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Computer Aided Inspection procedures to support Smart Manufacturing of injection moulded components

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Abstract

This work presents Reverse Engineering and Computer Aided technologies to improve the inspection of injection moulded electro-mechanical parts. Through a strong integration and automation of these methods, tolerance analysis, acquisition tool-path optimization and data management are performed. The core of the procedure concerns the automation of the data measure originally developed through voxel-based segmentation. This paper discusses the overall framework and its integration made according to Smart Manufacturing requirements.
The experimental set-up, now in operative conditions at ABB SACE, is composed of a laser scanner installed on a CMM machine able to measure components with lengths in the range of 5÷250 mm, (b) a tool path optimization procedure and (c) a data management both developed as CAD-based applications.

Keywords: Reverse Engineering, Computer Aided Tolerancing & Inspection, Injection Moulding, Product Data Management, Path Planning, Segmentation, Feature Recognition, Quality Inspection

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1. Introduction

Nowadays, Reverse Engineering (RE), Computer Aided Tolerancing & Inspection (CAT&I) procedures and Product Data Management (PDM) systems can help "Smart (or Intelligent) Manufacturing", with the planning,

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automation and post processing of component inspection. The benefits of their adoption are enhanced predictions of manufacturing problems and improvements in the product-process final quality.

Quality inspection by means of RE and automation of acquisition paths via CAD-CAM implementation are well known issues. Many commercial solutions are already available and provided as “smart” solutions (see for example Nikon or other acquisition system developers). Nevertheless, changes of a Company quality assessment must always pass through a strict evaluation of pros and cons, with consequences extending outside the metrology lab. For this reason, the introduction of CAT&I smart solutions must be customised according to an integrated product-process point of view, or, in other words, to the integration between product and process engineering. The requirements of CAT&I smart solutions related to the acquisition device (precision, accuracy and measure) affect product engineering. The requirements of CAT&I smart solutions related to the system integration, including part positioning, automation, and data management (measurement protocol, report and feedback) affect the industrial process and organization. In the case of injection moulded parts, RE and CAT&I may play a relevant role not only in quality inspection but also in die set-up [1]. For Companies with high volume of assemblies, it becomes extremely useful to evaluate supplies and manage a large number of suppliers per component, thanks to robust protocols and procedures that reduce repetitive and tedious actions and efficiently process large amounts of data.

In our previous works [2, 3, 4], we discussed the integration of RE in CAT&I applied to electromechanical components made by injection moulding, reporting algorithms and results that were focused upon automatic procedures for feature recognition and measure from a point cloud. In this research, we want to focus on the data treatment before and after the automatic measuring operation that Section 2 summarises briefly, since we aim to highlight requirements for the overall system set-up.

To obtain a reliable and effective measurement campaign, orientation of the pieces and their layout on the reference table must be optimised, not only in respect of the acquisition parameters but also considering that a large number of single, very small size components, must be evaluated per acquisition (typical scanned pieces have characteristic dimensions from 5 mm to 250 mm). In addition, algorithms for the laser scanner paths must also be defined according to the target of speed optimization, keeping in mind pieces orientation and obstacles presented by pieces in terms of visibility and scanner safety. Scanning without path planning may affect completeness and accuracy of the data [5]. Passing from the CAD model to its convex hull (through a STL model), the developed algorithm searches all possible balance positions for the part, and chooses the best three according to criteria such as stability and visibility. Then, for each chosen position, the view perspective is reproduced, evaluating how many points are visible. We take into account the amplitude of the measurement range, occlusion and obstacles represented by the pieces themselves and the angle between the local surface normal and the scanner (paying attention to the differences between camera and laser). In the recent years, the problems of path planning and shape digitizing, in inspection made with Reverse Engineering (RE), was solved through the use of a voxel structure starting from the CAD model [6, 7], or through the study of its surface mesh [8], due to the necessity of acquiring complex free-form shapes. We decided to use a STL based algorithm (conceptually similar to what is reported in [9]) looking for the definition of scan path on components which are obtained mainly by feature based surfaces (planes, cylinders, spheres, pockets) not free-form. All these concepts and procedures, applied before the measurement campaign, represent the macro-area named Computer-Aided Path Definition (CAPD), described in Section 3.

Subsequently, we analyze and discuss the automatic treatment of data after the automatic measure. These concepts are described in Section 4, named Product Inspection Data Management (PIDM). Generally speaking, PDM (and PIDM as a part of it) is now a commercial issue because its structure and use are stabilised. In particular, it is considered as a base for the Product Lifecycle Management (PLM) philosophies, which cover the whole life of the product [10]. All these concepts and methods allow product design to gain connection among value chain activities, according to Concurrent Engineering. The industry goal is to avoid waste time that, usually, is the major portion of the entire time to market in a business, and it can be attributed to the absence of an efficient knowledge management system [11].

In the article, CAPD and PIDM procedures and algorithms are described and some results and examples from case studies are provided in order to evaluate the proposed automation in comparison with the usual procedure (which involves intense work for the technician, often boring and thus not error-proof). To conclude the paper, we present future developments and targets according to a “Smart Manufacturing” implementation.

Nomenclature

CAPD	Computer Aided Path Definition
CAT&I	Computer Aided Tolerancing & Inspection
CMM	Coordinate Measuring Machine
GUI	Graphical User Interface
HC	Hierarchical Clustering
IM	Injection Moulding
IRS	Intrinsic Reference System
PLM	Product Lifecycle Management
PDM	Product Data Management
PIDM	Product Inspection Data Management
RE	Reverse Engineering
RG	Region Growing
STL	STereo Lithography interface format
TRL	Tecnology Readiness Level

2. Measurement workflow and methodology

Automatic measurement from RE requires feature recognition from the digitised point cloud. This issue has been discussed in literature for many years [12]. Usually, one of the preferred solutions is starting the procedure from tessellation. We choose to use voxel instead of tessellation because it is quicker and there is no loss of information. In fact, a voxel acts like a filter because it allows the operator to work with a single entity (the voxel itself) instead of all the points inside it. It is important for high dense clouds in terms of computation time.

As stated, we begin with a point cloud of the analysed piece and follow the workflow shown in Figure 1.

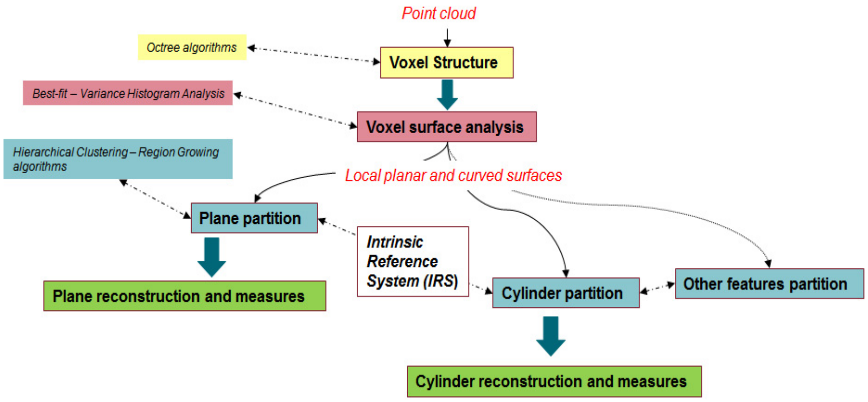


Fig. 1. Proposed workflow for feature recognition and measuring.

Our voxel structure is superimposed on the point cloud starting from a single cell structure. Through an octree algorithm, each voxel is recursively subdivided onto eighths. This procedure is stopped when a voxel is empty of points or the procedure has reached the threshold on the voxel number that has been specified by the user. At this point of the procedure, for each voxel, a planar best fit is calculated. By analysing the deviation from this plane, we are able to divide voxels with a micro-plane inside from those that do not. Then, through a hierarchical clustering routine and region growing algorithms, micro-planes are aggregated into planar features according to their orientation and adjacency. The obtained planar features are used to define IRS: following a process similar to the ideal model done by a typical designer, the specific direction related to the most populated cluster is chosen as the x-axis. The y-axis corresponds to the most populated cluster from all the perpendicular directions of the x-axis. Finally, the z-axis is made with the cross product of x and y directions.

With a few variations in terms of algorithms, an analogue procedure has been developed for the cylindrical case. We used Kasa and Levenberg-Marquardt algorithms [13] to fit micro-cylinders (Kasa and LM are 2D algorithms used for circular fitting, so we must project points into the three principal directions of the IRS, and the best cylindrical fit is chosen). As in the previous case, with similar RG and HC algorithms, the micro-cylinders are aggregated into clusters that become the cylindrical features.

Once the two sets of voxels (planar and cylindrical) are divided and their internal points are aggregated into different planar or cylindrical features, the process is completed by the measurement algorithms.

For the planar case, three methods have been developed in order to measure distances between planar features that have been compared with nominal quotes:

1. "Range Max" measures maximum, minimum and average distances between pairs of points of the two considered planes according to one of the IRS directions.
2. "10-90 percentile" is computed in the same way as method 1, but it excludes from the analysis 10% of the minimum and 10% of the maximum values.
3. "Caliber" solution measures the distance according to a best-fit plane of one of the two features involved in the measure.

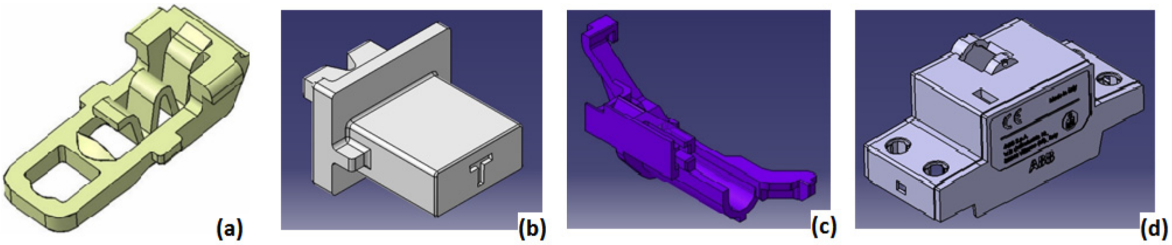


Fig. 2. Injection moulded components used as test cases: (a) "Attacco Rapido"; (b) "Tasto Test"; (c) "Porta Resistenza"; (d) "Calotta".

In order to have statistical proof of the quality of the used methods, some tests have been done on several components with different shapes and dimensions. Figure 2 provides some of the components used as test cases. They confirm~~s~~ that the methods are analogous, with relative errors lower than 2%. In Table 1, we report these data comparing them with results of the standard manual procedure, in order to have an overview of data soundness.

Table 1. Relative errors between the different methods for the analised components and with the standard manual procedure.

Name of the component	Max Relative Error M1-M2 (%)	Max Relative Error M1-M3 (%)	Max Relative Error M2-M3 (%)	Average Relative Error between Our Methods and "old" Measures (%)
"Attacco Rapido"	1.4	0.4	1.2	1.7
"Tasto Test"	1.3	0.2	1.5	1.0
"Porta Resistenza"	1.7	0.3	1.8	2.7
"Calotta"	0.3	0.0	0.3	1.9

It is important to have information about the accuracy of the three methods, but it does not help us to quantify errors introduced by the measuring procedure. In fact, tests on real components are affected by several errors due to different possible causes that cannot be predicted. Therefore, we attempted to evaluate errors caused by the measuring procedure and, also, those caused by the scanning operation, using real and virtual Gauge blocks (or Johansson blocks). These types of blocks are made of stainless steel, finished with high precision lapping in order to obtain two perfectly parallel opposite faces. The distance between the two considered faces (nominal thickness) is guaranteed within a close tolerance and a specified temperature range. In this analysis, we used a block with nominal dimensions of 10x25x2 mm. Furthermore, a virtual ideal model of the block has been made, with the same nominal dimensions as the real one, generating a point cloud not affected by any measuring error.

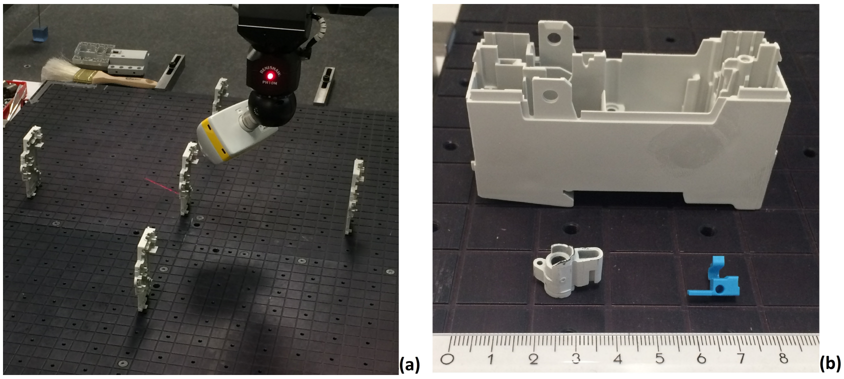


Fig. 3. (a) The laser scanner in use during the measurement of a series of components (b) Examples of component on the acquiring table.

From the analysis of the virtual and ideal block, it has been proved that the measuring algorithms do not introduce any significant error. On the contrary, from the examination of the experimental real block, we found relative errors lower than 5%, compared to the nominal values. These errors are principally caused by the wrong positioning of the component, by border effects that influence the voxel structure, and by the incorrect and non-uniform distribution of the opacifying spray used to avoid reflections.

Currently, we are developing similar procedures for the measurement of cylindrical features that provide reliable results. Generally, all measures found by the developed procedure will serve as input to the PIDM procedures, described in Section 4.

3. Computer-Aided Path Definition (CAPD)

An optimal scanning path plays a key role in accurate feature recognition and reduction of operational time. In fact, having a dense and complete point cloud with low noise is relevant for the accuracy of the measurement, while automatic and safe path definition are used to manage the acquisition of cavities, especially in multi-component scanning sessions.

In our analysis, the measuring system is composed of a laser scanner Nikon LC15Dx installed on a CMM machine 3COORD Hera 12.9.7 (in order to move the scanner onto a measuring table with an area of 500 x 360 mm). This system affords a good balance between acquisition time and accuracy [14, 15], because it allows the operator to acquire 20000 points/s with accuracy of 0.025 mm. These characteristics also confirm the applicability of laser scanning for the tolerance inspection of plastic components that are manufactured via injection moulding since, in the considered dimensional range (5÷250 mm), they typically have dimensional tolerance > 0.05 mm.

The scanning session, considered as a macro-area of the whole process, is one of the most time-consuming parts (about 20% to 30% of the whole measurement campaign of a component) Therefore, it is clear that a redesign and optimization of this step is fair and convenient. In order to scan a piece completely, it is evident that it must first be positioned according to different orientations and then acquired. Subsequently, different views must be aligned and merged to obtain a complete point cloud of the scanned component.

The old procedure provided the choice of positioning and acquiring without any computer assistance, but was only based on the experience and subjective judgment of the operator, after a preliminary examination of the piece. To solve this issue, we developed a GUI (Figure 4) for the optimization of the acquisition views after the component has been suitably positioned on the table. Position suitability is defined in terms of:

- Position stability. Evaluated in terms of a component's centroid, as derived by the nominal model STL. Its projection must be inside the support area interfaced to the acquiring table.
- Visibility: evaluated as the percentage of exposed surface of the piece (visible area from the laser blade);
- Handling during positioning: evaluates the ease of positioning on the table in the assigned area. This is relevant because the positioning must be made by the operator for every cavity to be investigated, according to each view that must be scanned.

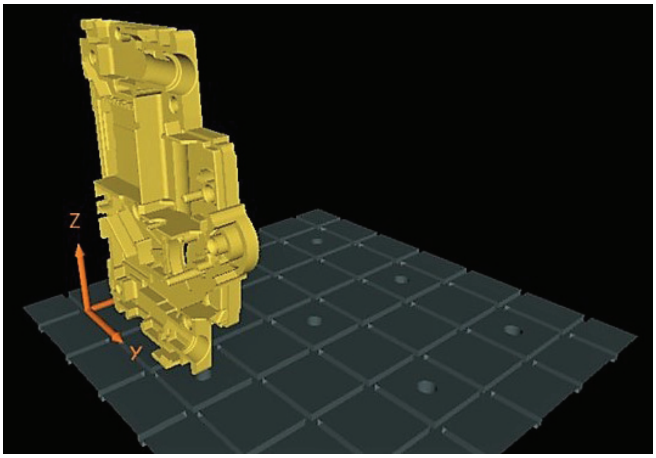


Fig. 4. An example of a component model in one of the selected orientation.

Through the developed algorithm, the user can choose 3 positions from an ordered list of 7 optimal solutions (defined by a combination that maximises the above criteria).

The developed routine, by default, chooses the 3 best positions (we reported an example of one of them in Figure 4) in terms of balance stability, but the user can also modify the choice by selecting, according to other criteria. It is useful in the case of components that are critical from a visibility or handling point of view (e.g. local details that reduce visibility, or in case of holes and pockets).

The adoption of the 3 positions represents the input for the subsequent part of the process: the algorithms and routine for defining the scanning views, that means finding the optimal angles and orientation of the laser scanner.

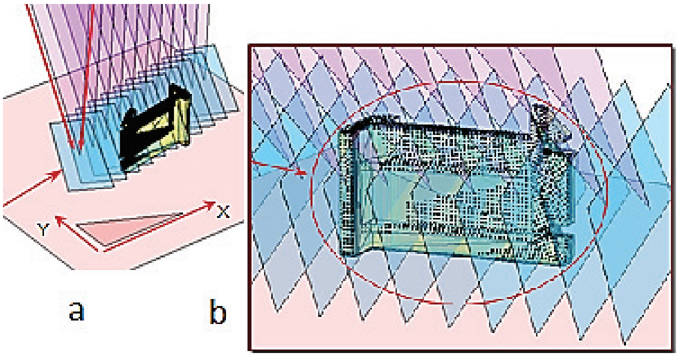


Fig. 5. (a) Example of creation of paths (model of the component in yellow, acquirable zones in pointed black); (b) particular (different positions of the laser blade in cyan).

The choice of parameters for the scanning head (angles and height) depends on positioning and orientation of the piece. Our algorithms can automatically provide these values in order to maximise the number of acquirable points during the passage of the laser scanner. The first acquisition path will be the one that returns the maximum number of points according to the first component position. The plan of the other runs is managed by maximising the number of points on the surfaces that have not yet been acquired. The iteration is stopped when the ongoing passage does not increase acquired points by, at least, 0.1%. At this stage, we have finished the definition of the scan paths of the first position.

Component positioning is then modified in position 2. Its related paths are generated looking for maximum number of acquirable points besides that already included in paths of position 1.

Scan paths of the third position are defined also to perform the "assembly match" of the clouds obtained in the previous scans. So that, the goal for path generation changes, searching points not acquired in any previous orientation and also those acquired in scan paths of position 1 and 2.

Other requirements of the scan path algorithm are: a) exclusion of repetitions; b) generation of codes and data for driving CMM and laser scanner; c) cleaning of points outside the component (for example, parts of the acquiring table can be scanned and they must be cut); d) filtering to reduce number of points.

Once the acquisition is made according to position 1, 2 and 3, the three obtained partial clouds must be roto-translated in order to have the same reference system. Then they are aligned and merged through a best-fit with the solid model of component (given as an IGES solid) guided by the information obtained in the "assembly match" scan paths of position 3. This merged cloud is the input for the procedure briefly outlined in Section 2.

As we said previously, in the standard procedure, this part was very time consuming, but, with the changes made through the CAPD, now it has gone from an average time of 10 hours to 0.5-1 hour, achieving a decrease of 90%, for a single component like the one in the upper part of fig. 3.b.

4. Product Inspection Data Management (PIDM)

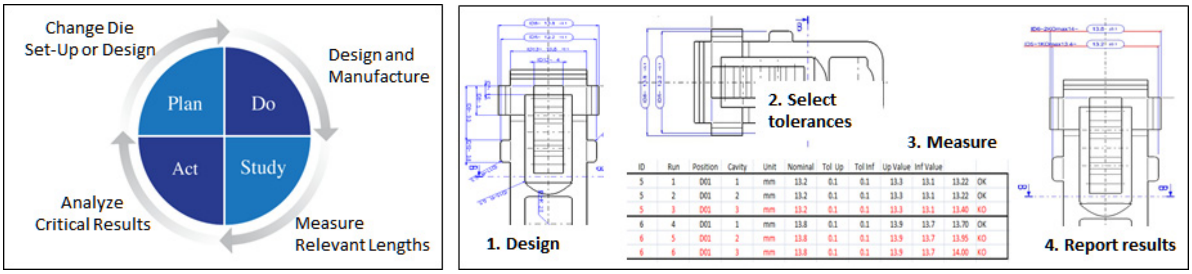
To achieve benefits from the automatic inspection via RE, a full integration of the inspection protocol into the PDM must be provided.

Die set-up of an injection moulding process of small components usually asks for time-consuming inspection analysis, since one die may mould more than one component (one for each related cavity). Considering that temperature gradients inside the die may induce local changes of a cavity's shape and lengths from one to another, the inspection evaluation must be carefully guided to aid impartial comparison of quality loss in terms of a single component's functionality and performance. Thus, tolerance evaluation can be seen as a quality index for die-set up, in addition to product quality. Important implications of this are the capability of assessing and aiding suppliers in process evaluation and set-up, according to their particular quality requirements.

According to this requirement, a Product Data Management (PDM) tool must be defined with the aim of:

- comparing interesting measurements with the nominal quotes derived from CAD model;
- reporting both detailed and "at a glance" overview of the measurement protocol results;
- aiding data analysis to decide which component's feature or length must be re-analyzed or modified in terms of a cavity's die set-up or component's design.

Fig. 6 summarises the optimization strategy for the integrated product-process of an injection moulded component, on the left; and the PIDM steps implemented to aid this strategy, on the right.



ID	Run	Position	Cavity	Unit	Nominal	Tol Up	Tol Inf	Up Value	Inf Value		
5	1	D01	1	mm	13.2	0.1	0.1	13.3	13.1	13.22	OK
5	2	D01	2	mm	13.2	0.1	0.1	13.3	13.1	13.22	OK
5	3	D01	3	mm	13.2	0.1	0.1	13.3	13.1	13.40	KO
6	4	D01	1	mm	13.8	0.1	0.1	13.9	13.7	13.70	OK
6	5	D01	2	mm	13.8	0.1	0.1	13.9	13.7	13.95	KO
6	6	D01	3	mm	13.8	0.1	0.1	13.9	13.7	14.00	KO

Fig. 6. Product-process integrated optimization of injection moulded parts: strategy (on the left); PIDM steps to support it (on the right).

Through the PIDM, the design documents (technical drawings and/or 3D models) can be filtered and aggregated, in terms of functional and not-functional dimensions or geometrical tolerances, assigning an identification number to each of them. This set of prescriptions can be now chosen by the CAD interface, with more intuitive interaction. This can also be chosen recursively by the quality inspection technician and then gathered for the inspection protocol according to the Company template. After the measuring, the final results must be released in the PIDM through a repository of the fulfilled protocol evidences of inspection results. Graphs and aggregated-data charts can be used to analyse the results. From the technical and designer point of view, graphical evidences on the technical drawings have been demonstrated as one of the most effective solutions, showing the results of manufacturing as that of the design output.

5. Conclusion and Future developments

RE with proper devices can be extremely useful for tolerance analysis in many ways:

- It can avoid problems related to significance of the number of measurement points.
- It embeds geometric analysis, thanks to dense acquisition on the component that is completely acquired.
- It allows global shape deviation analysis (relevant in case of plastic shrinkage or residual stresses) or local defect evaluation (sinks, burrs, ...).

The automation of the measures through specific feature recognition algorithms is useful to guarantee the reliability of the measurement (especially when many samples must be analyzed) and to reduce post-processing time.

CAPD and PIDM also help to decrease time and improve analysis capability because CAPD optimises acquisition conditions (view angle, laser distance, ...) and PIDM organises data visualization and report. The three implemented modules are being integrated with each other, although each of them separately is now in operative conditions (TRL equals 9 for CAPD and PIDM, TRL 4 for the measurement procedure).

Advantages of the three procedures are now under experimental investigation through the operative set-up. Concerning the CAPD, the automation for finding the positions, together with the CAM for driving the paths enhance the acquisition phase, reducing its duration. Moreover, the robustness of the positioning and of the laser set-up increases the quality of the point cloud, together with its accuracy in the next measurement step (evaluation of the accuracy will be performed in the next future). Generally speaking, time for inspecting a single component, is now decreased up to 40% compared to the old procedure.

Concerning the measurement methodology, we are now debugging all the developed procedures, using several test cases. We are also working on the measurement algorithms for cylindrical features, in order to have the same level of reliability obtained in the planar case. Furthermore, we are starting to develop strategies to evaluate the remaining class of micro-features (edges, fillets, chamfers…). In order to obtain better results for classical features and the recognition of the secondary features, we must develop and implement logics for boundary recognition, which will allow a better positioning of the voxel structure. In addition, one of the next improvements could be the selective increase of voxel resolution in zones with small features in order to improve accuracy.

The proposed PIDM is obviously strictly related to the Company habits. Generally speaking, a full integration of inspection results in the PLM are mandatory to speed-up Company improvements.

The adoption of CAPD and PIDM, together with RE and CAT&I, can be included in the Smart Manufacturing applications since the enhancements in terms of production data analysis are relevant both for: product-process integrated design, to assist process set-up and measure quality indicators related to geometry; and manufacturing, to perform quality inspection. Integration with augmented reality and big data analysis are two natural developments. Likewise, integration with CCD acquisition and bar code component identification can be useful to fully automate the process, reducing mistakes.

6. Acknowledgements

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