Intelligent Digital Built Heritage Models: An Approach from Image Processing and Building Information Modelling Technology

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Abstract: Conservation and maintenance of historic buildings have exceptional requirements and need a detailed diagnosis and an accurate as-is documentation. This paper reports the use of Unmanned Aerial Vehicle (UAV) imagery to create an Intelligent Digital Built Heritage Model (IDBHM) based on Building Information Modeling (BIM) technology. Our work outlines a model-driven approach based on UAV data acquisition, photogrammetry, post-processing and segmentation of point clouds to promote partial automation of BIM modeling process. The methodology proposed was applied to a historical building facade located in Brazil. A qualitative and quantitative assessment of the proposed segmentation method was undertaken through the comparison between segmented clusters and as-designed documents, also as between point clouds and ground control points. An accurate and detailed parametric IDBHM was created from high-resolution Dense Surface Model (DSM). This Model can improve conservation and rehabilitation works. The results demonstrate that the proposed approach yields good results in terms of effectiveness in the clusters segmentation, compared to the as-designed model.

1 INTRODUCTION

Historic buildings have exceptional maintenance, conservation, and restoration requirements, and because of this a detailed diagnosis and documentation are mandatory to the conservation, restoration and rehabilitation works. Recent decades have enhanced the consideration of the architectural object as a document itself, that contain lots of information. This knowledge is necessary for the understanding of the building in its physical reality, historical and cultural circumstances that have generated and transformed it.

Currently, the results of multidisciplinary surveys are dispersed on many platforms, making it difficult to understand the architectural object. On the other hand, new information and communication technologies still do little to benefit historic buildings. Intelligent models created by Building Information Modelling (BIM) technologies introduce promising application on this issue.

The BIM-enabled method provides a component-oriented systematic central database gathering shape, structure, materials, historical and life cycle properties, a benefit features for cultural heritage field ((Penttilä et al., 2007; Fai et al., 2011; Manferdini and Remondino, 2012)). Concerning to the historical assets, the difficulty to obtain both the as-designed and the as-built reference documentation makes the surveying starting from the real object, in a reverse engineering process. Thus, the first step for the creation of an as-is BIM model is data capture. In the data collection process for as-built/as-is documentation, choosing the best method for reality capture has proven to be challenging to address(Dezen-Kempter et al., 2015). High-resolution data capture, such terrestrial 3D laser scanning, lead to expensive equipment, arduous management, and professional post-processing, restricting the use of this technology. Photogrammetry can represent a low-cost technological alternative for the DSM (Dense Surface Model) generation. The use of high-resolution cameras coupled to UAV (Unmanned Aerial Vehicles), in high precision surveys, has been increasingly frequent, with results very close to 3D laser scanning. This paper describes a BIM-driven approach for historic buildings, based on (i) photogrammetric 3D building survey with a UAV, (ii) image processing and segmentation into architectural components and (iii) development of BIM as-is model-based.

This paper is organized as follows: Section 2

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presents related works. Section 3 describes the proposed approach. Section 4 describes equipment used and details about the method developed in this research. Section 5 presents the results from the individual stages. Finally, in the Section 6 shows conclusions and future works guidance.

2 RELATED WORKS

Many researchers have tried to construct *as-is* BIMs adopting various input types, also considering different levels of building information in their models (Lu and Lee, 2017). Although laser scanning is still the acquisition method mainly used, photography and its integrations are already accepted as a feasible and promising low-cost alternative, especially *Structure from Motion* point clouds (Bhatla et al., 2012).

Brilakis *et al.* proposed an information-rich model by merging data from laser and image collections (Brilakis et al., 2010), this fusion can be reached applying supervised IPC algorithm then smooth with scale-invariant feature transform. Once combined a textured 3D surface its estimated by mesh triangulation and pixel correlation. Even without implementation, authors recommend feature extraction from geometry and image canonical parts (Savarese and Fei-Fei, 2007) as descriptors for item labeling. The work defined a complete *as-is* BIM as an open challenge.

A semi-automatic approach for existing buildings was proposed by Dore and Murphy, also integrating laser and image data. The concept called *Historic Building Information Modelling* (HBIM) provides a parametric object library using geometric programming language (Dore and Murphy, 2014). A collection of predefined architectural elements its used to simplify manual modelling tasks. Pre-processing steps, such registration, and filtering are carried out first. Although experiments indicate more efficiency than existing BIM tools, pattern limitation, and low automation reduces usability and remain the manual effort necessary to process the information.

Another alternative proposed by Jung *et al* tries to increase automation for modelling in scenes captured with laser scanning. Rather than use point clouds, researchers suggest simple edge lines as guides for object shaping in BIM software (Jung et al., 2014). Borders are carried out segmenting data into subsets sorted has planes. Subdivisions are made using RANSAC (Fischler and Bolles, 1981) that calculates the probability of a point belongs to the best group, followed by refinement. Thus, each plane is projected onto 2D binary images where non-zero represents occupied positions. Boundary tracing search for not null pixels in value changing areas and iteratively connect neighbors. Despite the fact that this method adds autonomous stages the process appear semi-auto indeed, and hard to evaluate.

Wang *et al* have a similar approach, comparing with Jung *et al*, differing only in algorithm chose and BIM integration. Same sensors where applied on the acquisition (Wang et al., 2015), but data suffered efficiency enhancement as downsizing and outliers remotion. Hereafter, region growing its used to segment planes using curvature and angular similarity between points. Once disjoint, all areas have its edge computed by concave hull border extractor (De Berg et al., 2008). Instead of finish the process as soon as lines are delimited, previously defined rules classify the obtained forms, adding likely labels. This method was evaluated comparing its output with golden standard and reached high error rates.

The technique described in our paper, analog to Wang *et al*, uses region growing algorithm to identify architectural elements and similar pre-processing. Our contribution can be enumerated as follow: (1) a new UAV acquisition protocol is presented, specifying close-range methodology able to produce viable images for a 3D model generation; (2) project documents are used to evaluate the segmentation stage introducing trustworthy validation; (3) clouds acquired by laser scanning and images were compared and finally (4) every step, since acquisition until model verification, were profoundly presented and produced a replicable workflow.

3 PROPOSED APPROACH

This research applies a few methods described in the scientific literature for each one of the process steps of the IDBHM creation. It was required adjustments in peculiar characteristics of the case study. Figure 1 shows the proposed methodology approach.

The method is composed of six primally stage. Those phases can be generalized as:

Capture Planning: The use of UAV in the capture of elements in short and close-range domain, particularly in the case of historical heritage, still does not have techniques widely disseminated, which leads to the application of strategies created for terrestrial capture stations (Nex and Remondino, 2014). Particular challenges in specific structures require a case to case adaptation. Despite that, three parameters are the consensus among different conventions: (i) calibration of all sensors involved, (ii) the full angular range of capture and (iii) the high percentage of overlap between images.

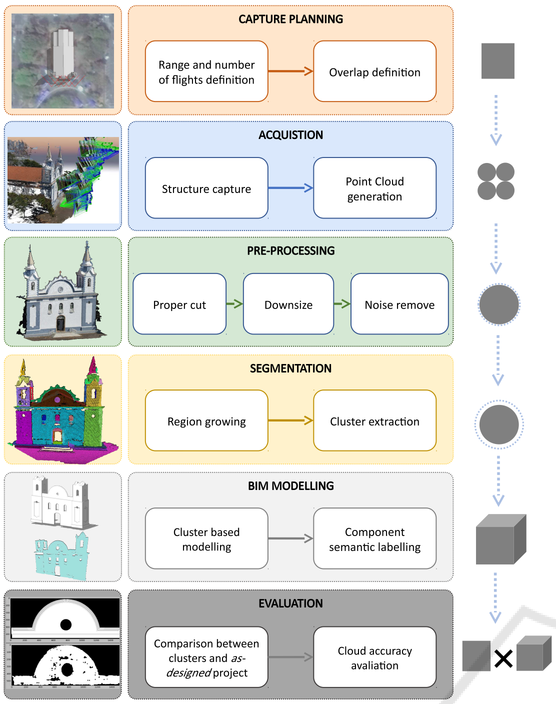


Figure 1: Methodology description of each step in the workflow.

Acquisition: Based on flight planning, the geometric object information was captured using UAV and modeled applying proprietary DSM generator.
Preprocessing: Several challenges are related to the point cloud segmentation task, such as noise filtering, low density and non-organized data (Nguyen and Le, 2013). In order to minimize such problems filtering operations or other kind of data preparation are usually necessary.
Segmentation: Segmentation is the process of partitioning an image changing its representation into something more meaningful. Even though its importance in image analysis and decades of research, segmentation remains a challenger task. The tridimensional case is found in the same statement, hard in the same way. Low angular variability is a well-known property of plane surfaces. This property is used for point cloud segmentation techniques like region growing, for instance.
BIM Modelling: The output of point cloud segmentation was a set of points from each building architectural element (clusters). The clusters enabled the development of the BIM Model corresponding to the development of parametric objects.
Evaluation: Quantitative metrics are toke based on comparisons between clusters, as-designed document, and point cloud accuracy.

4 METHODOLOGY

To validate the proposed approach, a 19th-century historical building in the city of Limeira (Brazil), the Boa Morte Church (BMC), was selected as the case study. The church was designed by the Italian *Aurélio Civatti* in 1867 in neo-classical style. The building technique used in the BMC was rammed earth, a feature from traditional Portuguese construction that uses mud and clay mixture woven together with wood and bamboo structure. The great thickness of the walls is a characteristic feature of this technique. The BMC main body walls are between 90 and 177cm thick.

Figure 2: [a] Original facade of BM's church (1867); [b] Facade after restoration (1890).

The facade collapsed only 12 years after its completion. In 1890, part of the Frontispiece was redone, replacing the rammed earth for baked clay brick.The *modenature* of the main door and the choir windows were also modified, like the triangular neo-classical pediment by an arched one of eclectic characteristics (Figure 2). The main architectural elements of the facade were identified, aiming at the segmentation process and the subsequent modelling of BIM parametric objects. Figure 3 highlights these elements:

The following subsections present the detailing of each step of the proposed workflow.

4.1 Capture Planning

The implementation of BMC, in the center of a square, foster the UAV imagery capture because there is no significative obstacle in the 15m in front of its facade. This way, the UAV could fly freely, both vertically and horizontally, operated either by application or manually (Figure 4). For the UAV scanning plan was considered the distance between the building and the UAV, the building height and width ($25m \times 25m$), the minimum desired overlapping (70%) and the camera performance. Thus, was proposed a flight with six horizontal lines, starting at the top of the building, the camera automatically snapped the shot every 2 seconds with the UAV flying at about $5m/s$.

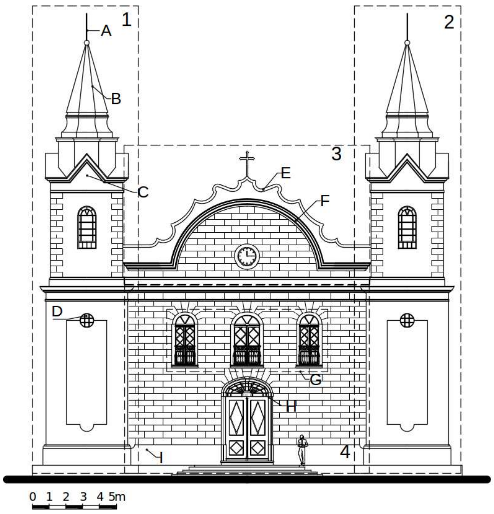


Figure 3: BMC architectural elements: (1) right bell tower; (2) left bell tower; (A) Pinnacle with with a golden weathercock); (B) octagonal dome; (C) triangular pediment of the bell tower; (D) oculus; (3) double pediment with a clock on the tympanum; (E) rampant scrolls; (F) straight cymatium; (4) frontispiece, with spare bell towers base (cornice highlighted in the figure made up of cymatium and friezes); (G) chorus windows, entirely open, in full arch; f. oculus; (H) main door with lintel in segmental arch and door frame both in carved stone;(I) basement.

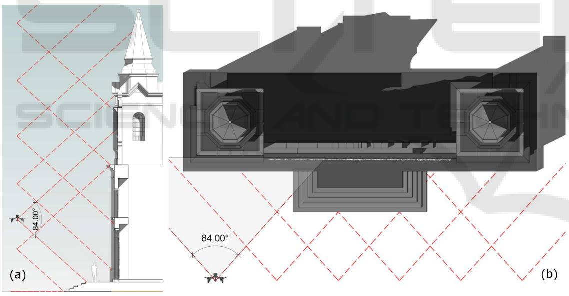


Figure 4: UAV positions for aerial photography, [a] elevation - vertical view and [b] cross section - horizontal view.

4.2 Acquisition

The following approach was taken (see figure 5):

- Improve georeferencing precision by placing UAV in high altitude, that enables a large number of satellites synchronization.
- Start object capture drawing a curved path, covering elevation ranges.
- Repeat previous steps changing sensor angle.

Our method combines elements from Murtiyoso *et al*, who established perpendicular flight succeeded by four others, changing sensor angulation in 45° (bottom, up, left and right) (Murtiyoso et al., 2016). Point clouds created using curve path instead of straight lines provides higher angle covering resulting in precise models.

The equipment used was Inspire 2 of DJI equipped with noise reduction camera Zenmuse X4S with $8.8mm/F2.8-11$ field of view 84°, 20MP 11.6 Stops resolution and 3-Axis Gimbal.

In facade acquirement, 369 photos were taken and used to create a point cloud adopting proprietary software (Pix4D, AutoDesk Recap, and AutoDesk Remake). A better outcome was shown by Pix4D, offering performance and unlimited input images. Specifically, 368 images were used (only one of then have was eliminated during software calibration), creating a point cloud containing 106 million densified 3D points with 14.286,2 average density per m^3.

4.3 Preprocessing

In the sequence, we list the preprocessing tasks used in this work.

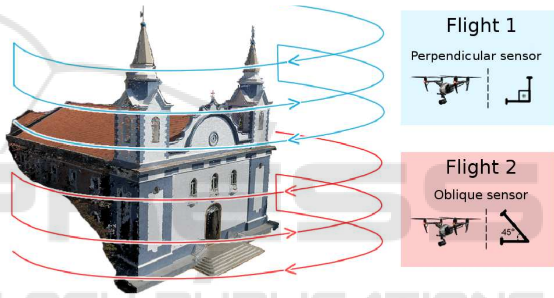


Figure 5: Flight examples with sensor angular adjustment. Perpendicular and oblique highlights.

- *Parameterized Cut:* It is possible to define a specific area, the target area, and excluding some regions of the point cloud (Alvarado, 2015), (Janssen, 2017). We define a limited volume in the point cloud and consider only the points inside it.
- *Downsizing:* We define a set of cubes as voxels representing the 3D space. For all points inside a voxel, it is considered only one, the central element (Moravec, 1996), as representative of the point cloud. The goal is decreasing the high number of points and the density of the point cloud (Wang et al., 2015).

  Noise Filtering: The scanning process using a UAV usually include incorrect points, generating data deformation (Mitra and Nguyen, 2003). An intuitive way to interpret points classifieds as noise is like outliers. In this work, we apply an outliers filtering technique proposed in (Rusu et al., 2008), based on the average and standard deviation in the neighborhood of a point, according to the Equation 1.

$$P^* = \{p_q^* \in P \mid (\mu_k - \alpha \cdot \sigma_k) \leq d \leq (\mu_k + \alpha \cdot \sigma_k)\} \quad (1)$$

where P^* represents all points in the point cloud; p^* is a subset in the neighborhood q; μ and σ are the mean and standard deviation on radius k.

4.4 Segmentation

Region growing algorithm initially developed for shape classification in images (Besl and Jain, 1988), divides point cloud into related subsets separated by surface changing (Rabbani et al., 2006).

Simplified algorithm (Rusu et al., 2008) is described in following steps:

- Let p_q be any point belonging to a set of points $P^k = \{p_1^k, p_2^k, \ldots, p_n^k\}$, a number of near points, equivalent to the regional descriptors, are defined following the equation:

  $$|p_i^k - p_q|_x \leq (1+\varepsilon) \cdot |q^k - p_q|_x, \quad (2)$$

  where q^k is the neighbor inclusion radius limited by $1+\varepsilon$ at the moment x.
- Once defined neighborhood, point correlation is used to estimate their normal vector (angle between surface and a common point, usually sensor position).
- Analogous, mean local curvature is calculated.

Before point operation, an evaluation on each normal vector $\vec{n}$ is computed by:

$$\arccos(\langle \vec{n}, \vec{n}_k \rangle) \leq \theta_{th}, \quad (3)$$

if the difference between $\vec{n}$ and $\vec{n}_k$ is less than θ_{th} threshold, points belong to the same region. Curvature checking is used for smooth evaluating surface likeness, also restricted by a parametric limit.

4.5 BIM Modelling

The clusters point cloud data was exported in OBJ format to be read in the BIM software. We used REVIT (Autodesk) to model the facade, and the software converts the point cloud raw formats into RCP (REVIT native format).

Although REVIT can index the point cloud in the Project Environment, the Revit Family Editor, where is created parametric elements (door, windows, wall moldings), does not support point cloud raw formats. It was necessary to convert the clusters OBJ format with Meshlab (open source software) into DXF format supported by REVIT Family Editor Environment.

Each BIM component was labeled using the OminiClass element, which is primitive of REVIT and later adjusting the analytical structure of the project to the classification system proposed by ABNT NBR 15.965 (based on OminiClass). Figure 6 depicts the final model of BMC facade with the point cloud cluster of the frontispiece highlighted in color (by lift), and the Family Model (parametric object) of the Front Door.

(a) (b)

Figure 6: BIM models of BMC shows [a] facade and [b] main door.

4.6 Evaluation

We evaluate the clusters obtained in the segmentation step then assess the point acquisition by comparing the spatial coordinates of control points. Firstly, we carry out the qualitative evaluation through precision, recall and accuracy metrics computation. This task considers segmented and as-designed images. Secondly, we define control points over the as-designed document and compare its spatial coordinates (or the difference) among those in the point cloud and measured by a Total Station.

We use the accuracy metric, which is calculated about the as-designed model. Accuracy, denoted by A, is calculated according to the Equation 6; Precision and Recall area given in Equations 4 and 5, respectively (van Rijsbergen, 1979).

$$Precision = \frac{TP}{TP+FP} \quad (4)$$

$$Recall = \frac{TP}{TP+FN} \quad (5)$$

$$A = \frac{TP+TN}{TP+TN+FP+FN} \quad (6)$$

where True-Positive (TP) and True-Negative (TN) are the pixels belonging or not to the reference and resulting images, respectively; False-Positive (FP) and False-Negative (FN) represents pixels belonging either to the reference image or the resulting image, but not to both. These parameters create the confusion matrix.

5 EXPERIMENTS AND RESULTS

In this section, we first introduce the dataset, the results of the proposed approach and method limitations.

Dataset. The results built upon the data acquired from the scan of the BMC, accomplished by a UAV. Initially, the point cloud had about 18 million points. Point Cloud Library[1] functions were used, as well as dedicated codes developed in Python.

Results and Discussions. After the preprocessing step explained in Section 4.3, the point cloud has now about 900 thousand points. Figure 7(b) illustrates the resulting image after the segmentation step using a region growing algorithm. Note that it was possible to divide the original image, Figure 7(a), in different clusters, representing the architectural components: this is an essential task to create a model of the scanned image.

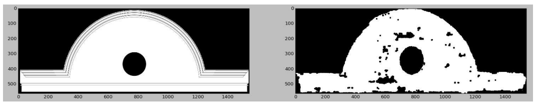
(a) (b)

Figure 7: (a) Original and (b) resulting image after segmentation (architectural elements represented by color).

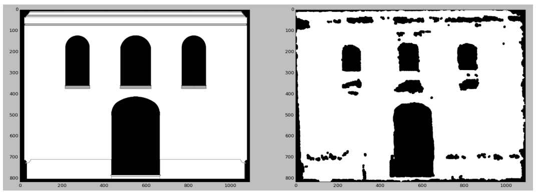
Table 1 shows the analysis of the proposed segmentation step for seven different architectural components. The clusters resulting from the segmentation stage are projected into 2D images before the comparison. This task is accomplished utilizing orthographic projection and density resizing reduction using morphological operations (Gonzalez and Woods, 2002).

Usually, clusters are mainly flats, since the property of the region growing algorithm uses the surface curvature information of the point cloud. The corresponding image as-designed is compared pixel-to-pixel according to adopted metrics. Figure 8 illustrates this comparison for two distinct components, pediment, and frontispiece: on the left, the as-designed images and, on the right, the clusters resulting from the proposed approach.

To check the accuracy of the acquired points by the UAV, we define some Control Points (CP) using a Total Station [2]. Figure 9 shows the CP defined to the facade of the Boa Morte Church. This CP was compared to the points obtained by the UAV and those from the as-designed model.



(a) Pediment (tympanum and cymatium)



(b) Frontispiece voids of windows and doors

Figure 8: As-design elements *vs* cluster projections.

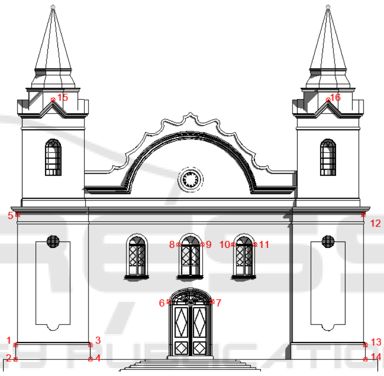


Figure 9: Control Points (CP) definition, in red.

Table 2 shows the analysis of distance between different control points using a Total Station and data of the as-designed Model and point cloud. It is possible to observe the excellent performance of the approach and acquired data. The absolute deviation of the point cloud is between $+0,06$ m to $-0,75$ m, while for the as-designed model this range is from $-0,12$ m to $+1,12$ m. Also, the average deviation is $-0,11m$ to the point cloud, or $-0,04$ m if we ignore the maximum difference (control points 2 and 14).

The photographic acquisition using the UAV, and the reconstruction employing software, provides a high precision 3D representation of the building. Its accuracy can be compared to others works, as reported by (Bayram et al., 2015), which presented a relationship among 3D laser scanning and photogrammetric reconstruction.

DSM models made from point cloud has non-structured features as lack of topology and semantic

[1] http://pointclouds.org

[2] TS650 model FOIF, angular precision $1s$, linear precision $2mm+2p.p.m.$

Table 1: Analysis of segmented regions compared to the as-designed model.

COMPONENTS	PRECISION	RECALL	ACCURACY
Frontispiece with voids of windows and doorways	87,7	93,4	85,8
Tower base (right)	94,6	86,6	84,8
Tower base (left)	94,3	94,7	90,9
Right Bell Tower	85,3	89,5	83,4
Left Bell Tower	84,4	63,9	69,5
Doble pediment (tympanum and cymatium)	55,7	39,3	82,3
Scrolled pediment	96,0	87,2	91,2

Table 2: Comparison analysis of distance (in meters) between Total Station (TS), as-designed model (AD) and Point Cloud (PC).

CONTROL POINTS	TS	AD	PC	$TS-PC$	$AD-TS$
1-2	0,99	1,00	1,00	-0,01	0,01
1-3	4,69	5,20	4,88	-0,19	0,51
2-5	10,17	10,26	10,14	0,03	0,09
2-14	22,88	24,00	23,63	-0,75	1,12
6-7	3,02	3,08	3,12	-0,10	0,06
8-9	1,59	1,93	1,65	-0,06	0,34
9-10	2,09	1,97	2,15	-0,06	-0,12
10-11	1,41	1,53	1,46	-0,05	0,12
13-14	0,97	1,00	0,96	0,01	0,03
2-15	18,16	18,52	18,10	0,06	0,36

discretization. However, the IDBHM created by BIM methodology, as we presented in this work, can provide a reliable documentation of the building, mainly the usual necessary information of historical heritage.

Limitations. The primary limitation of this work resides on its non-automated phase. Besides significant time reduction on pre-processing, segmentation and evaluation, steps as acquisition and modelling still need laboring work. Another weak point is the use of proprietary black-box software to create point clouds, which increase inter-operational dependence.

6 CONCLUSIONS

Our approach is organized in six steps, as follows:(i) capture planning; (ii) acquisition; (iii) preprocessing; (iv) point cloud segmentation; (v) 3D semantic model creation and (vi) evaluation.

We presented two main contributions, related to the data acquisition protocol and the evaluation of the image segmentation method. We proposed an evaluation model based on the confusion matrix and metrics widely used in the literature: precision, recall, and accuracy. These parameters provide useful information about the quality of resulting image obtained after the segmentation task. The comparison is accomplished between cluster image (segmented image from point cloud data) and component image (from the architectural project). Another relevant contribution was the validation step proposed in this work. This task compares points acquired by the UAV with those obtained by a Total Station and the container in the as-designed model.

The results obtained indicates a satisfactory performance of the cluster segmentation step, according to precision, recall and accuracy metrics. However, the values of these metrics are influenced by the existence of small holes in the clusters generated due to data acquisition failures. Also, we are investigating whether the projection technique used in the comparison as-designed model *vs* cluster projection could decrease the quantitative analysis performance.

In future work, we would like to improve the data acquisition process, defining a UAV flight protocol. This protocol must provide a comprehensive angular point range and high overlap rate. Besides, we also intend to implement and test different image segmentation techniques, to obtain information-rich clusters useful for further pattern recognition steps.

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