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Using 3D in design – an overview of measuring methods and experiences

Juho-Pekka Virtanen[1], Matti Kurkela[1], Hannu Hyyppä[1,2,3]

[1]*Department of Real Estate, Planning and Geoinformatics, School of Engineering, Aalto University, P.O. Box 14100, FI-00076 Aalto, Finland*
juho-pekka.virtanen@aalto.fi; matti.kurkela@aalto.fi; hannu.hyyppa@aalto.fi
[2]*Helsinki Metropolia University of Applied Sciences, FI-00079 Metropolia, Finland*
[3]*Finnish Geodetic Institute, PL 15, 02431 Masala, Finland*

Abstract
This paper discusses the use of 3D measuring in product and spatial design. Photogrammetry and laser scanning are introduced as possible measuring techniques. In the first case, a 3D scanner is utilized in jewelry design, working with rapid prototypes. In the second case, a store interior is measured and modeled from images. The third and fourth cases present the use of laser scanning to measure building interiors and exteriors. The size and complexity of the target have to be considered when choosing a measuring technique. Measuring and modeling can be used to produce 3D models usable in 3D CAD software. For design use, the modeling phase is crucial. In some cases, terrestrial laser scans can be directly visualized in CAD to reduce modeling work. To increase the utility of measuring techniques, the design and measuring processes should be more tightly integrated.

Keywords: 3D measuring, reverse engineering, 3D printing, photogrammetry, laser scanning

1 Introduction

In industrial design and architecture, the focus is in the design of physical entities. In both disciplines, various methods and tools may be used in creative work at the beginning of the design process [1], but towards the end, a 3D CAD is commonly used. As a result of practical design work, either 3D models, or drawings created from them, are usually made. 3D CAD is one of the important tools in both industrial design and architecture as it is commonly used to produce these models.

In cases where the geometry of an existing object has to be taken into account in the design process, 3D measuring and modeling technologies can be used to produce a digital model of a physical object [2]. Non-contact 3D measuring instruments that produce a dense data set of the measured object are often called 3D scanners. Typically, they are suited for measuring targets smaller than a car. In addition to the devices intended for professional use, some affordable 3D scanners are already on the market [e.g. 3]. For documenting larger targets, such as buildings, laser scanning or photogrammetry can be used [4, 5, 6]. Usually, the result of measuring is a 3D data set of the target. After this, modeling has to be performed to obtain a 3D CAD model that can be used efficiently in design. In engineering, the process of producing 3D CAD models from 3D scanned data sets is usually called reverse engineering (RE). In the context of the built environment, the work may be referred to as geodetic measurements, 3D reconstruction or as-built modeling [6]. With the combination of measuring and modeling techniques, the geometry of an existing building, space, or artifact can be utilized in design. In some cases, it is also possible to visualize the measured data set directly in the CAD software, and use it as a reference without a separate modeling phase [7].

3D scanning can also be used in design by digitizing models built during the design process [8, 9]. The geometry of a manually made model can be transferred to the 3D CAD, where it can be used in further modeling. In transportation design, this has been used to aid CAD modeling of complex free-form geometry [8]. Schnabel, Kuan, and Li have applied 3D scanning in experimental architecture, working with both the physical and digital models [10]. Ye et al. present the concept of reverse innovative design, using RE to obtain parametric CAD models of existing physical objects, and creating new products by variation of these parametric models [2].

By observing the processes of using 3D scanning, we aim to locate the potential problems in utilizing it in design. We present some of our experiences on using 3D scanning. To begin with, different measuring techniques suited for digitizing small and large targets are introduced. After this, we present a set of cases in which these 3D scanning techniques are used to produce 3D CAD compatible models from physical entities. In our experiments, targets ranging in scale from indoor environments to hand-held objects were digitized. Different 3D scanning methods were chosen for smaller objects and for building interiors.

2 Methods and materials

2.1 Photogrammetry

The techniques for producing 3D coordinates from two-dimensional images are called photogrammetry. By analyzing photographs taken from at least two different locations, it is possible to measure the 3D coordinates of the points of interest. An ordinary digital camera can be used, making photogrammetry affordable. If the object does not supply adequate natural texture, structured light can be used [11], or measuring targets can be attached to the object (Figure 1). Accuracy of 3D points will increase if targets are used [12]. Photogrammetry is widely used for e.g. architecture [13], heritage conservation [14], archaeology [15], construction engineering [16], industrial manufacturing [17], forensic [18], and reverse engineering [16]. In addition, photogrammetry is also used for combining images with other sensor data [e.g. 19].

In photogrammetric measuring, we have used a Nikon D700 camera with 14 mm lens in available light. The camera is equipped with a 23.9 mm by 36 mm CMOS sensor, producing an image resolution of 4256 pixels by 2832 pixels. The lens was equipped with a system preventing the accidental moving of focus or zoom. The camera calibration and measuring were performed in iWitness software. For calibration, iWitness targets were used.

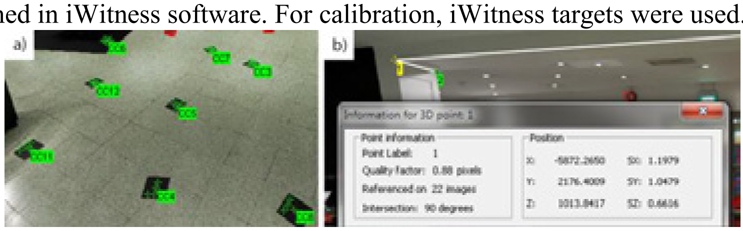

Figure 1.a) Targets automatically detected b) Pointing at a natural point for measuring.

Non-contact 3-dimensional measuring instruments, designed for digitizing individual objects, are often called 3D scanners. They can be used for e.g. reverse engineering [20], cultural heritage documentation [21], and industrial quality control and design [2, 8, 22]. 3D scanners based on structured light, using the triangulation principle (e.g. [23]), are most common [24]. In an engineering context, 3D scanning is often performed as a part of the reverse engineering (RE) workflow, aiming to produce a CAD model of the object from the 3D measurement data [25]. Common applications of 3D scanning and RE include documenting components in cases where original design documentation does not exist, or is not in a 3D CAD format, measuring molds for injection molding and sheet metal and industrial quality control [25, 26].

For 3D digitizing objects, we have used the Konica-Minolta Vivid 9i 3D scanner. The instrument performs non-contact 3D-measuring using the triangulation principle. A laser line is projected to a target and its deformation monitored with the device's camera. The 3D geometry of the target is calculated from the observed deformation. This measuring instrument is capable of attaining the accuracy of 0.05 mm on a measuring area of 111 mm by 83 mm, when using a 25 mm lens. The scanning was performed using the Polygon Editing Tools software, after which the scanned data sets were processed with the Geomagic Studio 11 software.

2.2 Laser Scanning

For measuring larger targets, such as buildings and natural environments, laser scanning can be used. In laser scanning (LS), a laser pulse is sent from the measuring instrument to a known direction, and its reflection recorded [27]. Based on the time difference of sending and receiving the pulse, the distance to the reflecting object can be calculated [27]. In Terrestrial Laser Scanning (TLS), the measuring instrument is typically mounted on a static tripod. TLS has been widely applied to building modeling [4], cultural heritage work [28, 29], and environmental studies [30]. The typical output of an LS measuring campaign is a dense point cloud data set, on which various analysis and modeling methods can be applied to obtain the desired results [31] (Figure 2).

For TLS, we use the Faro Focus 3D instrument. It is a terrestrial laser scanner using a laser wave-length of 905 nm. The measuring range of the instrument is 0.6 – 130 m, with the ranging error of 2 mm. The maximum measuring speed is 976,000 points per second. The device is equipped with a camera that can be used to retrieve color information for the point cloud. For co-registering the point clouds, Faro Scene 5.1 software was used. After the co-registration, the point clouds were written out in .pts format.

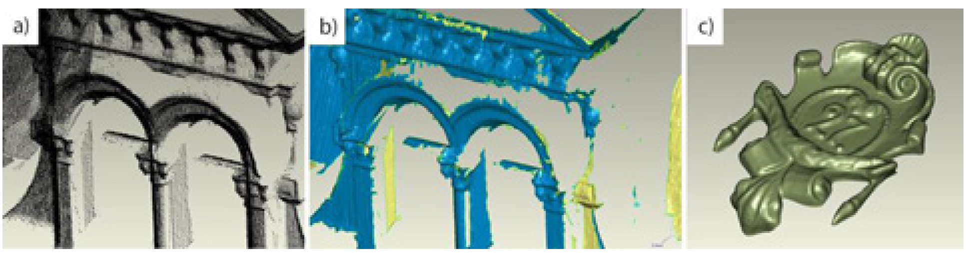

Figure 2. a) A point cloud, depicting a segment of a building's façade b) A mesh model created by triangulating the point cloud, showing gaps c) A nurbs surface model of a building façade detail, after reverse engineering. All holes have been algorithmically filled, and the surface has been smoothed. This model can be edited in e.g. Rhinoceros 3D.

2.3 Rhinoceros 3D

As 3D CAD software, we use the Rhinoceros 3D, version 4. The software is a typical surface modeling suite, commonly used in design. For visualizing laser scanner point clouds, the PointoolsPlugin for Rhinoceros was used. The Pointools Pod Creator software was used to convert the point clouds to .pod format required by the Pointools Plugin.

2.4 Stratasys Prodigy Plus

For rapid prototyping, we use the Stratasys Prodigy Plus machine. It is based on the fused deposition modeling (FDM) principle, building the printed objects in layers by extruding a heated thermoplastic material, in this case acrylonitrile butadiene styrene (ABS). The build envelope of the machine is 203 mm by 203 mm by 305 mm. Startasys Insight software was used to calculate the toolpaths for the machine.

3 Cases

3.1 Iterative design of jewelry with 3D scanning and 3D printing

In this test case, the design of a pendant was carried out using 3D scanning and 3D printing. The work started by a manual sketching phase, in which the overall design of the object was developed. After this, the wavy front surface of the pendant was manually crafted from clay. The clay model was 3D scanned with the Konica-Minolta Vivid 9i. The scanned surface was processed by the RE suite Geomagic Studio to a nurbs surface, which was used to create the first 3D CAD model of the object in Rhinoceros. After the first 3D CAD model was completed, it was 3D printed with the Stratasys Prodigy Plus FDM machine. The 3D-printed model was refined by applying putty and sanding. The refined physical model was then 3D scanned and partially reverse engineered. After this, some 3D modeling was performed, again in Rhinoceros, to finalize the design. The object was finally manufactured as subcontracted 3D printing from metal (Figure 3f).

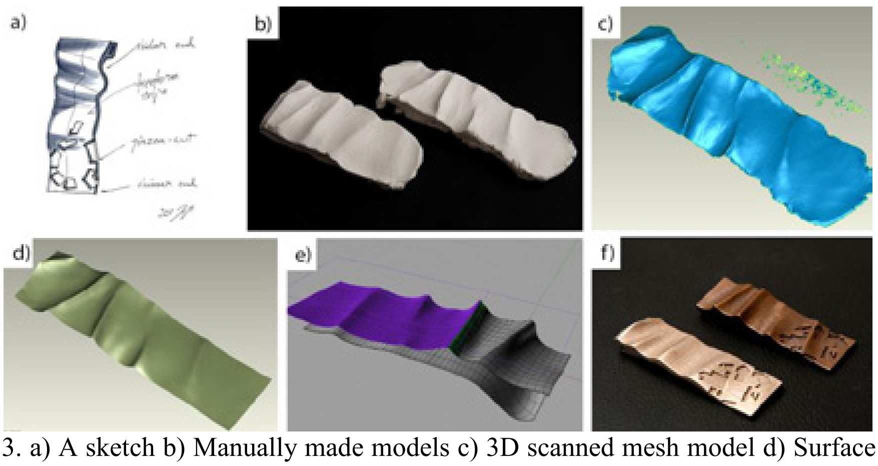

Figure 3. a) A sketch b) Manually made models c) 3D scanned mesh model d) Surface model created by reverse engineering e) Modeling the piece in CAD f) Completed pieces, manufactured with 3D printing from metal material

In 3D scanning and RE, it was easier to focus on measuring and modeling individual surfaces of the object, rather than trying to completely 3D digitize the entire piece. With the specified accuracy of 0.05 mm, the scanner could capture very small surface details. In the RE phase, the scanned mesh models had to be smoothed to eliminate surface defects of the manually modified pieces that were visible in the 3D scanning (Figure 3c). The surface models created with Geomagic (Figure 3d) were very accurate, with a standard deviation of only 0.068 mm from the mesh model in the example shown.

3.2 Image-based indoor measuring

In this case, a store interior was measured from images. The main objective of the measuring was to reconstruct a 3D CAD model useful for e.g. designing visual elements of commercial environments, such as vinyl graphics, or performing store layout design. The space had dark, light, and high-gloss surfaces, which would have been difficult to measure with a laser scanner. Measuring had to be performed outside business hours, in a limited time of two hours. Accurate corner points for the CAD model were needed. Because of these requirements, we acquired 3D coordinates by image-based measuring (Figure 4). We used a Nikon D700 camera with a 14 mm lens in available light. For creating automatic image block, we used targets. 3D coordinates of the objects was measured manually using natural texture points.

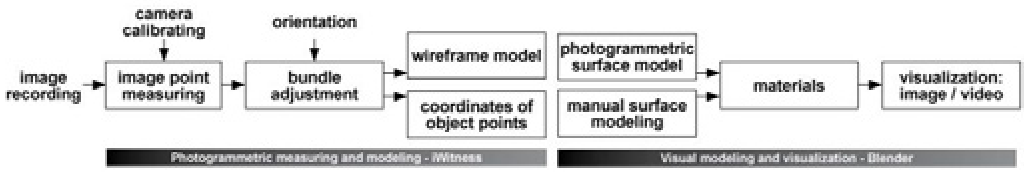

Figure 4. Photogrammetric measuring process [32].

The image block contained 81 photographs and 339 measured 3D points. The overall estimated accuracy of 3D point coordinates (RMS 1-sigma level) was 1:8300. The corner points of the shadow area were estimated in CAD using an intersection of two straight lines. Modeling work was based on measured 3D points, and it was done in Rhinoceros (Figure 5). Created surfaces were combined with the objects. For visualization purposes, we added rendering materials to individual objects (Figure 5).

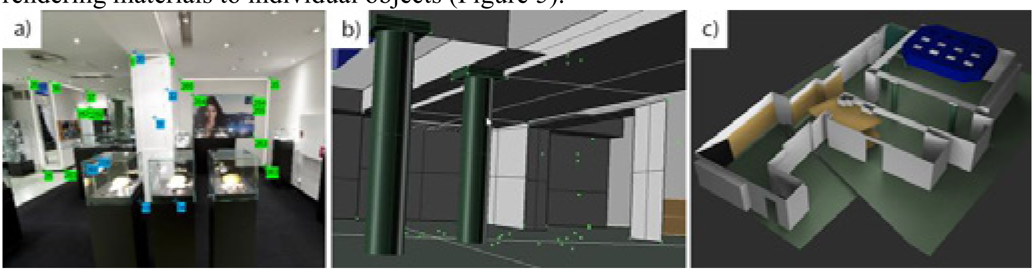

Figure 5. a) Green dots represent image-based-measured 3D points. b) The surface colors show the modeled objects. c) The final model created, shown with the roof surface removed.

3.3 Modeling a building from TLS data

A historic industrial building in Southern Finland was modeled in Rhinoceros 3D using TLS data set as a reference. No other documentation from the building was usable in the work. Pointools Plugin was used to visualize the TLS point clouds in Rhinoceros. The modeling was carried out by studying section views of the point cloud, and manually drawing the layout. A simple surface model was constructed from the drawn layouts. Both the exterior surface of the building and most of the interior spaces were modeled in the same way (Figure 6).

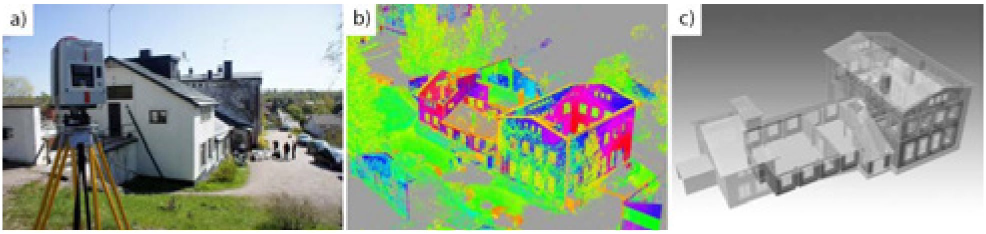

Figure 6. a) Overview of the building and the used TLS instrument b) the point cloud of the building's exterior surface c) the 3D CAD model built.

The method where the measured data set was visualized in the CAD, which was used for manual modeling, was efficient for building a rough model. As the modeling work was manual, building a more detailed model would have taken considerably more time. The accuracy and detail level of the TLS point cloud would have permitted more accurate modeling in most locations of the building.

3.4 TLS measurement of an indoor space

An old laboratory building was measured, consisting of a hall and a meeting room. The dimensions of the hall were 36 by 14 m with a height of approx. three floors. A complex balcony structure was located in the hall. The space was measured with the Faro Focus 3D laser scanner, using scan resolutions of ½, ¼ and 1/5 of the full resolution, with the average point densities at a range of 10 m being 3.068 mm, 6.136 mm and 7.67 mm respectively. In total, 11 scans were taken from the space in four hours. The scans were registered using 12 spherical targets installed in the space, with the Faro Scene 5.1 software. As the measuring campaign progressed from one end of the space to another, the targets no longer in sight were moved. In total, 31 target positions were used in registering the scans. The location accuracy of registering the scans remained high in the project (3.5 mm to 1.3 mm). In addition, a 2D layout image and some video material were rendered from the point cloud (Figure 7).

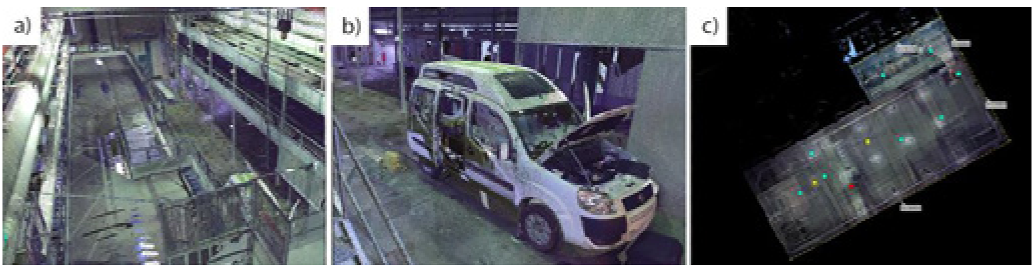

Figure 7. a) Rendered image of the point cloud. b) The high density of point cloud allows nearly photorealistic 3D visualization directly. c) A 2D layout of the measured space.

4 Results

In the jewelry case, the iterative process of working with both physical and digital models was found to be useful in designing complex surface geometries. Using 3D printing and 3D scanning to shift between the two mediums made it possible to utilize both of them efficiently. The complex freeform surfaces were created manually from clay, and more systematic features in a 3D modeling suite. An RE software, namely Geomagic, was required to efficiently work with 3D-scanned data sets. The utilization of 3D scanning and RE was efficient, as the focus was not in digitizing the entire physical object, but rather the general shape of some of its surfaces. Reverse engineering the entire object would have been more time consuming. The accuracy of the 3D scanner used was more than sufficient for this type of application, as it was able to digitize even the small surface errors in the manually made models.

In the interior design case, producing an interior model of the space was possible. The model containing the entire interior can be used for purposes like retail layout design, concept design and visualization. However, its detail level is not high enough for accurate design of fixed furniture installations, or decoration films. For these cases, limited areas of the space would have to be re-measured with more detail.

In the first TLS case, the use of point cloud as a modeling reference in 3D CAD was found efficient. The constructed model is not very detailed, but sufficient for visualizing the building and creating simple layout representations. Accuracy of the TLS point cloud is considerably higher than the accuracy of the simplified model built in the case. The point cloud would permit more detailed modeling.

In the second TLS case, a large indoor space was measured with the aim of producing a dense point cloud covering the entire space. The measuring work took four hours at the location, and a full working day was required for data processing, during which the point clouds were co-registered and colored according to images of the devices' camera. As the ranging error of the Faro Focus 3D measuring instrument is 2 mm, we can assume that in the individual point clouds, the errors remain below this. Between two point clouds, the registration errors remained below 3.5 mm, combined with the ranging error of the scanner; this gives an accuracy of 5.5 mm between two co-registered point clouds. Clearly, the resulting point cloud can be used for planning purposes.

5 Discussion and conclusions

Based on the presented cases and literature, we can say that 3D scanning can be utilized in industrial design and architecture. The measurement techniques can attain sufficient accuracy, and 3D CAD models that are compatible with commonly used 3D modeling suites can be created based on the measured data. The cases highlight the significance of the modeling stage. In most design applications, a 3D CAD model is essential for utilizing measured data. From the design perspective, the modeling is an integral part of the 3D scanning process.

Different targets require different measuring techniques. The TLS used is not applicable to measuring small targets; both the ranging error of 2 mm and the measuring range starting from 0.6 m prevent this. On the other hand, the Konica-Minolta Vivid 9i can only attain a measuring range of 1.7 m, and is ideally suited for measuring target within a range of 1 m. For measuring buildings, environments, and targets alike, TLS is better suited. For measuring individual objects, a 3D scanner is needed. Both of these techniques produce a dense data set of the target's surface geometry and are, therefore, suited for measuring free-form surfaces. If measuring is performed from a set of images, the measuring range is more flexible. However, with current software, the photogrammetric measuring is not ideally suited for digitizing free-form surfaces, as the measuring is carried out point by point. This limits its applicability to design. For measuring built environments, it can be useful, as the corner points of the space can be measured.

If comparing the measuring techniques used in this paper to traditional coordinate measuring machines (CMM) used in industry, we can see that their accuracy is not as high: e.g. the Zeiss Contura G2 can attain an accuracy of 1.8 + L/300, meaning approx. 3.5 µm (0.0035 mm) in measuring distance of 500 mm. Professional CMMs are large in size, and due to their weight, difficult to move. In this sense, non-contact measuring instruments, like the Faro Focus 3D or Konica-Minolta Vivid 9i, are more flexible to use.

Special equipment and software was required for 3D measuring. For the TLS and 3D scanner used in the cases, the purchasing price would be prohibitive for small design firms. In this sense, photogrammetry is an interesting alternative to 3D scanners, as the equipment needed is more affordable. Currently, the equipment price and requirement of know-how encourage the use of measuring as a subcontracted service. The possible emergence of affordable 3D scanners and TLS instruments is likely to affect the design discipline. If the equipment and software becomes more affordable, it can be more widely used to aid 3D CAD modeling and save time. The development of automated image based measuring methods may also result in tools that can be used in design.

In addition to the availability of equipment and know-how requirements, the integration of the processes is important for efficiently utilizing 3D scanning in design. In the cases, we found that even when discussing the design of a single object, it was more efficient to only digitize selected surfaces of the piece. Producing an accurate model of the entire object would have been more time consuming and not useful for the design work. This was also true for interior spaces: producing an accurate model of the entire space would have been very time consuming. The concept of carrying out an independent measuring campaign before any design activities, resulting in an accurate “general purpose” model, is clearly not feasible for all design applications. Instead, the design and measuring processes should run in parallel. In some situations, it may be useful to create a rough model of the overall target. This is especially true in architecture. In these cases, the model accuracy and amount of detail should be kept low enough. In the future, it might also be possible to have such a base model from existing data sets. The advance of Building Information Modeling (BIM), in which an accurate and detailed 3D model of the construction project is used, may lead to a situation where relatively up-to-date data from the built environment is available without measuring. In this case, such existing data sets could be used to start the design process.

The method of visualizing TLS data sets directly in 3D CAD software has the potential to solve some of these process issues. As the modeling can be performed with regular 3D CAD software, it is possible for the designer to carry out modeling “ad hoc”. It is also possible to use the point cloud itself as a rough overall model in some cases. The measuring work only produces a combined point cloud data set of the target, making it more efficient and easier to subcontract than in a case where the modeling is carried out by someone else than the designer.

To conclude, we suggest an integrated design and measuring process (Figure 8). In the process, rough measuring or existing data sources are used to obtain an overall model of the target. After this, the design process is initiated. Before detailed design is performed, the chosen areas of the target are measured and modeled with sufficient accuracy.

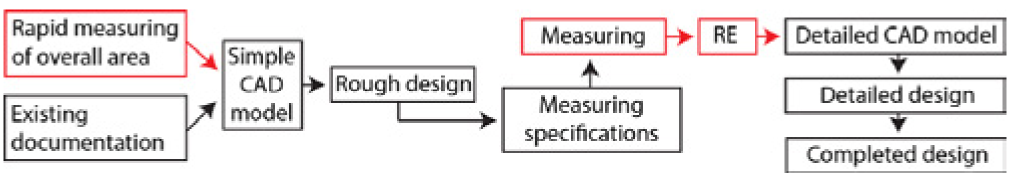

Figure 8. The integrated design and measuring process.

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