical inspection procedures has revealed several situations that lead to different choices for the algorithms employed for the steps being described. Table 1 provides an outlook on possible inputs, point sampling strategies and adopted pose planning algorithms.

In a previous work inspected objects are split in two main categories [28]. The first one contains those whose volume is roughly contained in the scanner field of view. In this case sensor approximately moves on a spherical
surface centered in the object. The second class contains objects whose extension is wider than scanning volume. Rather than moving around the part, the scanner follows its shape and covers the surface like painting. This strategy is referred as Sweep Positioning (SP).

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<th>Feature</th>
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Tab. 1 Possible inspected features and relative approach for points sampling and pose computing.

Due to the variety of possible mechanical inspection tasks, a wider classification has emerged and view planning algorithms must be chosen accordingly:

- **Standard GD&T inspection** (planarity, parallelism, perpendicularity,…): the focus is on target faces (usually planes, cylinders, cones…) that require complete coverage. Points sampling must cover the face and poses are generated iteratively to maximize coverage (see Fig 5 in the next section). In case of freeform shape control of large surfaces, SP is adopted;
- **Trims and cutouts in sheet metal parts**: the aim is the evaluation of the border profile (Fig.3). Pose direction is 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;
- **Large multi-faces surfaces**, refers to large object portions characterized by scarce curvature and many NURBS patches (see Fig 4 in the next section). In this case a SP strategy based on an interpolated surface is adopted;
- **Global coverage** is employed to maximize surface scanned area. Is based on a global shape sampling and in iterative pose adding;
- **Specific target points** are manually defined in order to verify their localization. They are clustered and poses iteratively added to maximize coverage (Fig.3).

![Fig. 3 Example of cutout border (left) and of specific target point (red arrow, on the right).](image)

In the following sections adopted algorithms are presented in more detail.

### 3.3 Sampled points clustering

Surface Sampling rule is composed of two steps. At first a face is subdivided in portions that are contained in the scanner field of view and whose normal directions variation is limited. Portions can be reduced in order to allow a suitable overlapping area between adjacent patches. To this aim, surface is analyzed and split along isocurves. Then, for each subdivision samples are chosen as surface Greville points that are contained in non-trimmed portions. Each subdivision provides a point cluster and then a possible viewpoint. This sampling rule is based on the consideration that control vertices basically determine shape and differential properties of NURBS. 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 normals variation is bound to approximately 90°.

In case of Global Sampling previous approach may lead to an excessive number of points. Starting from the set given by the sampled points for each face, decimation is accomplished considering both points distance and normal orientation. That leads to a curvature based adaptive sampling.

When objects extension is much wider than 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.4). Object surface is firstly segmented in faces subsets that contain homogeneous normals 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. 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 that is suitable to drive scanner sweeping as in Surface Sampling rule.
Fig. 4 Sweeping strategy: a NURBS patch is interpolated to the object faces in order to drive acquisition along its simplified parameterization.

3.4 Pose computation

Views computation moves from sampled point clusters. In its trivial form, it is drawn from a cluster mean point \( P_m \) and a cluster mean normal \( N_m \):

\[
P_m = \sum_{i=1}^{S} P_i \quad N_m = \sum_{i=1}^{S} N_i
\]  

(1)

where \( P_i \) is the i-th sampled point, \( N_i \) surface normal at \( P_i \) and \( S \) the number of cluster points. Scanner position is the point along \( N_m \) at focal distance from \( P_m \). Such approach is used only in the Normal Positioning to guarantee perfect alignment between camera plane and surface and combine 3D point cloud data with 2D edge detection output.

However, experience shows that by using optical scanners, 30-50° tilted position are preferred in order to maintain good quality on the read coordinates and add information from adjacent faces in order to correctly perform ICP alignment.

Visibility Map (VM) is then used to determine tilted occlusion-free directions [2]. VM is calculated for each cluster point by projecting the inspected faces onto a unit sphere centered at the point (Fig.5). The unit sphere is then sampled at constant azimuth / elevation intervals (5°) and the Boolean information whether something has been projected or not on the sphere is transcribed into a matrix which forms the VM itself. The great advantage of the VM is that it needs to be calculated only once and then the availability of scan directions for a certain point is stored in terms of azimuth / elevation couples.

VM computation is efficiently performed using graphic card. Viewing camera is located in the point of interest and pointed as the normal to the surface. Depth buffer coordinates are transformed in global spherical coordinates. For the entire point cluster, VM are overlapped producing a grey levels image referred as Combined Visibility Map (CVM). Each pixel contains the number of sampled points that are visible for the selected azimuth/elevation couple. Such procedure is based on the assumption that the distance of a certain viewpoint is sufficiently larger than surface dimensions [26].

Scanner optimal viewing direction is searched in the portions with higher ranking in order to maximize cluster coverage (Fig.6). Such point is chosen as the one minimizing the angular distance from the cluster mean normal \( N_m \). A second point for the projector location is searched at a fixed angular distance determined by sensor hardware. Among possibilities, the one forming the smaller absolute angle with the horizontal one is preferred. In this way camera and projector directions are determined maximizing visible surface portions and maintaining the best perpendicularity to the surface.

To determine actual scanner position a target point is finally needed. \( P_m \) is a valid choice that can be improved by considering other points or markers that are sufficiently close to it. Markers and sampled points that have normals compatible with the viewing direction are sorted out. Then, they are ordered by distance. In case original point cloud extension is smaller than scanner field of view, target point is translated in order to include additional points or markers. In any case such displacement should cause original cluster points to fall outside scanner field of view.
3.5 Pose simulation and path elaboration

The simulation algorithm works on the triangulated mesh, which approximates the NURBS surfaces to be digitised. Each facet must fulfill several [2-4]: inclusion in the sensor field of view, value of camera glancing angle, value of projector glancing 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 computers cards. In particular GPU Z-Buffer is useful to quickly detect occluded areas.

Simulation mainly supports the verification of the actual cluster points digitalization from a compute viewpoint. Due to previous assumptions, CVM and selected target point do not guarantee all cluster points coverage. For this reason view planning is iterative, and at each step process moves from uncovered points.

Poses are sorted on the basis of the number of points that are covered in addition to previously computed poses. If a pose at the end of such list does not add any new covered point is discarded. For any iteration this operation is repeated. Poses list is continuously optimised as more efficient poses are added and useless ones removed.

In order to correctly perform the registration process a valid sequence of the selected positions must be established. In case of using reflective markers, their identification leads to straightforward alignment in a global reference system by RPM. Otherwise, it is necessary to analyse couples of adjacent simulated point clouds in order to assess if 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 [4]. Finally, starting from RPM alignable poses, the shortest path connecting 3D viewpoints is sorted out.

4 Tolerance inspection system

The proposed tolerance inspection system architecture has been illustrated in other papers [4, 28]. Generally it is split in an off-line software system for view planning and simulation and an on-line system composed by the scanner, the robot, a rotary table, the robot controller and a software application (Fig.7).

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. In (Fig 8) part of the user interface is shown.

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

Such orientations are then physically reproduced using a rendering of the object from some standard positions S (Fig.10). During the on-line phase, the operator lays the object on the inspection plane in the same equilibrium position. Rendering are superimposed to the images of a camera that looks at the object from the corresponding viewpoint.

The virtual image is obtained reproducing the scanner camera geometry and optical parameters using standard graphic libraries. Before inspection, operator matches the object position grabbed by the scanner camera to the attended virtual image of the object. Repeating for a couple of different known viewpoints, the localization of the object is reached more precisely. An usability test of such procedure is planned for the future.

The second case refers to automotive sheet metal parts (doors and hoods) to be inspected to verify the location of points of interest. Such points are introduced in the system by coordinates provided in a specific control document coming from the quality department.

4.1 Test cases discussion

Die cast part example has allowed analysing view planning algorithm 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 that are necessary to cover faces that are the target of tolerances or datum. Such poses were too far each other and does not form a unique scanning path. Then 2 additional poses (pose number 2 and 9 in fig. 11) have being 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 matching by ICP algorithm in the elaborated sequence.

This application example was then physically tested by using a laser scanner (Minolta Range 7) mounted on a robot arm. Inspection poses have being 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 being successfully aligned by using a standard reverse engineering software (RapidForm by Inus Technology) confirming the simulated results.

The automotive application (Fig.12) 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 being more challenging due to models dimension and complexity. Efficient GPU based algorithms have been developed to cope with the high number of geometrical entities (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 to reach a full coverage of such points. Experimentation with a physical setup has confirmed the virtual analysis. Main reason is represented by occlusions caused by the marker frame that 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
The possibility of virtually test acquisition results dramatically shorten time to come to optimal solution.

The experimentation of the approach has permitted to target on object localization issues both in 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 one regards the choice of many parameters that are required by the proposed algorithms. It refers to distance and angular thresholds that can be enhanced by experimenting on a large set of test cases.

The second one 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 behaviour. However, quality of simulation must be systematically assessed towards real data. More important, the whole process accuracy must be analyzed from a metrological point of view. In fact, many sources of errors can affect the final results: 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.

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 in 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. When applicable, an iterative procedure has been elaborated to come to an optimized list of view. Finally, simulation algorithms allow investigating acquisition coverage and feasibility of scans alignment.


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