Measurements of building structures

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Abstract. The construction and operation of buildings and structures suggest taking measurements to determine accurate dimensions, shape, and mutual location of all structural elements. This is one of the most popular surveying services. All types of outlines (lineal, curvilinear, bevelled) and surfaces in both plan and elevation are subject to measurements and dimensioning. Depending on the goals that are set during measuring activities, measurement activities differ in the degree of accuracy and completeness. Building measurements are done to find their actual geometric characteristics and possible deviations from the project documentation for buildings and structures. Measurements are done to find structural dimensions, cross-section of individual elements, distances between structures in plan and height, elevations, and other parameters. This results in measurement diagrams. The article overviews existing measurements: schematic, architectural, and archaeological. Various measurements methods are considered: in-situ (conventional), photogrammetric, and geodetic. Their advantages and disadvantages are described. A measurement method is selected based on certain features of the surveyed facility. Sometimes all possible methods are combined to obtain accurate data.

1 Introduction

The surface laser scanning technology is becoming more and more popular for metrology purposes in various fields of construction and industry. A growing popularity of the laser scanning is related with a number of advantages provided by the new technology as compared to other measurement methods. Main advantages are faster and more accurate measurements and reduced labour expenses. New efficient models of scanners and improved software capabilities give a hope for further expansion of laser scanning applications.

When measuring complex architectural facilities using conventional methods, contractors often see that some measurements are missing during field surveys. Multiple outlines and a lot of individual objects inevitably lead to mistakes. The findings of laser scanning can provide more complete data about the surveyed facility. Before scanning, the laser scanner takes panoramic photography that greatly improves the informative value of scanning results.

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The surface laser scanning used to create 3D models of architectural and building structures greatly improves the productivity and reduces time expenditure.

The surface laser scanning is constantly improving. This relates also to improvements of laser scanner designs and developments of software used to control instruments and process the obtained results.

2 Analysis of existing methods to measure architectural and building structures

2.1 Types of measurements in architecture and construction

Measurement is a process, method, and result of surveying a work of art, mainly landmark buildings, in the form of drawings such as orthogonal projections, cross-sections, plan view, bottom view, all made at a certain scale indicating the actual dimensions. Measurements are used in scientific, educational purposes and as a necessary document for surveying, preserving, restoration or reconstruction of a monument.

Any measurement is intended to accurately survey the building, its appearance, dimensions, and specific features. Measurements have a variable accuracy and, depending on the final goal, are divided into schematic, architectural, and archaeological (architectural-archaeological as applicable to landmark buildings).

This categorisation is still rather conditional, e.g., for the same measurement goal, architectural specifics of the surveyed facility dictate the level of detail, precision and accuracy of measurements: in certain cases, simplification is permitted (the correct building lines, repeatability of details), while it is prohibited in others (irregular shapes, irregularity, non-verticality and non-horizontality).

A schematic measurement determines primary physical dimensions of a landmark building and its planning structure. In various institutions, this measurement is done to find the physical or construction volume of a building (housing and utility bodies, recovery-engineering institutions, technical inventory bureau, etc.). This measurement is done by design restoration organisations during the initial study of the building to get a more common understanding and outline a preliminary scope of work.

Architectural measurements are the main method to survey architectural facilities, which includes several stages: from in-site activities to issuing measurement drawings and documentation. The analysis of measurement findings gives a comprehensive insight into the type of the facility. Drawings of plans, sections, and parts are a basis for projects of restoration, reconstruction, and other conversions.

Architectural measurements are not only a mean to survey and depict landmark buildings to preserve and restore them, but they also enable studying and surveying these buildings and structures in the future.

Architectural measurements give detailed linear dimensions of a building and disclose its architecture specifics: layout of premises, location and nature of openings, stairs, colonnades, etc., flooring, roofing, decorations of building's front and interior. However, while this type of measurements surveys architecture specifics, it is not intended to find those individual properties that are sometimes invisible: insignificant deviations in dimensions of uniform parts, deformation of buildings and changes caused by natural aging.

Architectural-archaeological measurement gives more reliability in surveying the building, its linear dimensions, architectural and structural features, its losses, deformations, and destructions. Architectural-archaeological measurement is the primary method in
surveying buildings in field surveys and initial activities in restoration of landmark buildings.

Measurements of internal premises. This category includes interiors of apartments, houses, offices, sales areas, warehouses, etc. Usually, such measurement activities are related with the planned renovation, reconstruction, or replanning.

Measurement of building parameters. In this case, experts measure all facility components, from front systems to elevator shafts.

Measurements of individual structures of real estate units. This is a type of measurements for individual building structures and elements: fronts and foundations, staircase landings, roofing systems, and other building components.

Measurements of engineering structures. In this case, it means measurements of bridges, flyovers, tunnels, and other complex facilities.

2.2 Type of measurements for architectural and building structures

2.2.1 Angular measurements

Angular measurements are taken to find mutual location of points of detail in space. To find the horizontal position of points, a horizontal angle is measured. To find overshoots between points, vertical angles (incline angles) are measured. The vertical angle is an angle between a side and its projection to horizontal plane. Vertical angles are always counted from a projection to the side. If the side is higher than the projection, the angle is positive, otherwise it is negative. Vertical angles can vary within -90° to +90°.

The tools used before theodolite such as a geometric circle or various graduated circles (angle meter or opisometer) were applied to measure either vertical or horizontal angles.

For angular measurements in the geodetic grid, angle meters of various type and accuracy are used. Angle meters are classified and manufactured in accordance with the applicable state standards.

2.2.2 Linear measurements

Linear measurements (distance measurements) are a necessary element of surveys of any type. For direct measurements, a known reference (a measure of length) is placed along a specified line. A certain method of linear measurements depends on the required accuracy, type of survey, and availability of respective tools.

2.3 Measurements methods for architectural and building structures

Measurements are done to more accurately find out the shape, dimensions, and mutual location of all premises and structural elements of the buildings. Linear, bevelled, and curvilinear outlines and all types of surfaces in plans and elevations are measured and recorded.

2.3.1 In-Situ (conventional) method of measurements

The in-situ method is still important and used to measure small buildings (pavilions, arbours), building interiors, and architectural details available for direct measurement (Fig. 1).
The cost of in-situ measurements is much higher as compared to other methods. The final choice is determined mainly by specific features of the measured structure:

- shape and dimensions,
- configuration,
- its location within the existing building environment and landscape,
- required level of detail,
- required accuracy of measurements.

Measurements employ both conventional, well-known tools and complex instruments and advanced technologies.

The final choice is based on the goal that defines the accuracy and level of detail of measurements as well as their timing. However, when using new measurement methods, one should remember that they are developed based on prior experience and older methods.

Tape-measure, plummet, and level. Tape-measures can be both linen and steel, the former being more convenient for measuring from internal angles and for height measurements (especially using a pole), but since time they stretch and lose accuracy. Therefore, a linen tape-measure must be regularly compared with the steel one to make corrections.

When measuring a facility, all measurements must be done using the same tape-measure, since using two tape-measures for that purposes (a new one and an old one) can cause differences in measuring the same value.

Rangefinders used in geodetic and topographic activities are divided into electromagnetic (electronic) and optical. For linear measurements in geodetic grids, light and radio rangefinders based on the physical principle are used, which ensures a higher accuracy. They measure the distance to objects upon the time of electromagnetic waves passing along the measured line. The accuracy of linear measurements by electromagnetic instruments is very high.

2.3.2 Measurements of buildings using a total station

Building measurements are required to get a more accurate and objective evaluation of the actual condition, and issue technical documentation. Measurements are done in plan and elevation, e.g., floor levelling. To record even smallest inconsistencies or deviations of walls, modern electronic total stations are used (Fig. 2).
Tacheometry is a combined method intended to pinpoint both horizontal and vertical positions of points. The position of points is found relative to surveyor’s pickup stations: horizontal position using the polar method, and vertical position using traverse levelling. The total station is a geodetic instrument used in tacheometry to measure distance and horizontal and vertical angles.

The distance in electronic total stations is measured upon the phase difference of emitted and reflected beam (phase method) and sometimes (in some modern models) upon the laser beam passing to the reflector and back (pulse method). The measurement accuracy depends on technical capabilities of a certain total station model and on multiple external parameters: temperature, pressure, humidity, etc.

The distance measurement range depends on the total station operation mode: either reflective or non-reflective. The measurement range in the non-reflective mode depends on reflective properties of the surface for which the measurement is done. The measurement range for a bright smooth surface (plaster, glazed tile, etc.) exceeds the possible distance measured for a dark surface by several times. The maximum range of linear measurements for the reflective mode (prism) is up to five kilometres (or even more for several prisms); and up to one kilometre for the non-reflective mode. Total station models that have a non-reflective mode can measure distance almost to any surface, but one should be careful about measurements done through branches, leaves, and similar materials since it is not known where the beam will be reflected and to which object it will measure the distance.

The accuracy of angle measurements using a modern total station is half of a second of angle (0°00’00.5") and up to 1 mm per km for distances (for example, in TS30 by Leica Geosystems).

The accuracy of linear measurements in the non-reflective mode is ± 2 mm per km.

Most modern total stations are equipped with calculators and memory devices that can save the measured and project data, calculate point coordinates unavailable for direct measurements by using direct observations, etc. Some modern models are additionally equipped with a GPS system.

An electronic total station is used to carry out various types of activities in terms of purpose, complexity, accuracy requirements, type of findings. Therefore, the mathematical processing may differ in scope and the used software module in each specific case. In general, three primary processing stages exist:

— primary processing of direct measurement findings using the total station firmware;
— transferring data from the total station to a computer;
The primary processing of angle and distance measurements by the total stations is done automatically after entering a respective menu mode or station mode, and it supports all measurements. The firmware is part of the electronic total stations used to input data, set (configure) parameters, calculate referencing elements, determine coordinates and other geodetic values, solve applied tasks, and configure the interface. It also controls individual operations and instrument operation in general ensuring a highly productive and convenient way to operate it. In some cases, the primary processing of measurements by the total station is sufficient, especially when searching for coordinates of individual points in real time. All models of total stations can find coordinates using polar and back sight. The linear-angular back sight is found in the SET total station by equalising with the least square method by evaluating accuracy of coordinate determination using up to ten approximations until the differences of coordinates in consecutive iterations are below 0.5 mm. No additional processing of such measurements is required usually.

However, the mathematical processing of passes and other complex constructs and processing and mapping of survey findings must be done using special programs. Universal software packages and suites are used currently for that purpose. Information of field measurements is transmitted from the electronic total station to a computer for processing.

2.3.3 Photogrammetric method

The photogrammetric method can be used for architectural measurements as follows:
- single images;
- a pair of images.

The single-image measurement method can be used to measure structures mainly consisting of flat elements with large forms [1-4]. Depending on the pre-set accuracy of measurements, their purpose and available photogrammetric devices, one can take architectural measurements by single images using various paper methods of the image processing:
- conversion;
- optical-graphical;
- analytical;
- graphical.

The conversion method can be used to make photographic maps of fronts, interiors, and landmarks at the required scale [5]. If drafting plans are required, photomap outlines are drawn with a drafting ink and the photo image is bleached.

The optical-graphical method suggests encircling the outlines of the converted image with a pencil to get a drawing plan at the required scale. Usually, the optical-graphical conversion uses single projectors with the backing frame size of 8×6 cm. Therefore, for large image sizes, smaller reversal film must be made on their basis. The optical-graphical conversion can be also ensured using photo transformers. The optical-graphical conversion method is technologically simpler than the conversion method, but it has lower performance and complicates the control of drawings.

The analytical method lies in calculating the point coordinates using the formula of the link between single image and facility coordinates. Images are measured in stereocomparators, and calculations are done using computers. The analytical method of single image measurements can mainly find out dimensions between points lying in the same plane, which restricts the method capabilities.
The graphical method lies in making a drawing plan using perspective geometry methods and image properties in central projection. The graphical method provides lower accuracy than others and is low-efficient.

The image-pair measurement method can take dimensions between any points of the building located in various planes. This method provides the highest capabilities for architectural measurements. The necessary condition of this method is availability of images taken in different points. Images can be created by a single or several cameras. Images can make up a stereo pair (i.e., a stereo effect can be observed) or a pair of images can be used, which do not provide the stereo effect (usually, archive images). The pair of images can be processed by the following methods:
- universal;
- analytical.

When processing images using the universal method, images must make up a stereo pair and be made by a single photo theodolite. Stereo pair images are processed (measured) by universal devices: stereo projector, stereograph, stereonautograph, etc.

When using devices in which the focal distance of projection cameras is set irrespective of each other (stereograph, stereonautograph, etc.), a stereo pair of images made by different cameras can be used.

The processing of images in universal devices results in a drawing layout of the building front at the required scale [6-10]. Universal devices can be used to obtain point coordinates, distance between points, and height of structural elements. This method of dimensioning is called analog-analytical.

The universal method provides the highest capabilities for architectural measurements.

For the analytical method, images are measured in stereocomparators and monocomparators. Images can make up a stereo pair. Images for which no stereo effect is obtained can be used, but such images must be overlapped, i.e., they must show general details of the building.

The analytical method is based on using mathematical dependencies between the coordinates of the pair of images and the facility.

The analytical processing results in a digital model of a building (X, Y, Z coordinates of individual points), which can be used to learn dimensions between any points and to make a graphical layout. It is most convenient to make drawing layouts using automatic coordinate plotting machines and data plotters.

Architectural measurements can be done using combined methods when various methods used, such as conversion, analytical method, etc. Moreover, sometimes it is required to additionally shoot invisible parts (dead zones) by in-site measurements or using low-size cameras.

The advantages of the photogrammetric method include:
- Remote measurements in the conditions when it is not safe for the human to be present in the facility.
- No need to buy expensive equipment.
- No special training is required.
- Secondary and further monitoring of facilities can be done using photos without a total station.
- The disadvantages include:
- Environmental effects on the quality of photos.
- Manual highlighting of model building areas.
- Low level of detail.
- Lower accuracy as compared to the laser scanning.
- Impossible to shoot from a moving object (train).
2.3.4 Laser scanning in architecture and construction

Surface 3D scanners (Fig. 3) are intended for surveying various objects on the ground surface. During survey, the laser scanner is often fixed and can be mounted on the initial geodetic station with known coordinates. Survey objects can be a multi-story building, a coal pit, a smelter blast furnace, a subway shaft, a landmark or a sculpture [6].

![Leica RTC360 surface laser scanner](image)

In terms of characteristics and purpose, surface laser scanners greatly differ and it is hard to classify them. First of all, there is no universal scanner that could be used for all tasks. Some scanners are best for surveying middle-size objects (at a distance below 100 m), while others are used for large objects (200 m and more), and for small objects located within several metres. A certain type of laser scanners can be used to address a certain range of purposes. Let us use the most common classification where surface laser scanners are divided by the principle of determining coordinates into pulse, phase and triangulation scanners.

Pulse 3D scanners determine distances based on accurately measuring the pulse flight to the target and back [11]. Since this method for direct measurement of distance uses a light pulse, the major advantage of pulse scanners is the distance of measurements (up to several meters) ensured by a rather high laser power. It must be remembered, however, that emission of such lasers can be harmful for eyes. Apart from the measured distance, horizontal and vertical angles of laser head rotation are recorded to obtain the point’s spatial position. The measurement accuracy of pulse scanners may reach several millimetres, but it goes down as the distance to the object increases. It is important to understand that the maximum measurement range of scanners given in various leaflets and specifications is calculated when a laser beam is reflected from a surface with a high reflection factor. In real conditions, the reflection factor of a surface of the scanned object is almost always lower (open pit slope, building wall, etc.), so the maximum measurement distance falls down respectively.

In terms of the distance measurement principle, surface laser scanners are divided into three groups:

- pulse
- phase
- triangulation

Pulse laser scanners calculate the laser beam covering the double distance from the scanner to the target. The pulse method is based on measuring the time of laser beam propagation from the emission source to the object and back taking into account the constant propagation rate of electromagnetic oscillations. The laser system generates short pulses that return to the source after being reflected from the object. Precise electronics
determines the propagation time of each signal and calculate corrections for its propagation rate in the atmosphere. To accurately measure the laser pulse propagation time in space, a highly stable crystal oscillator is used.

The range of pulse scanners varies from several metres to several hundred metres. The pulse measurement method has a lower accuracy than the phase method. This happens because the actual accuracy of each measurement depends on a number of parameters, each of which can affect the accuracy of a certain measurement. Such parameters are:
- duration and form of the transmitted pulse
- reflective characteristics of the object
- optical properties of the atmosphere
- texture and orientation of the object’s elementary surface causing reflection of the transmitted beam relative to the sight line.

Phase 3D laser scanners have the range of hundred metres. The scanners of this type implement the distance measurement method based on measuring the phase shift of the emitted and received signals. Since this method uses a modulated light signal, the distance determination requires no high laser power, so distances can be measured with an accuracy up to several first millimetres, but the range of scanners of this type is rather limited. The spatial position of points is determined in the same manner as in scanners. Phase scanners use an eye-safe laser and have an extremely high measurement speed that exceeds pulse scanners by dozens or even hundreds of times [12-15].

Triangulation 3D laser scanners also belong to active scanners that use a laser beam to scan an object. Similar to time-of-flight 3D scanners, triangulation devices transmit a laser to the scanned object, and the camera records the location of the point where the laser arrived. Depending on how far the laser transmits beam along the surface, the point appears in various places of the camera field of view. This technology is called triangulation because the laser point, the camera and the laser emitter form a kind of triangle. The length of one side of this triangle is known: the distance between the camera and the laser emitter. The laser emitter angle is also known. The camera angle can be found by the position of the laser point within the camera field of view. These three parameters fully define the shape and size of the triangle and indicate the laser point angle location. To accelerate the data acquisition process, a laser stripe is used in most cases instead of a laser point.

3D scanning has following advantages over the conventional methods of tacheometry and laser tape-measuring:
- high level of automation;
- acquiring data using non-destructive methods;
- pinpointing spatial coordinates of object points in field conditions;
- quick acquisition of results;
- 3D visualisation allowing to find dead zones;
- one point is enough to mount equipment so as to scan the object surface oriented towards it;
- high measurement accuracy;
- remote data acquisition ensuring safety of surveying in hard-to-reach sites;
- ability to survey in daytime and at night;
- using survey results for various purposes.

This technology has also a few disadvantages:
- Impossible to survey in case of no visibility. Scanners cannot be used to survey surfaces located above their action boundary such as building roofs or bridges. Aerial photography is used in this case.
- Complications in scanning glass structures of absolutely smooth surfaces. To ensure high-quality survey, it is done before glazing or they apply special whiting putty paints.
• No geodetic referencing. The scanner cannot independently pinpoint its geographical coordinates, so other geodetic instruments must be used – either a total station or a GNSS receiver.
• Dependency on weather conditions. Low temperature, strong wind or heavy precipitation impair the survey quality and create noise in the point cloud. Unfortunately, it is impossible to correct weather, making one to wait until it gets better.

2.3.5 Optical scanning

Optical scanners (Fig. 4) are based on using optical methods for image generation. There are several methods to implement the optical method:
• optical method of reflection
• optical method of clearance

![Artec Eva optical scanner](image)

The optical method of reflection uses frustrated total internal reflection. When light falls on the interface of two media, the light energy is divided into two parts: one reflected from the interface, and the other passes through the interface to the second medium. The share of reflected energy depends on the light flux incidence angle. Starting with some value of this value, all light energy is reflected from the interface.

This is called total internal reflection. In case a denser optical medium (finger surface) contacts with a less dense surface, the light beam goes through this interface. Therefore, only those light beams will reflect from the interface that have come to certain points of total internal reflection, to which the papillary picture of the finger was not applied. To capture the obtained light image of the finger surface, a special sensor is used (CMOS or CCD depending on the scanner model).

Disadvantages:
• Inefficient protection against dummies
• Sensitivity to soiling

Leading manufacturers of such scanners are BioLink, Digital Persona, and Identix.

Optical method of clearance. The scanners of this type represent a fibre-optic matrix where all wave-guides at the output are connected with photo-sensors.

Sensitivity of each sensor allows recording residual light passing through the finger in the point of contact between the finger and the matrix surface. The image of the entire fingerprint is formed using the data from each photo sensor.
This method has a high reading reliability. However, it also has a significant disadvantage: it is hard to manufacture. Scanners of this type are produced by Security First Corp.

3 Conclusion

The analysis of measurements methods for architectural and building structures showed that each method had its own advantages and disadvantages. Therefore, the method is selected during measurements based on specific conditions and depending on the required accuracy, performance, and economic feasibility.

References