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Use of 3D laser scanning for flatness and volumetric analysis of mortar in facades

Uso do escaneamento 3D laser para análise de planicidade e volumetria de argamassa em fachadas

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Abstract

The ongoing process of industrialization of construction sites encourages the use of new building systems that conflict with traditional techniques associated with the risks of incompatibilities and continuance of control fixed ideas with a significant variability. A practical example is the cement mortar for plastering, commonly used as a corrective factor for facade flatness failures caused by the inaccuracy of the plumb line, rudimentary method used in geometric control of concrete structures and facade of mapping during the execution of the work, favoring the accumulation of errors that reflect the mortar thickness, increasing consumption, losses and defects. Alternatively for improvement, this study analyzed through a case study, the innovative application of 3D laser scanning technology consolidated on the facade of a building to map the surface flatness of the façade and, in an unprecedented manner, to quantify the volume of mortar. The results showed the feasibility of the technique as a solution to accurately identify the critical areas of the facade on the peripheral concrete structure and masonry and calculate, based on the volumes, the financial impact associated with mortar overthicknesses in critical areas compared with the reductions thickness after treatment of these areas.

Keywords: 3D laser scanning; facade; mortar; volumetric.

Resumo

O processo contínuo de industrialização dos canteiros de obra estimula o uso de novos sistemas construtivos que conflitam com técnicas tradicionais associada aos riscos de incompatibilidades e permanência de controles executivos com significativa variabilidade. Um exemplo prático é a argamassa cimentícia para reboco, comumente utilizada como fator corretivo de falhas na planicidade das fachadas causadas pela imprecisão do fio de prumo, método rudimentar usado no controle geométrico das estruturas de concreto e no mapeamento da fachada durante a execução da obra, favorecendo o acúmulo de erros que refletem nas espessuras de argamassa, potencializando consumo, perdas e defeitos. Como alternativa para melhoria, este trabalho analisou através de um estudo de caso, a aplicação inovadora da tecnologia consolidada de escaneamento 3D laser na fachada de um edifício para mapear a planicidade superficial da fachada e, de forma inédita, para quantificar o volume de argamassa. Os resultados mostraram a viabilidade da técnica como solução para identificar com precisão as áreas críticas da fachada sobre a estrutura de concreto periférica e alvenaria e, a partir da volumetria, calcular o impacto financeiro associado às sobrespessuras de argamassa nas áreas críticas comparada com as reduções de espessura após tratamento dessas áreas.

Palavras-chave: escaneamento 3D laser; fachada; argamassa; volumetria.

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1. Introduction

Currently the conception of new real estate projects has signaled a deadline versus cost balance that makes it possible to reduce the working time and investments return. It is a relationship that implies the need to industrialize the worksites through a gradual change from rudimentary to modern constructive techniques aiming at higher productivity, but with risks of incompatibilities and continuance of control fixed ideas with a significant variability. The elimination of such risks is a critical factor to prevent failures during the execution of the works and impacts both on the system technical performance and the quality and durability of the constructions, reflecting on the actual costs and the sustainability of the projects (BARROS [5]).

A practical example is the regularization of facades with mortar for plastering, a step that, after being influenced by previous phases, may result in an increased consumption of materials, time and workmanship, when compared to what is initially foreseen in the project.

The influences on the regularization of facades begin in the geometric control of surfaces of pillars and facades by the plumb line that is made out of wires one end of which is attached to metal or wood rods placed on the cover of the building and the other end of which is attached to weights that are usually made of concrete test specimens or paint cans filled with concrete to tension the wire and assure the alignment as illustrated in Figure 1-a (BARROS [5]).

This rudimentary technique used to check the alignment and leveling of concrete molds of every floor and also between the floors is also used as a reference for mapping the mortar thicknesses on the facade after the masonry is completed, the tolerance of which for deviations (±15 mm) as per ISO 7976-1 standard is higher in relation to the other instruments under the same standard to check the verticality (BARROS [5]).

Despite the fact that the use of the method of the plumb line during the process of mapping the facade makes it possible to identify some critical points of irregularity of the substratum and an estimate of the mortar volume, it is a manual and artisan method, wherein its little extent in relation to the mapped area - approximately 30% of the number of external walls in each floor - and its inaccuracy result in the misalignment between the floors and consequently a lack of square and plummet of the concrete structure and masonry (COSTA [8]; OLIVEIRA [16]).

In this case, a few points should be emphasized, such as: the natural difficulties to attain a perfect alignment of the concrete structures (beams) on the peripheries, in view of the access to support the struts; the problem of accumulating errors in function of the transfer of levels and position of structural elements that is often accomplished floor-by-floor but not from external references.

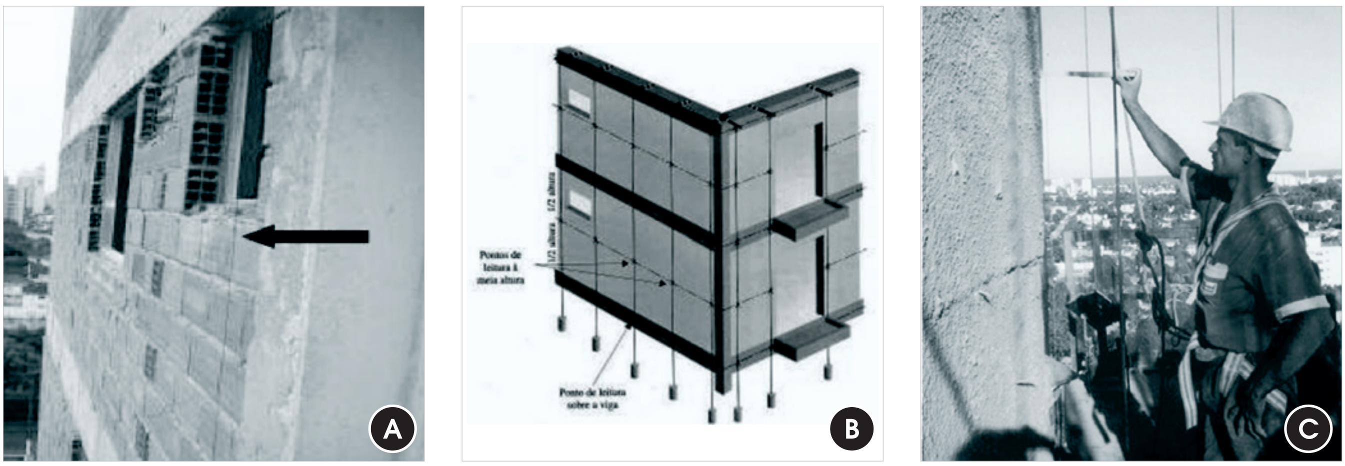
This condition favors the accumulation of errors and brings about changes in the average thicknesses of the mortar cover of the facade, from 26% to 73%, and the thicknesses below the 2 cm - 3 cm interval, indicated by NBR13749 (ABNT [3]) standard as permissible for external coverings may turn into fragile points that might cause failures, thus compromising the protective function of the covering, while the overthicknesses, besides representing losses of material that may range from 6% to 39% and risks of failures deriving from fissures in the coverings and additional loads in the structure (COSTA [8]), are considered in many studies as one of the greatest mortar waste factors (PICCHI [18]; PALIARI [17]; AGOPYAN [1]; SOIBELMAN [21]).

In addition to the cost of wasted material, the increased cost associated to the workmanship is quite representative, since, in the case of mortar thicknesses higher than the recommended ones, special care should be taken to assure the adherence thereof, thus increasing the amount of H.h/m² (BAIA [4]).

Therefore, once the plumb line is established as the method for aligning the structure and the mortar thickness reference method, the exactness in the calculation of the mortar volume is reduced and the difficulty in correcting and acting effectively in the improvement of the final thickness of the mortar covering is increased.

In this sense, the emergence of 3D laser measuring methods for a huge number of applications in the latest years (SU [22]) stimulated by specific needs, has contributed to the availability of different types of 3D scanners in the market (GRYZAGORIDIS

Figure 1 – (a) Plumb line positioned on the facade; (b) Reading pointfor mapping the facade by using a plumb line (DIOGO, 2007); (c) Mapping of the facade (BARROS (5))



[14]). In connection with the evolvement of technology, it has become possible to carry out procedures in the field in a relatively short time and, though the equipment costs (hardware and software) still represent a restriction (SU [22]), they are not an obstacle to its applications in the worksite.
The development of an equipment able to scan large surfaces such as facades, the provides reliable accurate measurements, extended the possibility of applying this technology in the worksite, thus making the technique increasingly recognized in the civil construction field (ZHANG; ARDITI [24]) and used more often in the whole life cycle of a building. Usually known as information models, they are used for many purposes, including the detection of errors made during the construction and maintenance control of the building (XIONG [23]).
The 3D laser scanning is a reliable, practical and functional technique for comparing the consumption of materials foreseen in the project with the actually consumed material in the work (ZHANG [24]). Thus, the purpose of this study is to verify - by means of the study of a case - the viability of using the 3D laser scanning to map the flatness of the facade and quantify the mortar volume as a necessary and efficient solution aiming at reducing the mortar consumption, without necessarily needing to subject same to a higher geometric control of the structure and sealings (PALIARI [17]), since despite the fact that the geometric control is present in all the building construction phases and represents an important tool in the constructive rationalization (COSTA [8];BARROS [5]), it still has not been executed integrally and correctly in a great number of constructions in Brazil.
Since it is a relatively new technology to be used in the worksite (ZHANG [24]) and a study on this technique applied to mortar volume has not been found to date, a brief review on the functioning of 3D laser scanners 3D will be presented hereinbelow.

1.1. Basic principles of the 3D laser scanning technology

The 3D laser scanning is a high precision detailed remote measurement and digitalization in three-dimensional surveys, providing a few errors in relation to traditional methods, translated into the accomplishment of special complexity technique projects in different areas such as engineering, architecture and infrastructures [25].
Its name derives from the use of the laser in linear measurements, and the use of horizontal and vertical scanning in angular measurements, and also the fact that it is stored as crude data, essentially X, Y, and Z coordinates (3D), calculated in real time from linear and angular measurements [11].
We may divide its evolution to date in four generations (table 1).
There is a variety of technologies for the digital acquisition of the shape of a 3D object. The classification is divided into two types: the ones that require a contact with the surface that is being

Table 1 – Evolution of 3D laser scanner

Year of manufature	Portability	Measurement frequency (points/second)	Reach (m)	Laser directing prism	Software/hardware	Field works	Accessories
1997	Low	1,000 to 5,000	200	Fixed – limited to one window, manual rotation to obtain a cluster around the equipment	Complex / slow	Limited – too much time to be carried out and amount of data generated	Not integrated – external computer to store data and power source
2000	Low	100,000	600	Horizontal 360° turn	Complex / slow	Possible - mining	–
2007	High	500,000	2,000	–	Friendly / productive – integrated	Extended to other areas of use, e.g., architecture	Integrated (storage, battery and camera)
2010	High	1,000,000	4,000	Horizontal 360° turn and vertical 270° turn – cameras associated to the movement	Friendly / use of complex algorithms for modeling and fast extraction of information – data processing in the field	Applicable in many areas of use	Integrated

digitized, used for small objects, and those without any contact at all. The solutions without any contact can be subdivided into two main categories: active and passive. There is a variety of technologies that fit into the extent of each of these categories, the active one being the category that is of interest to the study in question (CURLESS [9]).
In the active technology, the physical process of the laser scanner takes place through the emission of a light source (laser) and detection of the reflection, generating precise three-dimensional representations of the surface of said object. The main scanners used in this type of technology are of three types, as given in table 2 (ZHANG [24]).
The current scanners applied in civil engineering and architecture are those of spherical scanning comprising the vertical rotation of a mirror combined with the horizontal rotation of the scanner, so that the scanner digitizes its whole field of sight – point-to-point - moving the direction of the telemeter, a precision device designed to measure distances in real time, however, the laser telemeter only detects the distance from a point in its direction of sight, thus reproducing the distance from the origin of the scanner to the object [25] in a reliable way. The result of a scanning is a "cloud of points", a cluster of points (like a data file) in a three-dimensional system of coordinates (X, Y and Z), representing the external object surface (figure 2-a) that, after having been captured by a 3D laser scanner, can be processed and combined in precise 3D models (figure 2-b) composed of millions of points, usually using a suitable software (SU [22). The density of the points depends on the speed the laser sweeps the surface. A laser scanner may provide a fast good quality precise analysis, besides detecting the characteristic of any object (ZHANG [24]). Measurements of individual points may have a precision of a few centimeters or less than one millimeter depending on the detector, the interval and the surface that is being digitized (XIONG [23]).
A unique laser scanning characteristic along the survey is the ability to manipulate and visualize high resolution data, usually without being limited by environment restrictions during the operation (Golparvar-fard [13]). More recently, mobile digitalization systems have become available, reducing the work time thanks to some precision of the registered cloud of points. When applied to the facades of a building, the method begins with a cluster of clouds of points that, when moved to a common coordinates system - a process usually called alignment or registering system - from several points of the facade are merged to form a complete semantically rich 3D model containing the geometric information and the identity of the facade (BERNARDINI [6]; XIONG [23]).

Table 2 – Use of 3D laser scanner – equipment vs. precision

Type	Principle	Main advantages	Main limitation	Final maximum precision in the field	Measurement frequency (points/second)	Reach	Applications	
							Type	Description
Time of flight	Measurement of the time the emitted laser pulse takes to return to the equipment to calculate the distances of the object points	Long reach	Low data capture speed – only one point is calculated at a time	10 cm	10,000 ~ 100,000	20 km	Civil engineering: topographic survey of roads and buildings	
Phase based	Measurement of laser light phase shift to calculate the distances between the scanner and the object	Higher data capture speed	Medium reach < 500 m	20 mm	>1 million	500 m	Industrial plants, civil engineering or architecture	Definition of spaces Filling of detailed models of information on the construction of existing buildings
Phase shift	Pulse over the wave phase, associated to previous ones	Maximum precision and lower noise (inaccuracy)	Short to medium reach < 150 m	0.5 mm	>1 million	150 m	Mechanical devices, equipment, instalations and industrial plants, civil engineering and architecture	Whenever the precision and number of details have a more relevant role

Figure 2 – (a) Illustration of a cluster of points captured by the scanner (Source: T1 Engenharia); (b) 3D model processed from the cluster of points captured by the scanner

Despite the high precision of a laser scanner, a number of limitations and challenges in the implementation thereof in the worksite can reduce the benefits observed (Golparvar-fard [13]). Such limitations include the fact that only the data on the objects that are inside the line of sight of the scanner can return, thus causing a discontinuity of the space information by obstacles/interferences that prevent the laser from reading (JASELSKIS [15]), called a shaded zone in this work, being able to create concealments in the target object and even generate mistaken interpretations of the model. Moreover, it is dependent on a number of factors, including the minimum and maximum distance between the object and the scanner, the reflectivity of the target surface, the measurement angle and time for a complete scanning (AKBARZADEH [2]).

Despite the fact that most of the works assume that the concealments are minimum or that the concealed regions of a point of sight can be observed from another point (FRUEH [12]) (PU; [19]), there are many solutions proposed for the general problem of reconstruction of concealed 3D surfaces, also known as “fulfillment of holes” (DAVIS [10]; SALAMANCA [20]).

In studies directed to the problem of reconstruction of exteriors of buildings, using laser scanner data, for example (FRUEH [12]), in general the emphasis has been on the creation of realistic visual models instead of geometrically precise ones. By using algorithms, plain corrections are extracted from the data (cloud of points), but they do not explicitly recognize the identity of the concealed components (XIONG [23]).

2. Materials and experimental program

The viability of the use of the 3D laser scanning in the work encompasses different intervening factors that range from the selection of the scanner to the characteristics of the worksite and the project. In order to reach the object of the work, the study of a case in a building in construction was developed, wherein a series of analyses and interpretations have been carried out using the scanned model of one of the facades.

2.1. Selection of the equipment

The time for a complete scanning was pointed out in some previous studies as a limitation of 3D scanning, thus the first aspect to make it possible to use this technology in the facade of buildings was to identify an equipment able to quickly scan the surface in question and sufficiently portable to be carried and assembled, favoring its conveyance and use in the worksite.

Figure 3 – SURPHASER 25HSX scanner

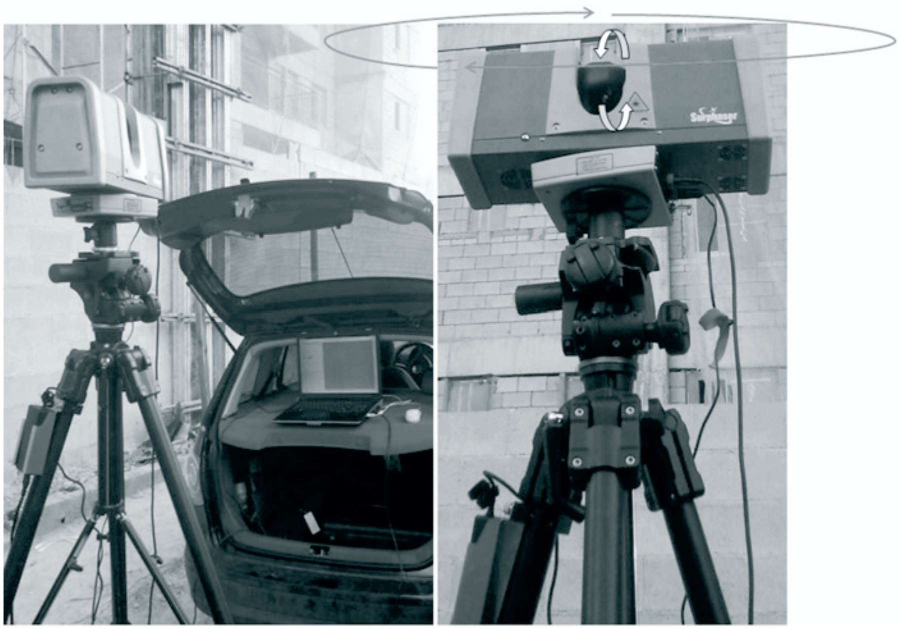
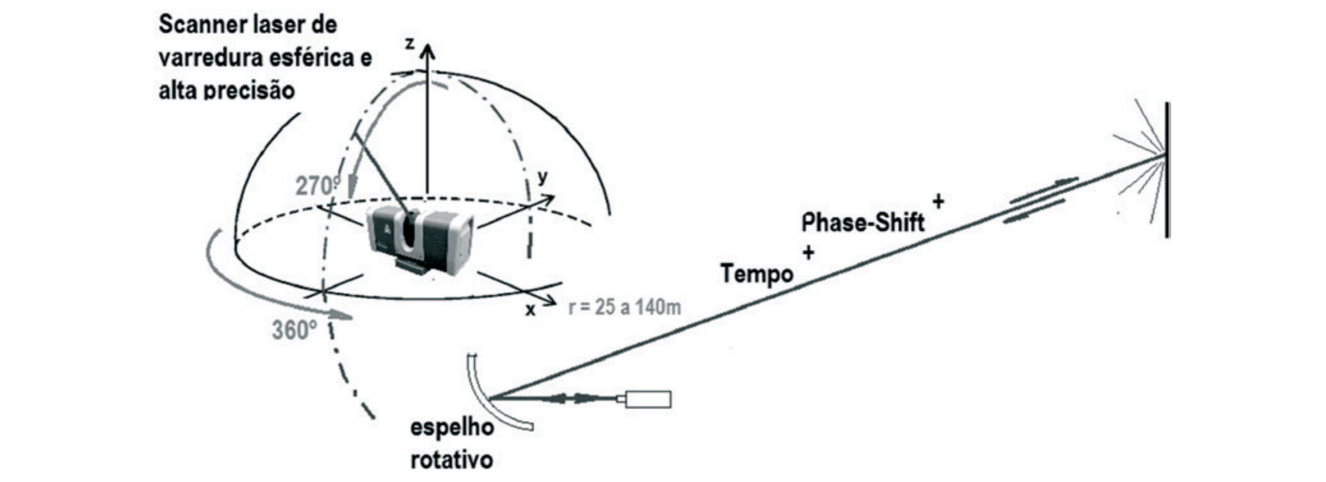


Figure 4 – 360° scanning scheme. (Source: T1 Engenharia Digital)



The selected scanner was SURPHASER 25HSX (figure 3-a) that uses the high precision phase-shift type laser hemispheric scanning technology. The laser is scanned around the scene that is being digitized in three dimensions, gathering distance measurements at specific angle intervals (figure 3-b). The equipment has a 0.1 mm to 0.2 mm precision, a maximum reading radius of 25 meters, a maximum angle of 85 degrees and a capture speed that varies from 300,000 to 1,200,000 points per second, making it

Figure 5 – (a) Schematic representation of the distance of the scanner in relation to the facade; (b) Schematic representation of the scanning area of the facade in relation to the capacity of the scanner and scanning volume within a 25 meter radius

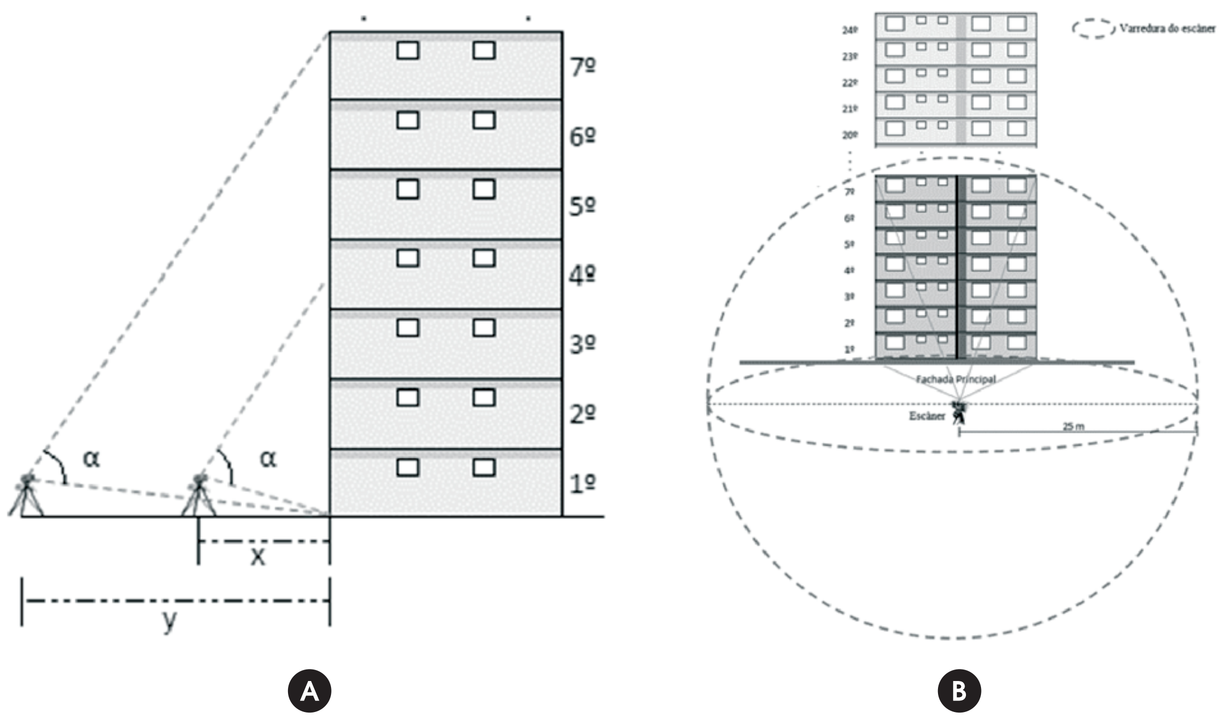
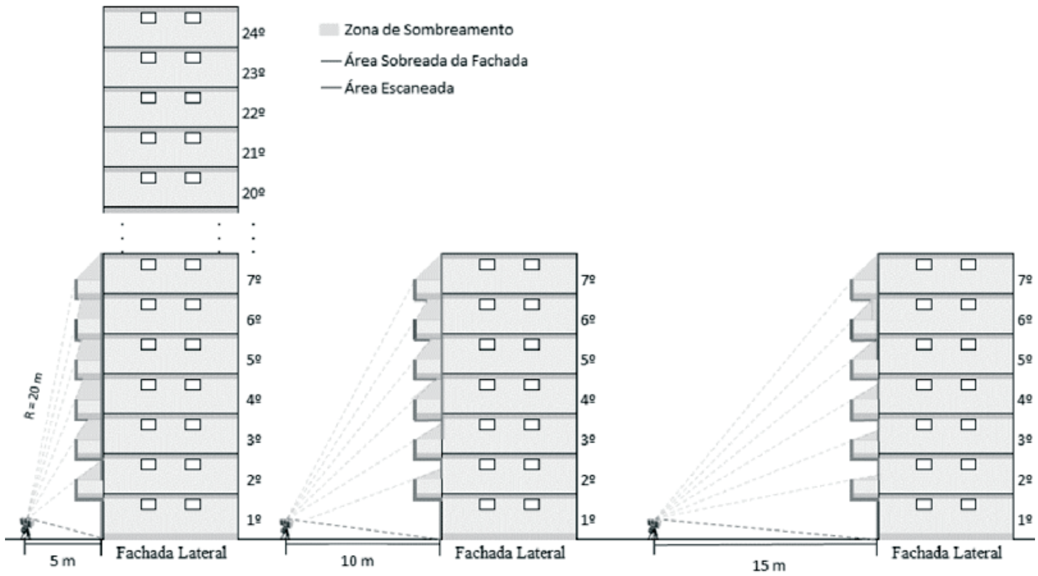


Figure 6 – Reduction of the shaded area of the facade as a function of the distance of the scanner in relation to the building facade



possible to scan a facade in a few minutes. The noise level (inaccuracy) below 0.2 mm associated to the density of points makes it possible to capture precise details of the scanned surface.
In order to keep the stability, the equipment is connected to a tripod and the data collected during the scanning are stored in a notebook connected to the equipment either by means of a USB cord or wireless.
As illustrated in figure 4, to produce a 3D model 3D, in this type of scanner the blue head may turn 360º horizontally, while the capsule where the rotating mirror is located - in the central part of the head - emits the infrared laser as it turns 360º vertically to measure the distance of the object on its way, thus making it possible to perform the hemispheric scanning and a 360º x 270º field of sight.

2.2. Contour conditions

The viability of the use of the 3D laser scanning in the worksite also encompasses contour conditions related to the characteristics of the worksite and the project. Thus, the second step was to identify and deal with these points.

Conditions for assembling and using the equipment in the work:

- Power outlets in the reading sites.
- A flat place of approximately 2 m² for assembling the equipment (installed on a tripod).
- A combination of distance (gap) versus reading angle between the equipment and the facade:
- Restrictions for removing or approaching the equipment in relation to the building can generate reading angles above 85 degrees that make it impossible to scan the whole facade with a sufficient quality of the model for analysis (Figure 5-a).
- In constructions above the threshold reading radius, the scanning shall be performed by either a higher capacity equipment or more than a shot, wherein the combined model is combined with the aid of a software later on (Figure 5-b).

Conditions for accomplishing the reading:

- Absence of shaded areas, that is, areas/points that - after the localization of the scanner and the reading angle are defined - generate obstacles (blind points) between the equipment and the surface to be evaluated, thus concealing the scanner reading. Shaded zones are as follows:
  - Verandas and balconies outside the main plan of the facade and decorative elements.
  - Scaffolds and facade screens, balance beams, walls or any element/object located between the scanner and the reading surface.
- The shaded areas can be reduced or eliminated:
- Depending on the distance and/or position of the scanner in relation to the facade (Figure 6). To make it possible to position the scanner outside the shaded zones it is required to use devices such as, for example, lifting planks (Figure 7-a) or rods (Figure 7-b) extending from the facade. This procedure increases the complexity and the cost of the service, so it is recommended to make a viability analysis considering the new scenery.
- By reconstructing the surfaces with the use of specific software, however, since the aim is to capture the imperfection of the facade, the reconstruction surface techniques that use specific software are not effective since they operate with visual models that are not geometrically precise and do not explicitly recognize the identity of the concealed components.

Compliance with the time schedule of the work:
- To assure the full scanning of the facade without causing any change in the routine of the worksite or interventions in operational stages, the required alignment shall be performed by the time the masonry step is finished, and if the scaffolds/balance beams and facade screens that are required for performing the covering of the facade have not been installed yet.

2.3 Selection of the work

From the number of available works, the study was carried out on the work that better fulfilled the contour conditions and the requirements established as necessary in the planning stage for a full reading of the substratum surface.

Characteristics of the work:
- Work in a reinforced concrete structure whose alignments and levelings of the concreting molds were performed by the wire technique.
- Sealed masonry in concrete blocks lined up and leveled by the same technique.
- Area of the facade without shaded zones (concealments).
  - Phase of the work: concrete and masonry sealed structure finished, mortar blasting and regularization in mortar not initiated.

The chosen work was a 24 floor building, however, the maximum possible span between the scanner and the facade was approximately 10 m, and a portion of the facade was covered with a screen (Figure 8-a), only seven floors of a front facade have been scanned, that is, the analyzed area represented 14.3% of this facade as illustrated in Figure 8-b.

2.4 Use of the Geomagic software

In order to analyze the flatness of the facade and quantify the mortar volume by using the Geomagic software after the scanning of the facade, the following steps have been carried out:

2.4.1 Flatness of the facade:

- Position the complete 3D model in relation to the original project;
- Calculate the reference plane of the facade that passes through the axis of the beams from the medium point of the surfaces thereof;
- Generate the map of colors showing visually all the depressions and protuberances of the substratum in the software, from the medium plane;
- Visualize the areas with higher impact degrees on the flatness of the facade (structure and masonry) and identify the places with the maximum and minimum mortar thicknesses;
- Calculate the planes by simulating different mortar thicknesses, showing by means of a scale of colors the thickness changes by calculating the distance from each point of the planes to the surface of the scanned facade;

Figure 7 – (a) Use of lifting planks, and (b) rods extending to the facade as a resource to reduce the shaded areas (Source: T1 Engenharia Digital)

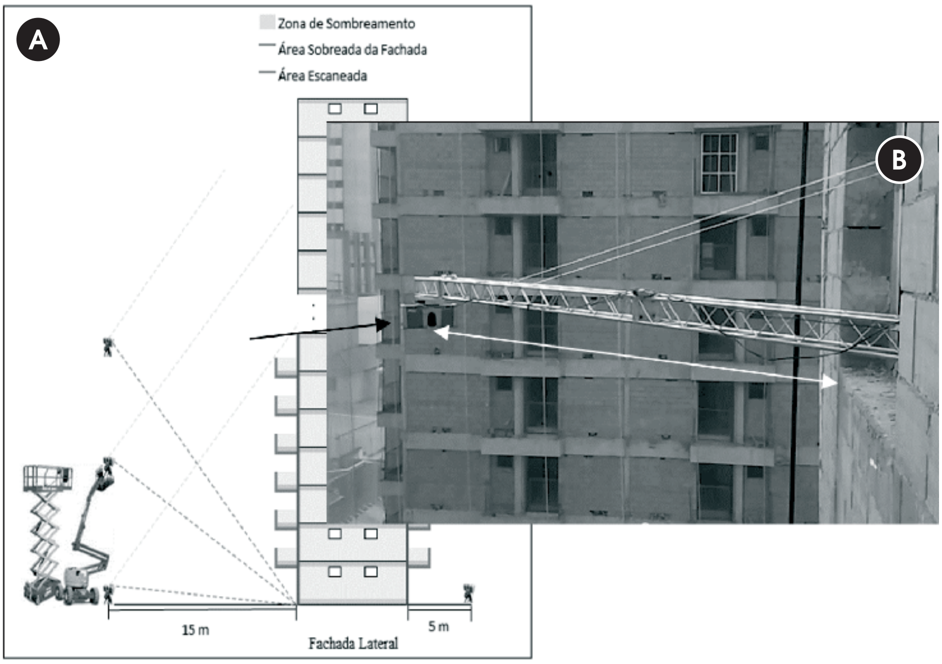
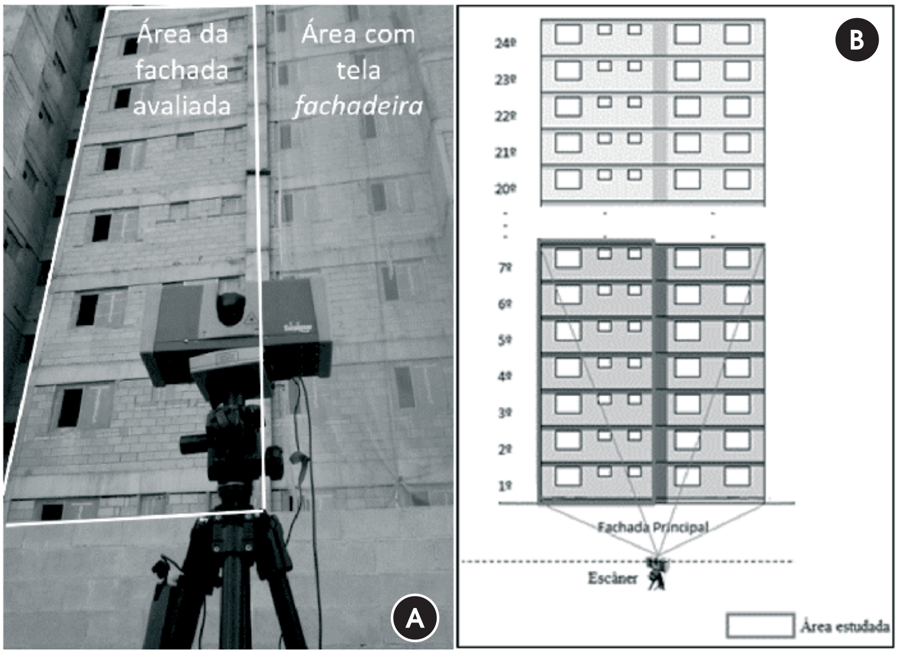


Figure 8 – (a) Image of the work showing a detail of the evaluated facade and the facade screen; (b) Schematic representation of the scanner position in relation to the building



- Compare the highest thickness and average thickness of the mortar in each plane with the 25 mm thickness (average of the thickness between the 20 mm to 30 mm interval for mortar in the facade as per NBR13749 (ABNT [3]) standard;
- Identify the planes with maximum and minimum area percent with a minimum thickness of 25 mm and spots where these areas are concentrated.

2.4.2 Mortar volume measurement

- Position the whole 3D model in relation to the original project;
- Calculate the reference plane of the facade that passes through the outmost point of the facade, showing the distribution of thicknesses in the regions of the facade behind the plane by means of a scale of colors;
- Generate the map of colors showing the total area percentage with a minimum thickness of 25 mm;
- Calculate the planes by simulating different mortar thicknesses up to at most 25 mm on the outmost point of the facade (100% of the facade with a minimum thickness of 25 mm), and show the thickness changes in a scale of colors by calculating the distance from each point of the planes to the surface of the scanned facade;
- Compare the mortar consumption in each plane versus the total area percentage with a minimum thickness of 25 mm;
- Identify the savings in the mortar consumption from the volume percent reduction in comparison with the plan where 100% of the facade, irrespective of the irregularities, with a minimum thickness of 25 mm;
- Analyze the economic viability of the use of the 3D scanning technique in this study of a case.

2.5 Experiment performed and definition of reference planes

In order to accomplish the scanning, the scanner was positioned facing the facade (Figure 9a). From the scanned model and using resources of the Geomagic software that has been developed by the manufacturer of the equipment, two reference planes used as the base for the studies of mortar consumption were created.

As illustrated in Figure 9-b, the first reference plane P0 passes through the axis of the seven beams and passes through the medium point of the surfaces thereof. Five new parallel planes named as P1, P2, P3, P4, P5, at a distance of 5, 10, 15, 20 and 25 mm, respectively, from P0 (Figure 9-c), were traced, simulating different mortar thicknesses.

While the first plane of reference was traced from the beams of the facade, the second reference plane was traced from the outmost point of the facade as illustrated in Figure 10-a. Three new planes spaced apart 5, 15 and 25 mm, respectively, (Figure 10-b) were created for the purpose of simulating a mortar covering to comply with a thickness of 25 mm (medium thickness between the 2 to 3 cm interval as per NBR 13749 (ABNT [3]) standard over 100% of the area of the facade with coverings that did not comply with this premise (5 mm and 15 mm).

Figure 9 – (a) Distance of scanner in relation to the facade; (b) 1st reference plane; (c) Planes simulating different mortar thicknesses (5 mm – blue / 10 mm – red / 15 mm yellow / 20 mm – green / 25 mm – grey) and parallel t the 1st reference plane

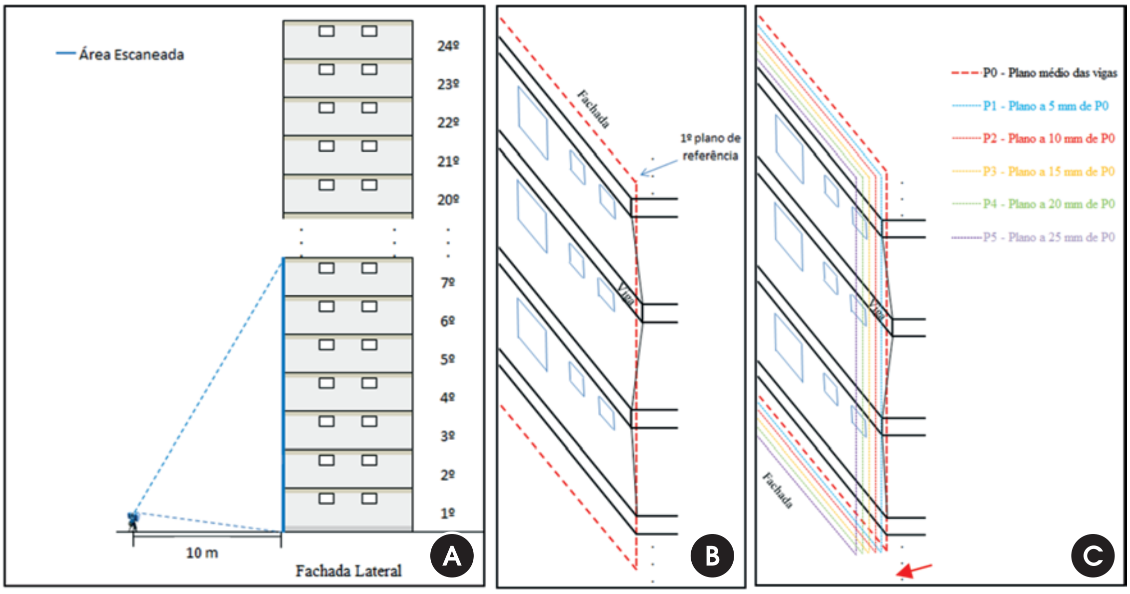
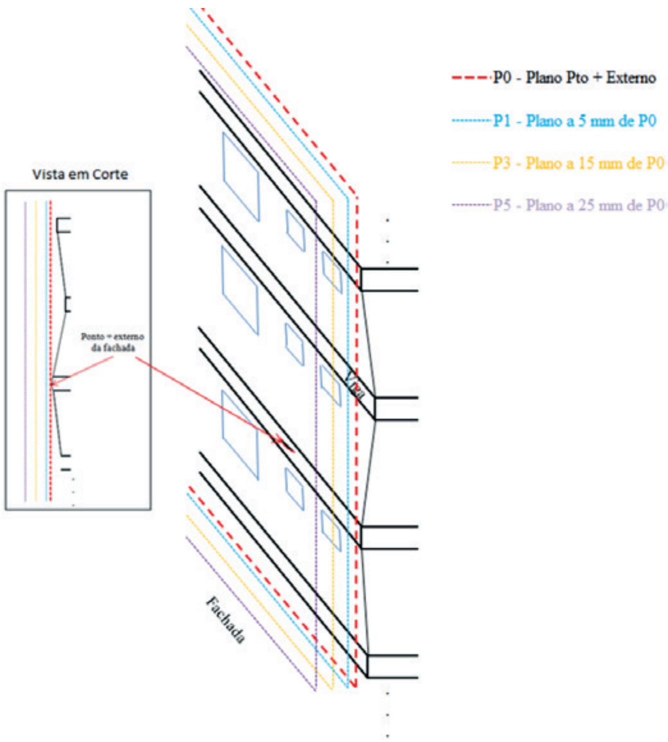


Figure 10 – (a) Detail of the outmost point of the facade in Plane 0'; (b) Illustration of the planes at 5 mm (blue), 15 mm (yellow) and 25 mm (grey) in relation to the plane (red) traced from the outmost point of the facade



3. Results and discussions

From the scanned model (Figure 11) of the facade under study, a series of analyses and interpretations have been made, by considering the following items:

- Execution quality of the substratum, measured through the detailing of the flatness generated by the 3D image;
- The influence of the structure leveling degree on the flatness of the masonry and the mortar thickness;
- The impacts of the outmost critical areas of the facade (generated due to the lack of geometric control of the structures) on the mortar consumption based on the mortar thickness required to regularize the substratum and assure the performance of the covering system;
- Financial profits versus economic viability of the technique in view of the reduction of the mortar consumption by the volumetric analysis;
- Advantages of the technique and possibilities of the use thereof in other worksite applications.

3.1 Flatness of the facade

The 3D laser scanning provides a thorough sight of the plane and, by means of the generated model (Figure 11), it is possible to observe details of the elements that constitute the surface such as, for example, the positioning of each concrete block in relation to others and in relation to the structure (beams), besides the conditions of application of the masonry mortar.

3.2 Facade alignment and leveling refinement

The image of the first reference plane (figure 12-a) evidences the effect of the lack of geometric control of the structures on the facade flatness, making it possible to identify the actual critical irregularity points over 100% of the scanned area, and not only the points under the plumb line (figure 12-b).

By using a scale of colors (Figure 12-c), the software shows the regions of the facade in front of and behind the plane, represented by hot and cold colors, respectively. The critical areas in front of the plane are usually located in the structure and its irregularities influence the leveling and flatness of the masonry, generally positioned behind the plane, and both of them determine the final mortar thickness.

These assertions can be evidenced in Figure 12-b through the interpretation of the scale of colors wherein the green colored areas are the ones closest to the reference plane:

- Beams 1, 5 and 7, predominantly yellow and/or orange colored, are the most distant from the plane;
- Beam 1, dark orange colored in a large portion of its area, is located in the outmost point of the facade;
- Beams 2 and 4, light blue colored, are located closer to the plane. The slight bulge in the center (green colored area) probably was caused by deformation of the mold during the concreting.
- Beam 3 exhibits the right side area out of the plane (yellow) and the left side area inside the plane (blue), that is, it is located across the plane;
- In a lesser degree, beam 6 also is located across the plane, but completely inside same with different shades of blue;
- The innermost regions are located on the masonry between the 5th and 7th beams, whose area is represented by a dark blue shade.

Figure 11 – Scanned image of the facade generated by the software. (Source: T1 Engenharia Digital)

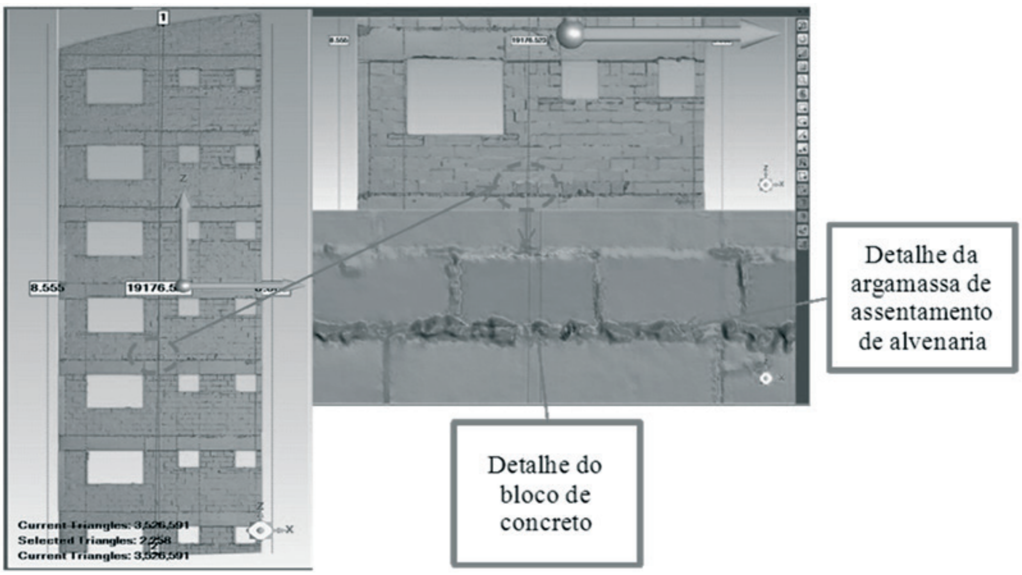
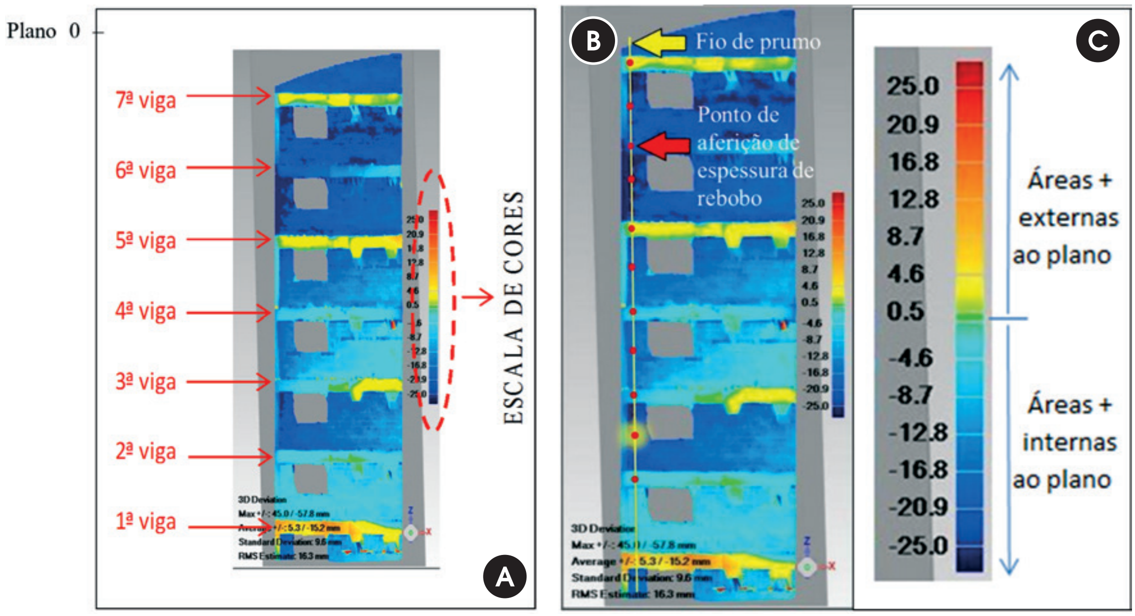


Figure 12 – (a) Image of the first reference plane generated by the software and identification of beams; (b) Critical irregularity points over 100% of the area of the scanned facade vs. points below the plumb line; (c) Scale of colors. (Source: T1 Engenharia Digital)



- A scaling of beams positioned inside and outside is observed. Outmost odd beams and innermost even beams;
- The extreme points (innermost and outmost) are located 57.8 mm behind the reference plane and 45.0 mm ahead same, that is, a variation of 102.8 mm between the outmost point and the innermost point of the substratum.

The other plane traced that simulates different mortar thicknesses (Figure 13) made it possible to measure the distance from each

Figure 13 – Image of planes parallel to the 1st reference plane at a distance of: (a) 5 mm; (b)10 mm; (c) 15 mm; (d) 20 mm; (e) 25 mm (Source: T1 Engenharia Digital)

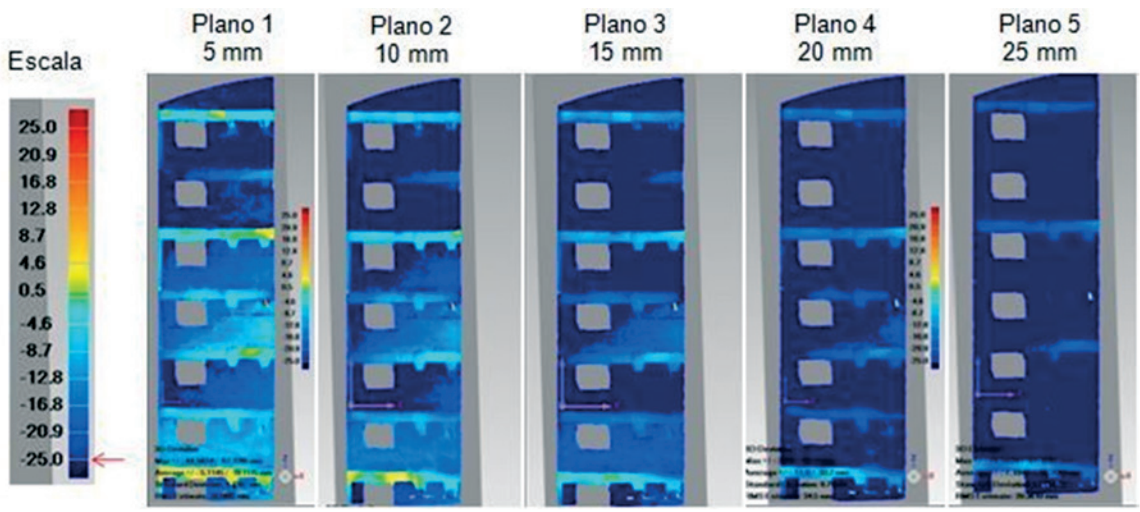


Table 3 – Brief results of planes traced from the 1st reference plane in relation to the scanned image

	Plane	Principle			
		a' Covering average thickness (mm)	b' Distance of every plane to the innermost point of the scanned substratum (mm)	c' % of the area having a minimum mortar thickness of 25 mm	d' % of the area of column c' located on the masonry
Line a	P0 (beam axis)	15.2	57.8	4%	100%
Line b	P1 (at 5 mm from P0')	19.1	67.1	27%	96%
Line c	P2 (at 10 mm from P0')	23.6	72.1	42%	95%
Line d	P3 (at 15 mm from P0')	28.3	77.1	56%	93%
Line e	P4 (at 20 mm from P0')	33.2	82.1	75%	89%
Line f	P5 (at 25 mm from P0')	38.2	87.1	86%	81%

point of the planes to the surface of the scanned facade. By using the software, the information shown in Table 3 was generated, and the analyses of such data show that:

- Assuming the volume between the scanned surface of the facade (substratum) and the planes would be filled with regularization mortar, the average thicknesses calculated in P3, P4 and P5 (column a' - Table 3) were above the 25 mm thickness, interspersed between the 20 mm to 30 mm interval for the mortar in the facade as per NBR 13749 (ABNT [3]) standard.
- The distance from each plane to the innermost point of the facade surface (column b' - Table 3) shows that the thickness of mortar at P0, P1, P2, P3, P4 and P5 in those spots would be approximately 2.3; 2.5; 2.7; 2.9; 3.1; and 3.3 times, respectively, the average mortar thickness (25 mm) for the facade considered in the study, representing a large waste of material and workmanship, besides the risks of failures.
- In a comparison between columns c' and d' of Table 3, it is seen that the planes with a higher area percent having a minimum thickness of 25 mm present such areas concentrated on the masonry. This proves that the masonry is generally displaced from the beams inwards to the plane and was directly influenced by the lack of alignment and leveling of beams.
- In the planes of Figure 13, assuming the areas dark blue colored represent the spots where every plane is at a distance of 25 mm from the scanned substratum, then, approximately 75% and 86%, respectively, of the areas of planes P4 and P5, are covered with at least 25 mm of mortar.

Figure 14 – Planes traced from the 2nd reference plan. (Source: T1 Engenharia Digital)

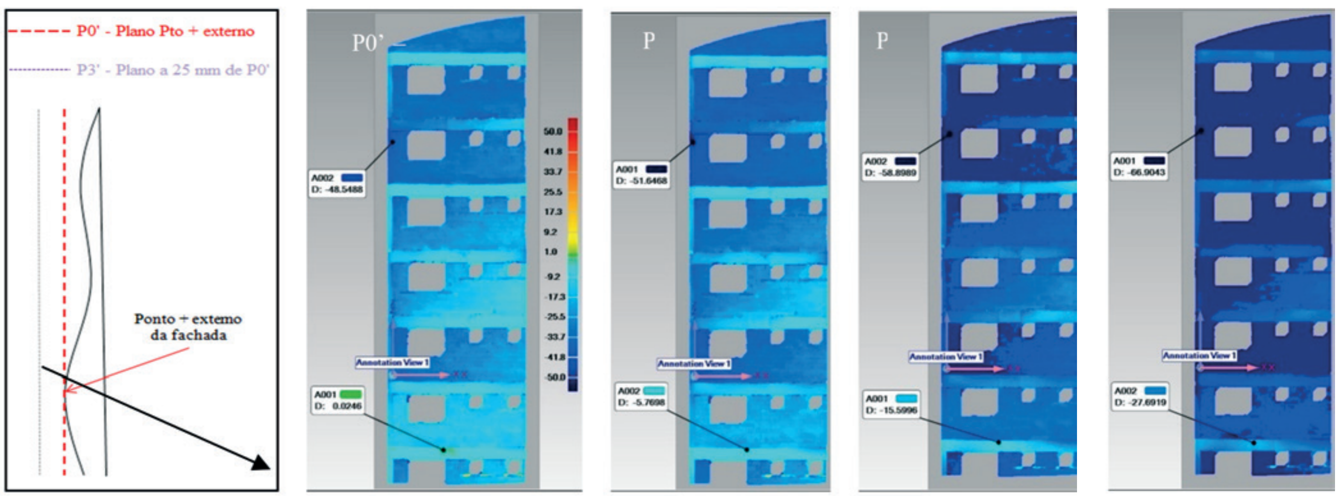


Table 4 – Results obtained from the 2nd reference plane

	Plane	Column a' Mortar consumption (m^3)	Column b' Consumption increase percentage in relation to P0'	Column c' % of the area having a minimum mortar thickness of 25 mm	Column d' % of the area of column c' located on the concrete structure
Line a	P0 (outmost point)	2.59	–	39%	46%
Line b	P1 (at 5 mm from P0')	3.05	18%	53%	57%
Line c	P2 (at 15 mm from P0')	3.95	53%	82%	100%
Line d	P3 (at 25 mm from P0')	4.85	87%	100%	0%

3.3 Benefits in volume measurement

In the 3D laser scanning technology, the consumption is calculated by measuring the volume from a 100% coverage of the facade area. The calculation of different volumes of mortar represents the sum of the thicknesses between the scanned model of the facade (Figure 11), considering all the surface irregularities and each of the different planes under study.

Beginning with the second reference plane (P0') traced parallel to the facade and facing the outmost point of the scanned surface, as illustrated in figure 14, it was observed that, in order to attain the ideal condition wherein the whole facade has a 25 mm mortar thickness (Figure 14-e), there was an increase representative of the mortar consumption, increasing the cost, environment impact and a future risk of imperfections and failures in the covering.

On the other hand, the images of Figure 14 show that either plane P1', located 5 mm from P0', or plane P2' located 15 mm therefrom, show a area representative of the cover exhibiting the recommended 25 mm thickness and an expressive mortar consumption reduction (Table 4). Thus, by dealing with the points that do not exhibit the 25 mm thickness in order to assure its performance, it is possible to attain gains representative of quality, durability and savings.

The results given in Table 4 show that:

- Reference plane P0' consumes a mortar volume of 2.59 m³, however, only 39% of the complete scanned area have a minimum thickness of 25 mm;
- Plane P3' located 25 mm from P0', that is, a situation wherein 100% of the facade would present a minimum mortar covering of 25 mm, increased the consumption in 87%, totalizing 4.85 m³;
- On the other hand, plane P2' located 15 mm from the reference showed a 53% increase in the consumption, a total of 3.95 m³ of mortar and 82% of the area having thicknesses from 25 mm on;
- In plane P1', located 5 mm from P0', there is an increase of only 18% in the consumption, representing a 53% covering of the facade with a minimum thicknesses of 25 mm;
- In planes P1' and P2', 57% and 100% of the area with a minimum thickness of 25 mm, respectively, are on the concrete structure (column d'), so it is possible to think about a solution wherein this substratum may function with lower thicknesses without compromising the performance and durability.

3.4 Economic potential of the technique

Although Boehler [7] has classified the laser scanning as a technique of prohibitive cost at the time he studied same, the return on the investment in comparison with the conventional methods of survey had already been noticed. Thus, a point of paramount importance that was brought about during the study was the economic viability of the use of the technique in view of the actual

Table 5 – Mortar volume vs. cost in different planes under study

Plane under study	Thickness (mm)	Mortar consumption (metric ton) In scanned area (7 floors)	Mortar consumption (metric ton) In the facade	Cost* (R$)	Volume reduction in relation to P3' (%)	Cost reduction in relation to P3' (R$)
P0'	0	4.4	15.1	R$12,582.96	-47%	-R$11,222.64
P1'	5	5.3	18.1	R$15,060.69	-37%	-R$8,744.91
P2'	15	6.8	23.3	R$19,433.14	-18%	-R$4,372.46
P3'	25	8.3	28.6	R$23,805.60	0%	R$-

* Cost of applied mortar: R$1,417.00/m³ | Mortar consumption: 1.7 metric ton/m³

financial profits generated. For that purpose, the savings generated by the reduction of mortar thickness in planes P0', P1' and P2' in relation to plane P3' were calculated and compared with the cost for accomplishing the scanning.
The analysis took into account the mortar consumption calculated by the software in each of the plans and the R$1,417.00/m³ cost of the regularization mortar of the facade applied, the average value in force in the city of São Paulo in the first semester of 2013 (Source: Sinduscon - SP). This cost encompasses the material, workmanship and equipment, and the values found based on the area of the seven scanned floors of one of the facades were surpassed for the 24 floors of this same facade.
Thus, as per the results of Table 4 and Table 5, it can be noticed:

- Plane P0' - 39% of the area with a minimum thickness of 25 mm (Table 4 - column c') and a 47% reduction in relation to P3' in mortar consumption (Table 5), resulting in a savings of R$11,222.64;
- Plane P1' - 53% of the area with a minimum thickness of 25 mm (Table 4 - column c') and a 37% reduction in relation to P3' in mortar consumption (Table 5), resulting in a savings of R$8,744.91;
- Plane P2' - 82% of the area with a minimum thickness of 25 mm (Table 4 - column c') and a 19% reduction in relation to P3' in mortar consumption (Table 5), resulting in a savings of R$ 4,372.46.

Taking into account an estimated value of R$5,000.00 (five thousand Reais) for accomplishing the scanning in a facade plus the analysis of the data, the use of the technology paid itself and generated a surplus in planes P0' and P1', however, only 39% and 53% of the area had a minimum thickness of 25 mm. On the other hand, plane P2', despite the deficit of R$627.54 to cover the cost of the scanning service, an area percentage of 82% with a minimum thickness of 25 mm was attained.

3.5 Other applications

During the use of the equipment in the worksite and after the analyses have been intensified, other applications related to the facade have been identified. They are as follows:

- Use of a high degree of detailing of the surface generated by the scanned model, to verify the block alignment regularity, the masonry positioning in relation to beams and pillars, the mortar thickness to settle the masonry, thus making it possible to use the technique as a method for controlling the quality of the production/operational process of the masonry stage;
- Use during the construction of the structure to survey and correct the failures in the alignment and leveling of molds, making it possible to correct the failures before the concreting.

These two cited applications are considered to be preventive measures, thus preventing failures to take place and reflect on the following stages, contrary to the corrective use proposed in this work.

4. Conclusions

- In the work object of this study, the purpose of the work was reached as the 3D laser scanning showed to be precise and economically viable, for the volumetric survey of the mortar consumption of the facade by applying the proposed method, signaling a reduction in the applied mortar cost that ranged from 18% to 47% by identifying the overthicknesses generated by the imperfections in the facade flatness.
- Also it showed to be an efficient tool for mapping the facade, displaying the influence of the degree of geometric control of the structure in the surface regularity of the facade, being able to contribute to the decisions taken referring to the corrective measures of the imperfections that impact the mortar thicknesses all over the extent of the critical areas.
- For the analysis of the data, small critical areas represented by inner points, a great part of which is located on the masonry, and outer points mainly located on the structure, influence the final thickness of mortar by reaching 3.3 times the 25 mm reference thickness in the work under study, representing a large waste of material and workmanship, besides increasing the risks of failures.
- The level of detailing of the images, reach and portability of the currently available equipment and the degree of development of the software make the 3D laser scanning technique far better than the plumb line for mapping the facade, however, its use depends on the fulfillment of contour conditions intrinsic to the worksite.
- The most critical points are the shaded areas that generate interventions, making it difficult or impossible to capture the facade failures in such places, for the precise calculation of the mortar volume and the need of alterations or interventions in the routine/steps of the work so that the scanning can be accomplished as well as the delay in the installation of scaffolds and removal of facade screens that act as obstacles to the scanner reading.

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