Combining LiDAR and BIM to record and measure deformation in historic structures

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Abstract. Culturalheritageplaysafundamentalroleinp reservingthecollectivememoryofanation.However,itis notedthatmanyhistoricalbuildingssufferfromseriousd eformationthatmayleadtodeterioration or loss. In this paper, we propose an approach for documentation and deformation assessment ofhistorical buildings based on the combination of Terrestrial Light Detecting And Ranging (LiDAR) technologyand Building Information Models (BIM). In order to digitally archive the current state of a historical building,classical surveying techniques (Traversing, Levelling and GPS) are integrated with Terrestrial Laser scanner(TLS). ALeica ScanStationC10is usedtoaccomplishthe 3D point cloudacquisition. Inaddition, LeicaGNSS Viva GS15 receivers, a Leica Total Station TCR 1201+ and a Leica Runner 24 are used for classicalsurveying. The result is a 3D point cloud with high resolution, which is referenced according to the localgeodetic reference system Ain el Abd UTM 37N. This point cloud is then used to create a 3D BIM thatrepresents the ideal condition of the building. This BIM also contains some important architectural componentsof the historical building. To detect and assess the deformation of building's parts that require an urgentintervention, a comparison between the 3D point cloud and the 3D BIM is performed. To achieve this goal, themain parts of the building in the BIM model (such as ceilings and walls) are compared with the correspondingsegments of the 3D point cloud according to the normal vectors of each part. A case study that corresponds to ahistorical building in Jeddah Historical City named 'RobatBanajah' is presented to illustrate the proposedapproach. This building was built to serve pilgrims that want to perform the fifth pillar of Islam.Then, it wasendowed(waqf)asacharity housing forwidowsanddisabled. The results of assessing deformations of thecase study show that some rooms are in a degraded condition requiring urgent restoration (distortions reach upto 22cm),whileother buildingparts areinanon-criticalcondition.

Introduction

Jeddah city is located on the Red Sea coastline, in the west side of Al Hijaz region. It is considered as theeconomic and the touristic capital of the Kingdom of Saudi Arabia. Also, its locationclose to the two holy cities of Islam, Makkah and Medina, gives this place a fundamental role in the history of Islamic Civilization.

Its old city contains several historical buildings that have their own characters. These buildings take a major place in the collective memory of the Saudi society. In addition, they are considered as attractive landmarks for visitors that come from all over the world. Unfortunately, some monuments inside the old city of Jeddah are under deteriorating conditions due to various human and natural factors (climate, disasters…). Hence, it is necessary to detect and repair any potential deformation at an early stage to preserve the loss of valuable historical buildings.To do so, monitoring and analysis of structural deformations must be performed to check the current condition of such buildings [1].

This study aims to develop an approach for documenting historical buildings and measuring their deformation by combing LiDAR (Light Detecting and Ranging) technology and BIM (Building Information Modeling). To achieve this goal, a comparison between a 3D BIM model (that represents the ideal condition of the building) and a 3D LiDAR point cloud (that represents the current condition of the building) is conducted. In the following sections, an overview of methods used for documentation and deformation assessment ispresented. Then, the proposed methodology based on the combination of BIM and terrestrial LiDAR is described. Finally, a case study that corresponds to a historical building in Jeddah Historical City named 'RobatBanajah' is presented to illustrate the proposed approach.

Generaloverviewofmethodsforherit age documentation anddeformationassessment

Heritagedocumentationmethods

The documentation of a historical building may bedefinedastheprocessofacquiring,processing,presentingand recordingtherequireddataforthedetermination of the current position and form accordingto a specific coordinate system [2]. The selection of anappropriatemethoddependsmainly onseveralfactorssuch as: 1) the required level of details, 2) the accuracy ofthe acquisition method, 3) the completeness of the modelto be generated and 4) the maintainability of the currentconditions without any alteration due to the acquisitionprocess.

As mentioned previously, data acquisition is the firststep in the documentation process. In the following, threemethodsthatmaybeusedforacquiringdatainthedocumentationprocesswillbepresented:1)TotalStation,2)Close-RangePhotogrammetryand3)Terrestrial LiDAR. These three methods do not requireany direct contact with the object or the building duringtheacquisitionprocess.

TotalStation:

A total station is a traditional surveyinginstrument thatallows measuring horizontal and vertical angles of a pointof interest, in addition to the slope distance to that point.Furthermore,itcanalsomakesurveyingcomputationwith angleanddistanceobservations.Therefore,thecoordinates of the measured point are calculated in realtime, according to a specific coordinate system. Thesefunctionalitieshavemadetotalstationoneofthepredominantinstrumentsusedinsurveyingnowadays.

Close-RangePhotogrammetry(CRP):

Close-Range Photogrammetry (CRP) is the art, science,and technology used for obtaining precise mathematicalmeasurementsandthree-dimensional(3D)datamodelfrom two or more images captured with a camera at closerange[3]. It allows recording the current position, formandotherarchitectural aspects of the historical buildingby photographs. If more than two photos are captured, abundleadjustmentsolutionispossible,includingallavailable measurements on photos at the same time [4].The 3D model generated from a photogrammetric processmay be converted to a set of 3D data points with a veryhighdensity[5].

TerrestrialLiDAR:

TerrestrialLiDAR,alsocalledTerrestrialLaserScanning, provides remotely sensed 3D data that capturethe surrounding environment. Terrestrial LiDAR is basedon the use of a continuous laser beam to measure thedistance between the target and the scanner. While thisscanner rotates around its vertical axis, its mirror alsomoves the emitted laser beam up and down to cover mostof the surrounding area. In general, two main techniquesareusedtocomputethedistancetothetarget:pulse-basedandphase-basedmeasurements[6].Pulse-basedLiDAR convert the travelling time that takes some of theemitted energy pulses to return-back to the scanner. Then,this time is converted to distance between the scanner andthetarget takingintoconsideration that thelaserpulsehas a speed of light. Regarding phase-based LiDAR, thescanner measures the phase shift between the emitted andreturnedsignal.This differencein phaseis proportionaltothetravelingtime,soitcanalsobeconvertedtodistancebetweenthetargetandthescanner.

In addition to the distance measurement, additional dataincluding the horizontal angle of the rotating laser andvertical angle of the oscillating mirror are recorded. Thescanner automatically combines all these data to calculatean accurate 3D X, Y, and Z coordinates position for eachpoint. The set of acquired points is named ‘Point Cloud’.While the scanning with laser is happening, photos of thereal world (with true colours RGB (Red Green Blue)) canbe taken. These photos are used to assign to each point ofthecloud thecorrespondingRGBvalue.

Deformationassessmentmethods

Deformationassessmentmethodsconsistofmonitoringtheintegrityofstructurestoearlydetectpotentialdamageandreactappropriatelyinatimelyfashion[7]. To carry out deformation analysis, there arethreemainapproaches:1)Point-to-Point,2)Point-to-Surfaceand 3)Surface-to-Surface.

Point-to-Pointanalysis:

If the deformation analysis is performed on two triplets ofcoordinates that represent the same position, but in twodifferentdates,asimplecomparisonbetweenthetwotriplets ofcoordinatesgivesthecorrespondingdeformation.However,ifwehavetwopointcloudsrepresentingasceneintwodifferentperiods,itisuncertain that the exact same point appears in the twocloudsformanyreasons(differentdensity,differentscanning points…).To overcome this problem, a rangeimage is generated from each point cloud based on thesame point of perspective [8]. The value of each pixel oftherangeimagecorrespondstothedistancetothescanningstation.Then,pixelvaluesfromthetwogeneratedrangeimagesaresubtractedtoassessthedeformation.

Point-to-Surfaceanalysis:

InthePoint-to-Surfaceanalysis,apointcloudiscompared to a reference surface. This surface may be anexisting 3D model of the object of interest, or it may begeneratedfromanotherpointcloudbyusingspecifictechniquessuchastessellationorsurfacefitting.Thedeformation corresponds to the shortest distance that iscalculated according the normal of the reference surface[9].

Surface-to-Surfaceanalysis:

Surface-to-Surfaceanalysisisallowscomparingbetweentwo surfaces, that may come from existing 3D models orthataregeneratedfromtwodifferentpointclouds.This typeofanalysisrequiresdefiningamathematicalparameterization for planar patches of each surface[10].Then, the plan parameters and their covariance matricesareusedtoperformSurface-to-Surfaceanalysisfordeformationassessment [11].

Discussion

Theuseoftotalstationmaybeconsideredasaconventionalmethodsinceitallowsusingasetofdiscrete points across the structure (very limited numberofpoints)intheprocessofdeformationassessment.

When using a total station in deformation monitoring, the3D coordinates of specific points on the structure may bemeasured and compared to their coordinates on a modelthatrepresentstheidealconditionofthebuilding.Inaddition, it is possible to make different measurements ofthe same point at a regular interval of time, so one candeduceinformationaboutpossibledeformationonthestructureoverthe time.

On the contrary, Close Range Photogrammetry (CRP)and Terrestrial LiDAR offer the possibility to acquire averydense3Dpointcloudthatmaybeusedintheprocess of deformation assessment. This 3D point cloudmay be compared to an existing model representing theideal condition of a structure. Also, if we have a set ofdata corresponding to two different dates, a deformationanalysismaybecarriedoutthroughacomparisonbetween the two point clouds. CRP is very efficient torecord the texture of elements and to automate extractionoffeaturesinthestructure.However,TerrestrialLiDARis much more appropriate for complex structures wherethe use of CRP may require complex processing [12].TerrestrialLiDARcancapturethefullsurfaceofanobject, even cracks and tiny deformations and map themup to millimeters of accuracy. In addition, the texture isacquired through the photos that are simultaneously takenduringthescanningprocess.

2 ThecombinationofBIMandTerrestrial LiDAR for documentation anddeformationassessment

TheuseofaTerrestrialLiDARallowsadigitalarchiving of the as-built condition of a building. Indeed,Terrestrial LiDAR provides a very dense and accuratepointcloudthatcapturesthecurrentcondition of thisbuilding. Then, based on the acquired point cloud, a 3Dmodel could be generated. This 3D model may representeither the as-built condition or the ideal condition of suchabuilding.

Inthissection,wewillintroducetheconceptofBuilding Information Modelling (BIM) and how it can beusedtoassessthedeformationofhistoricalbuildings.

TheimportanceofBIM inculturalheritage

BuildingInformationModels(BIM)differfromconventional3DmodelsbecauseBIMarebasedonknowledge-richparametricbuildingelements[13].These

parametric objects,which represent the components ofthebuilding,areassembledtogethertoautomatethegeneration of building information and to facilitate thecreationofrichbuildingmodels[13].Theparametric objectsaredefinedaccordingtoasystemicapproachwhere each object is characterized by its descriptive dataand its relationship with other components of the building[14]. The concept of BIM is widely used in the field ofcultural heritage preservation [15 - 18]. In [19] a plug-inprototypelibrary,namedHistoricalBIM(HBIM),for parametric objects used to model historical monumentshas been developed. HBIM offers interactive parametricobjects that represent architectural elements, and it wasusedtomodelhistoricalmonumentsfromTLSpoint cloud [14]. The BIM provides a powerful approach toautomate the documentation of cultural heritage thanks toitsparametricmodellingprocess.Itallowsgenerating highlysophisticated3Dmodelsandofferadvancedvisualizationtools.

TheintegrationofLiDARandBIMfordeformationassessment

The proposed approach for deformation assessment consist of integrating Terrestrial LiDAR with Building Information modelling. First, we proceed to the scanning of the exterior facades, then the interior components of the building. It is necessary that all scanning stations must be referenced according the same reference system, so we can register all stations in the same point cloud. After cleaning the resulting point cloud, the next step is to create a 3D BIM from this cloud. For this purpose, it is possible to use some commercial software such as Autodesk' Revit and Graphisoft'sArchiCAD [20]. This BIM must represent the ideal condition of the building because it will be compared to the point cloud corresponding to the as-built condition. Once the BIM is completed, the point cloud will be segmented according to the components of the BIM against which deformations will be assessed. Indeed, each segment of the point cloud is compared to the corresponding BIM component through a Point-to-Surface deformation analysis (see section 2.2). The result of such a comparison will provide a useful information about the current condition of the assessed part of the building, and hence if any restoration is needed.

Conclusion

The study's goal is to provide a method for archiving cultural properties and measuring their degree of distortion.The point cloud must be divided into manageable chunks before deformation analysis can begin.
depending on the incorporation of BIM and Terrestrial LiDAR. The use of terrestrial LiDAR to allow digital preservation of cultural artifacts in the form of a 3D point cloud is an intriguing prospect. The density of this point cloud is extraordinary. Additionally, every vs their equivalent elements in the BIM. Our focus in this analysis will be on the partitions between rooms, both above and on the ground. So, the Each cloud point is equipped with precise three-dimensional coordinates relative to a known frame of reference. Moreover, the point The first step is to seal off the space (or spaces) that will be evaluated. Next, a Point-to-Surface deformation analysis is performed using the BIM model's ideal ceiling as input. Using this study,

you can see where the utilized point cloud deviates from the ideally-represented ceiling design. Realistic photographs obtained during the scanning process provide data on the building's texture that may be stored in the cloud.
The generation of 3D Building Information Models is a crucial use of Terrestrial LiDAR point clouds.

The following diagram depicts the outcome of a deformation study performed on the room in "RobatBanajah" that recorded the highest values for deformation.

models. Useful in many fields, including archaeology, history, and culture, these 3D models have a wide range of potential uses. With this study, we hope to have brought attention to the value of BIM in the context of deformation analysis. Point-to-surface analysis, as shown by the 'RobatBanajah' case study, may be done to determine how good or bad a historic structure really is. The results suggest that there is a distortion of roughly 22 centimeters in certain areas of the building; additional research by professionals is needed to determine whether or not repair and maintenance actions are necessary.

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