Title:
On the Use of Quality Metrics to Characterize Structured Light-based Point Cloud Acquisitions

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Introduction:
Accurately transferring the real world to the virtual one through reverse engineering is of utmost importance in Industry 4.0 applications. Indeed, acquiring good quality 3D representations of existing physical objects or systems has become mainstream to maintain the coherence between a real object and its digital twin. Compared with traditional contact measurement, contact-less scanning is undoubtedly a fast and direct acquisition technology. However, for a given acquisition, finding the right scanning configuration remains a challenging question whose resolution has attracted researchers in recent years. Using heuristics and visibility criteria, some approaches try to automatically plan the positions and path to be followed by a robot when scanning an object being manufactured [1]. Similarly, Joe Eastwood et al. use a genetic algorithm and a convolutional neural network to optimize the locations of the cameras with the purpose that maximize surface cover-age and measurement quality [2]. However, all those techniques base their reasoning on theoretical models whose real behavior may diverge as compared to real measuring. Thus, being able to take decisions based on the results obtained from real acquisitions is crucial to minimize the deviations between what was planned and what has been obtained by the end. To do so, ad-hoc metrics need to be used to accurately characterize the quality of point clouds that are then used in the next engineering steps (e.g. reconstruction, control, simulation).

The methods for evaluating point cloud (PC) quality can be divided into two types, i.e. subjective and objective. The former mainly evaluates the point cloud from a perceived visual quality for immersive representation of 3D contents [3][4], whereas the latter is more quantitatively based on values. For quantitative metrics for evaluating the quality of PC, some researchers only considered the properties of the PCs, assessing the qualities of the PC from four aspects [5]: noise, density, completeness, and accuracy of the point cloud data. Based on these achievements, some scholars [6] further proposed an indicator for surface accessibility, to characterize how a region on the surface of the workpiece can be reached or not by the scanner. Besides, the coverage rate was proposed to reveal how much the area is scanned. Additionally, the normal angle error was figured out in [4]. However, all those metrics can behave differently

Proceedings of CAD'22, Beijing, China, July 11-13, 2022, 344-349

depending on the adopted technology: laser scanner, photogrammetry, or structured-light measuring for instance. Catalucci et al. [7] compared the photogrammetry and structed-light measurements on additively manufactured parts and pro-posed quality indicators of PC that include measurement performance indicators and statistical indicators on the whole part measurement. However, their work focused on whole scans of the part that consist of many point clouds acquired from different scan positions and configurations. Although many criteria have been proposed, it remains to be investigated which are the most accurate and obvious metrics to evaluate the quality of the PC during a structured light-based scan.

Main Idea:

This work first summarizes comprehensively the existing metrics for point cloud quality assessment, then it introduces novel calculation strategies, and it studies how those metrics behave on different test cases. The metrics to be studied are listed in Tab. 1.

Type of metrics	Metrics
Inherent features	Number of raw points
	Number of final points
	Efficacy ratio
	Density
Geometric characteristics	Registration error
	Coverage ratio
	Normal error
Metrological metrics	Point-to-triangle dispersion

Tab. 1: Metrics for evaluating the quality of point clouds.

Inherent Features of Point Clouds

This type of metrics focuses on the inherent features of the PC. Catalucci et al. [7] validated some of them on different point clouds coming from photogrammetry and structured-light scanner.

The number of final points refers to the remaining points of the raw point cloud after removing background, noise and outliers. When the number of raw points is small, the scanning strategy is considered as not sufficiently efficient. The efficacy ratio is defined as the number of useful points divided by the number of original points.

The density is an indicator that describes the number of points in a region. There are two common forms: number of points per unit area, and number of points per unit volume. In this paper, a new format of density is defined and is based on the linear density and spatial distribution.

Geometric Characteristics of Point Clouds

The geometric metrics consider the relationships between the acquired point cloud and a nominal geometric model, i.e. a CAD model in the context of this work. They take the registration process and the scan region into consideration.

The registration error characterizes how well the point clouds coming from multiple acquisitions have been properly aligned in a common coordinate system by minimizing the alignment error (ICP) [8].

The coverage describes how much of the part's surface is represented by the final point cloud, established from the points and nominal geometric model. The coverage is computed on results of the point-to-triangle distance. If the distance of a point to the facet of the CAD mesh is less than the threshold, the point is considered to be a corresponding point of the facet. Then, depending on both the resolution of the scanner and number of points associated to each facet, a facet can be identified as covered or not. This helps computing the coverage ratios based either on the covered area, or on the number of covered triangles. Good quality acquisitions minimize this metric.

Proceedings of CAD'22, Beijing, China, July 11-13, 2022, 344-349

Metrological characteristics

Point-to-triangle dispersion is an indictor based on the definition of point-to-triangle distance to reveal the projected distance's distribution of the point to corresponding facet in the normal direction [7].

Experimentation of quality metrics:

Experiment workbench setup and data processing

The experimentations have been performed using the structured light-based GOCATOR 3210 by LMI Technologies. To study the way the previously introduced metrics behave on different scan configurations, three different parts have been scanned while changing the acquisition viewpoint on a rotating table (acquisition angles of 0^o, 10^o, 20^o and 40^o). In this extended abstract, only the results on the so-called pocket workpiece are discussed (Fig. 1).

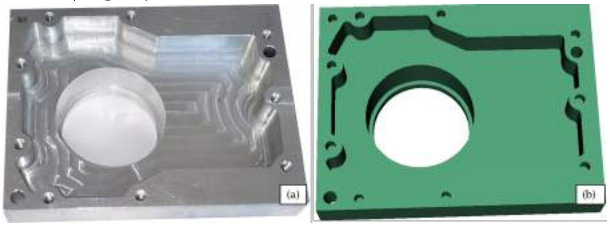

Fig. 1: The pocket workpiece (a) and the nominal CAD model (b)

Data processing includes the removal of the background related to the surrounding environment near the workpiece, removal of the outliers and isolated points and registration between the point cloud and CAD model. In this paper, the background was deleted manually first. Then the registration was done by the algorithm point-to-plane registration. Meanwhile, outliers were deleted. Finally isolated points were deleted by density analysis.

Position	Num of raw PC	Num of final PC	Efficacy ratio
0^o	1439322	1389531	96.54%
10^o	460229	444295	96.54%
20^o	1155815	1114418	96.42%
40^o	1434403	1388178	96.78%

Tab. 2: Efficacy ratio for the pocket's scans

Discussion about inherent features

First, metrics related to the inherent features are analyzed. The results of the **number of raw and final points**, and the **efficacy ratio** of the four acquisitions on the pocket workpiece are listed in Tab. 2. Besides, the **densities** of the four scans are shown in Fig. 2. Even though the density distribution of the acquisition at position 20^o is different from the others with low mean density, the values do not vary significantly and the efficacy ratio has little change. Thus, those metrics are not able to finely capture differences between acquisitions and would therefore be less interesting for optimizing scan configurations.

Discussion about geometric characteristics

Second, metrics related to the geometric characteristics of point clouds are analyzed.

All these indicators are related to the CAD model of the pocket. Thus, the CAD model is meshed using MeshLab, with an edge size 0.5 mm. For the four positions's acquisitions, the **registration errors** vary from 0.074mm to 0.075mm. Here again, it can be noticed that those values do not vary and that therefore such a metric can hardly be used as an objective function to be minimized. The coverage of each of the 4 scans are then shown in Fig. 3 where coverage status of each facet of the mesh is related to the number of points in the PC corresponding to the facet with 3 type: (a) covered (green, the number is

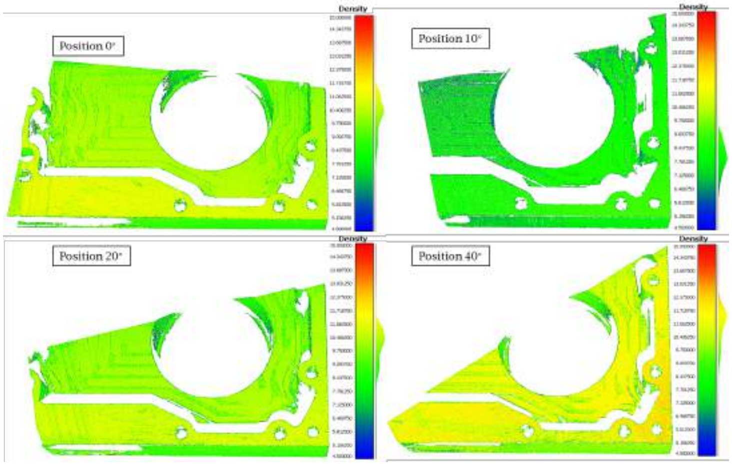

Fig. 2: Density analysis of four acquired point clouds of the pocket workpiece

over the threshold); (b) uncovered (red, the number is less than the threshold; (c) zero(grey, the number is 0), and detailed values are summarized in Tab. 3. For the **coverage ratio**, a new indictor is proposed as Eqn. 2.1 where N_C, N_I, N_{uc} are respectively the number of covered, ideal covered and uncovered triangles. This indictor considers both the coverage ratio and the ratio between the covered and the uncovered. The bigger it is the better it is. Actually, it can be seen as the signal-to-noise ratio when the covered triangles are treated as noise.

$$Score = e^{N_C/N_I} ln(N_C/N_{uc}) \tag{2.1}$$

Position	Num of ideal visible facets(N_I)	Num of covered facets(N_C)	Num of uncovered facets(N_{uc})	Coverage Ratio	Score
0^o	142322	66345	8234	46.62%	3.33
10^o	109040	40522	12449	37.16%	1.71
20^o	123572	55357	7539	44.80%	3.12
40^o	116461	50221	5210	43.12%	3.49

Tab. 3: Coverage ratio and score of 4 scans of the pocket workpiece

From the results, it is obvious that the PC at position 20^o has low score on coverage and it is consistent with the fact that this PC has a higher percentage of uncovered area than the other PCs. Thus, the indicator can capture differences between scan configurations, and could therefore be used as a metric to be maximized when looking for optimal scan configuration/position.

Concerning the **normal error** the experimentation results show that this metric is not sensitive enough to be used to optimize scan configuration.

Discussion about metrological features

Finally, the results on the **dispersion** distribution of the point clouds show very similar results that, again, do not allow for a good comparison of scan configurations.

Conclusions:

In this paper, several metrics to reveal the quality of point clouds are studied to identify the ones that could be used for optimizing acquisition positions to perform automatic scan. The study reveals that the

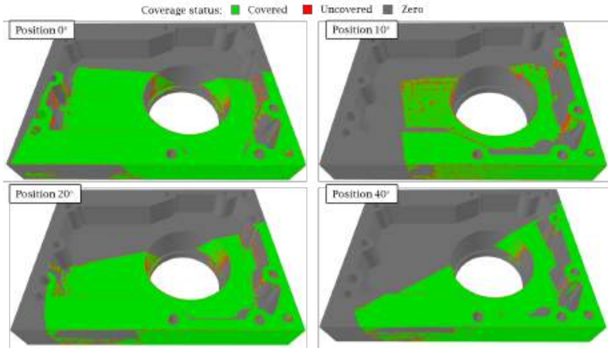

Fig. 3: Coverage of scans for different positions of the GOCATOR 3210.

indicators number of points, number of covered/uncovered triangles vary greatly, and may be affected by external factors (such as the location and configurations of the device). Other indicators such as the efficacy ratio, registration error, normal error and metrological characteristics keep stable and are therefore not interesting to get a good understanding of the pertinence of some acquisition positions. However, the indictors coverage ratio and score have significant changes and can be of interest to assess the quality of the measurements.

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Proceedings of CAD'22, Beijing, China, July 11-13, 2022, 344-349