RESUMEN

Las obras arquitectónicas históricas constituyen nuestro patrimonio arquitectónico, por lo cual debemos conservarlas para transmitirlas a las generaciones futuras. Un método eficiente y económico para la conservación consiste en la reconstrucción virtual, que permite almacenar todo tipo de información respecto a un edificio histórico, mediante un modelo tridimensional del mismo. Este documento 3D es muy útil, porque en caso de colapso, ruina, deterioro o abandono del patrimonio, se podría recurrir al mismo. Gran parte de la literatura científica que investiga la salvaguarda de obras patrimoniales históricas, aplican los métodos de digitalización 3D basado en imágenes para su documentación, como el uso de los UAVs (Unmanned Aerial Vehicle). El potencial que aporta la información obtenida de los vuelos realizados con UAVs, se ve incrementado, si es combinado con softwares basados en algoritmos especiales como SfM (Structure-from-Motion). Su uso se ha incrementado progresivamente, siendo un instrumento de investigación estándar para la adquisición de imágenes y la creación de nube de puntos 3D y ortofoto. La integración de esta nube de puntos en entornos BIM (Building Information Modeling) genera un modelo tridimensional muy preciso. Su variante orientada al patrimonio se conoce como HBIM (Historic Building Information Modeling).

En esta tesis doctoral se ha profundizado en el estudio de la combinación del método UAV-SfM y la metodología HBIM para reconstruir virtualmente obras del patrimonio cultural, con propósitos de visualización, archivo, difusión y puesta en valor del mismo. Con la composición de ambos métodos se ha demostrado que es posible obtener resultados muy exactos, con precisión centimétrica, lo cual permite mantener la legitimidad del inmueble. La utilización del HBIM en obras del patrimonio cultural es una excelente solución para la gestión, mantenimiento, restauración y conservación de edificaciones históricas. Estos modelos tridimensionales son el núcleo contenedor de toda la información gráfica de una edificación y debido a su interoperabilidad pueden tomarse como base en cualquier proyecto de intervención del patrimonio.

FOTOGRAMETRÍA UAV Y MODELADO HBIM PARA LA RECONSTRUCCIÓN VIRTUAL DEL PATRIMONIO CULTURAL
LOURDES MARÍA YERO PANEQUE / TESIS DOCTORAL / 2021

TESIS DOCTORAL

FOTOGRAMETRÍA UAV Y MODELADO HBIM PARA LA RECONSTRUCCIÓN VIRTUAL DEL PATRIMONIO CULTURAL

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UAV PHOTOGRAMMETRY AND HBIM MODELING FOR THE VIRTUAL RECONSTRUCTION OF CULTURAL HERITAGE

DOCTORADO EN TECNOLOGÍA DE INVERNADEROS
E INGENIERÍA INDUSTRIAL Y AMBIENTAL

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ESCUELA SUPERIOR DE INGENIERÍA
SEPTIEMBRE, 2021

“Siempre he afirmado que los lugares son más fuertes que las personas, el escenario más que el acontecimiento. Esa posibilidad de permanencia es lo único que hace al paisaje o las cosas construidas superiores a las personas”.

Aldo Rossi

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En esta tesis doctoral se ha profundizado en el estudio de la combinación del método UAV-SfM y la metodología HBIM para reconstruir virtualmente obras del patrimonio cultural, con propósitos de visualización, archivo, difusión y puesta en valor del mismo. Con la composición de ambos métodos se ha demostrado que es posible obtener resultados muy exactos, con precisión centimétrica, lo cual permite mantener la legitimidad del inmueble. La utilización del HBIM en obras del patrimonio cultural es una excelente solución para la gestión, mantenimiento, restauración y conservación de edificaciones históricas. Estos modelos tridimensionales son el núcleo contenedor de toda la información gráfica de una edificación y debido a su interoperabilidad pueden tomarse como base en cualquier proyecto de intervención del patrimonio.

ABSTRACT

Historical architectural works are our architectural heritage and we must preserve them in order to pass them on to future generations. An efficient and cost-effective method of conservation is virtual reconstruction, which allows all kinds of information to be stored about a historic building by means of a three-dimensional model of it. This 3D document is very useful, because in case of collapse, ruin, deterioration or abandonment of the heritage, it could be used. Much of the scientific literature investigating the safeguarding of historical heritage works applies image-based 3D scanning methods for their documentation, such as the use of UAVs (Unmanned Aerial Vehicle). The potential of the information obtained from UAV flights is increased if combined with software based on special algorithms such as SfM (Structure-from-Motion). Its use has progressively increased and it has become a standard research tool for image acquisition and the creation of 3D point clouds and orthophotos. The integration of this point cloud in BIM (Building Information Modelling) environments generates a highly accurate three-dimensional model. Its heritage-oriented variant is known as HBIM (Historic Building Information Modeling).

In this doctoral thesis we have studied in depth the combination of the UAV-SfM method and the HBIM methodology to virtually reconstruct works of cultural heritage, for purposes of visualisation, archiving, dissemination and enhancement. The combination of both methods has shown that it is possible to obtain very accurate results, with centimetre precision, which allows the legitimacy of the property to be maintained. The use of HBIM in cultural heritage works is an excellent solution for the management, maintenance, restoration and conservation of historic buildings. These three-dimensional models are the core container of all the graphic information of a building and, due to their interoperability, they can be used as a basis for any heritage intervention project.

CAPÍTULO 01 INTRODUCCIÓN

1- Introducción general.

El concepto de patrimonio cultural ha ido cambiando a lo largo de la historia, como muestran las diferentes declaraciones oficiales recogidas en la figura 1 (Gómez, 2008; Zetina Nava, 2015; UNESCO World Heritage Centre, 2008). Se puede definir como la herencia cultural propia del pasado de una comunidad, mantenida hasta la actualidad y transmitida a las generaciones presentes (UNESCO World Heritage Centre, 2017). Las obras arquitectónicas son legados históricos que nos han dejado nuestros antepasados y constituyen nuestro patrimonio arquitectónico. Debemos conocerlas, estudiarlas, valorarlas y conservarlas para transmitirlas a las generaciones futuras (Terán Bonilla, 2003).

Los conjuntos arquitectónicos históricos forman parte del patrimonio cultural tangible - inmueble (figura 2), por lo cual su documentación gráfica debe preservar su autenticidad. Un método eficiente y económico para la conservación consiste en la reconstrucción virtual. Este método permite recuperar visualmente el estado original de una obra patrimonial, a partir de un modelo digital 3D, que almacena información referente a su forma geométrica, materiales, características arquitectónicas, etc. La documentación geométrica registra su transformación a lo largo del tiempo y es la base necesaria para el estudio de su pasado, así como el de su futuro. Este documento 3D es imprescindible; ya que, en caso de colapso, ruina, deterioro o abandono del patrimonio, se podría recurrir al mismo.

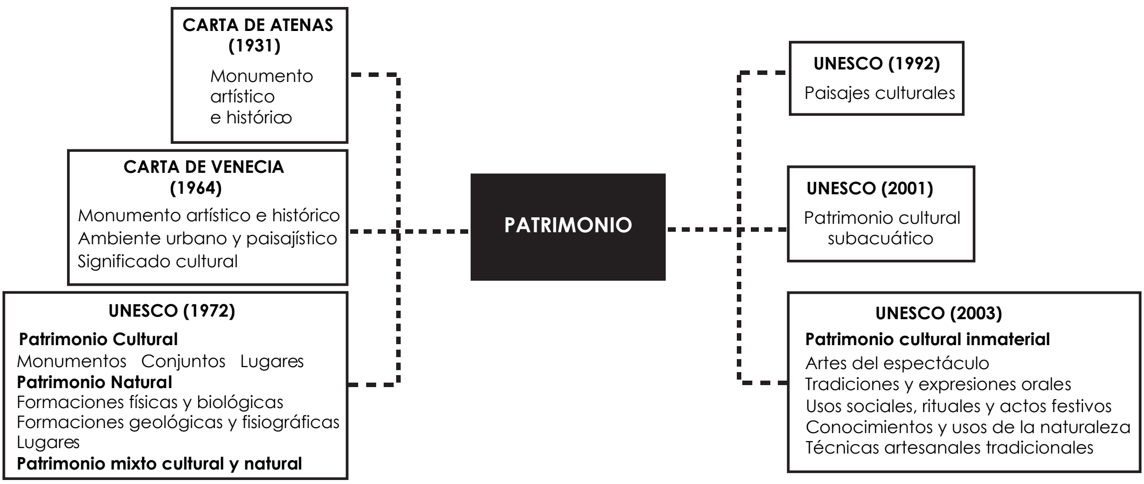


Figura 1. Evolución del concepto de patrimonio según declaraciones oficiales. Fuente: elaboración propia.

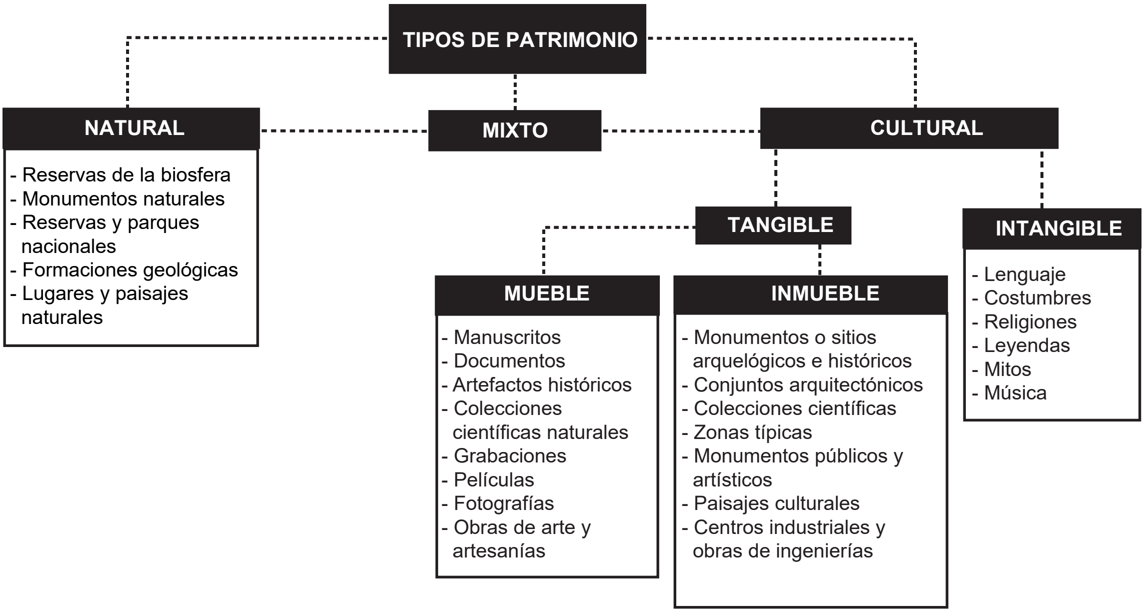


Figura 2. Tipologías de patrimonio de la humanidad vigentes definidas por la UNESCO. Fuente: elaboración propia.

El preámbulo de la Ley del Patrimonio Histórico Español protege los inmuebles y objetos muebles de interés artístico, histórico, paleontológico, arqueológico, etnográfico, científico o técnico. También forman parte del mismo, el patrimonio documental y bibliográfico, los yacimientos y zonas arqueológicas, así como los sitios naturales, jardines y parques, que tengan valor artístico, histórico y antropológico. Los bienes más relevantes deberán ser inventariados o declarados de interés cultural (Ley 16/1985, de 25 de junio). La Ley prevé que la declaración de un Bien de Interés Cultural (BIC) puede ser cualquier imnueble u objeto mueble original que reúnan los valores mencionados anteriormente, en cualquiera de las manifestaciones científicas, artísticas y literarias; tal y como se muestra en la figura 3.

Figura 3. Clasificación del BIC según la la Ley del Patrimonio Histórico Español. Fuente: elaboración propia.

Para que un elemento patrimonial pase a formar parte del BIC, debe reunir una serie de documentos que justifiquen sus valores, para la posterior tramitación de un expediente. Su valor histórico se evalúa en función de su memoria histórica. Su valor artístico lo define su estética y estilo correspondiente. Su valor de identidad está dado por la importancia que tiene para la sociedad por su singularidad o significado. Su valor cultural se debe a su uso o simbolismo, ligado a valores inmateriales históricos, para que pueda trascender lo estrictamente arquitectónico, urbanístico o paisajístico. Por lo tanto, las obras arquitectónicas históricas son el resultado de transformaciones a lo largo de su historia, por lo cual no pueden entenderse como un único elemento. Su diseño y construcción no está concebido partiendo de modelos estándares y prefabricados, ya que cada elemento constructivo constituye una singularidad (Smart Building Spanish Chapter, 2018).

Gran parte de la literatura científica que investiga la salvaguarda de obras patrimoniales históricas, aplican los métodos de digitalización 3D basado en imágenes para su documentación; como el uso del TLS (Terrestrial Laser Scanning) y los drones, conocidos también como "vehículo aéreo no tripulado", correspondiente a sus siglas en inglés UAV (Unmanned Aerial Vehicle) (Sánchez-Aguero et al., 2020; Gallardo-Salazar et al., 2020). En esta tesis, se ha utilizado el término "UAV" para identificar un vehículo aéreo no tripulado, que puede tener un vuelo autónomo con o sin motor, ser controlado remotamente y poder recolectar datos (Giordan et al., 2020). La fotogrametría a partir de imágenes tomadas desde UAV ha sido acuñada como "fotogrametría UAV" (Martínez Carricondo, 2016; Eisenbeiß et al. 2009). El potencial que aporta la información obtenida de los vuelos realizados con drones, se ve incrementado, si es combinado con softwares basados en algoritmos especiales como SfM (Structure-from-Motion) (Clapuyt et al. 2016). El resultado del procesamiento mediante SfM es una nube de puntos densa con millones de puntos que describen con más detalle la superficie y geometría de un objeto, aportando coordenadas tridimensionales tipo XYZ y una descripción colorimétrica RGB. Todos estos avances han desembocado en un nuevo concepto: la "*fotogrametría UAV-SfM"* (Martínez Carricondo, 2016). Su uso se ha incrementado progresivamente en la última década; y hoy en día, comienza a ser considerado un instrumento de investigación estándar para la adquisición de imágenes y la creación de modelos 3D detallados y ortofoto (Giordan et al., 2020).

En los edificios históricos existen muchas zonas ocultas e inaccesibles a través del TLS, por lo cual los UAVs suponen una ventaja en este caso (figura 4), al ser una tecnología económica y emergente, que puede equiparse con cámaras de alta resolución para realizar fotogrametría basada en SfM, para su aplicación al seguimiento y gestión del patrimonio histórico (Martínez-Carricondo et al., 2019; Achille et al., 2015; De Reu et al., 2013; Chiabrando et al., 2011; Verhoeven, 2009; Hendrickx et al., 2011; Mesas-Carrascosa et al., 2016; Mozas-Calvache et al., 2012; Ortiz et al., 2013; Sauerbier & Eisenbeiss, 2010).

Las nubes de puntos obtenidas de la fotogrametría UAV suelen estar compuestas por menos datos, lo cual es una ventaja para su gestión frente al TLS; ya que se tiene un mayor control sobre los errores de medida, careciendo de los errores de reflexión que con el TLS se obtienen en ciertas superficies.

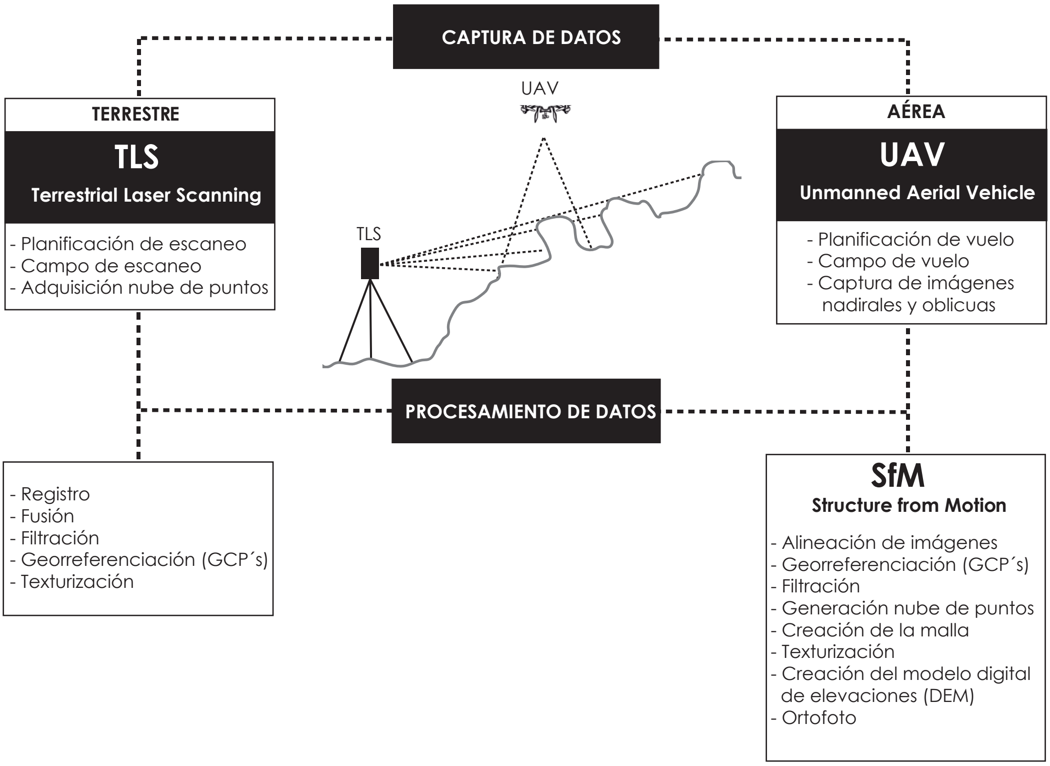


Figura 4. Métodos de captura y procesamiento de datos: TLS vs fotogrametría UAV. Fuente: elaboración propia.

La integración de esta nube de puntos en entornos BIM (Building Information Modeling) genera un modelo tridimensional muy preciso (Carvajal-Ramírez et al., 2019), con información gráfica y alfanumérica muy completa (Nieto Julián, 2012). El acrónimo BIM hace referencia tanto a una metodología, como a las herramientas destinadas a crear un sistema de información digital de un edificio asociado a su documentación gráfica, siendo ésta generalmente un modelo tridimensional del mismo (Smart Building Spanish Chapter, 2018). La variante orientada al patrimonio se conoce como HBIM (Historic Building Information Modeling) (Dore & Murphy, 2012, Murphy et al., 2017), pues permite obtener una completa documentación digital de los inmuebles históricos.

1.1- Objetivos.

Teniendo en cuenta las consideraciones anteriores, el objetivo principal que se plantea para la realización de esta tesis doctoral, consiste en utilizar la fotogrametría UAV, vinculada con la metodología de modelado tridimensional HBIM para reconstruir virtualmente obras del patrimonio cultural, con propósitos de visualización, archivo, difusión y puesta en valor del mismo. El objetivo principal se desarrolla a partir de objetivos específicos, que se abordan a continuación:

- Profundizar en detalle la técnica de toma de datos “fotogrametría UAV” para la realización de levantamientos tridimensionales de obras patrimoniales.

- Demostrar las ventajas de la nube de puntos 3D mediante el uso del método UAV-SfM.

- Generar un modelo HBIM inteligente a partir de la nube de puntos 3D. Demostrar la interoperabilidad del modelo HBIM.

- Demostrar la precisión del modelo HBIM obtenido respecto a la nube de puntos 3D.

- Obtener resultados de mapeo fotorrealistas.

1.2- Metodología y estructura de la tesis.

La tesis doctoral se ha estructurado en seis capítulos, divididos en dos partes fundamentales: fundamentos teóricos y aplicación práctica. Este, el primer capítulo, aborda la introducción general al tema de investigación, las razones técnicas que llevan a plantear los objetivos propuestos y la metodología a desarrollar. Los fundamentos teóricos abarcan el capítulo 2, donde se ha realizado una búsqueda actualizada de documentos y publicaciones científicas en el ámbito de los UAVs y el flujo de trabajo de la metodología BIM y HBIM, aplicadas a la reconstrucción virtual del patrimonio cultural y su visualización. Analizando la información consultada, se realiza una síntesis que servirá de guía para el proceso de trabajo.

El capítulo 3 muestra la aplicación práctica de la investigación, analizando dos obras del patrimonio cultural, actualmente abandonadas y en estado ruinoso: el *“Embalse de Isabell II”* y el *“Cortijo del Fraile”,* ambos ubicados en Níjar, Almería. De éste último se incluye una copia de un estudio realizado al mismo, publicado en la revista *Building Research & Information.* Por otra parte, el capítulo 4 abarca las conclusiones generales y aportes de la investigación, así como las futuras líneas a desarrollar.

En el capítulo 5 se incluye como anexo, copia de una discusión científica presentada en *27th International CIPA Symposium: "Documenting the past for a better future"* y publicado en los archivos de ISPRS (The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences). Finalmente, el capítulo 6 es la bibliografía utilizada para el desarrollo de la tesis doctoral. En la figura 5 se muestra esquemáticamente el diseño de esta investigación.

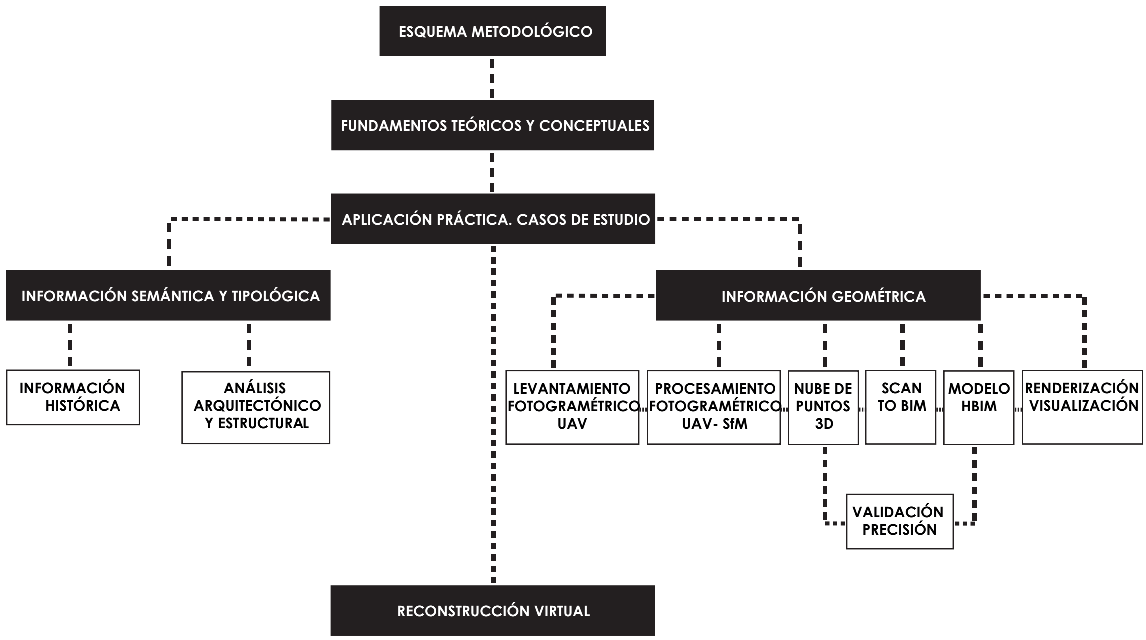


Figura 5. Esquema metodológico de la investigación.
Fuente: elaboración propia.

CAPÍTULO

02 FUNDAMENTOS TEÓRICOS

2- Fotogrametría UAV. Utilización del método UAV –SfM.

Al utilizar la fotogrametría UAV como método de captura de datos, primeramente es necesario seleccionar la cámara fotográfica y el tipo de dron a utilizar (tabla 1). Para vuelos sobre edificaciones históricas es conveniente utilizar un dron de ala rotatoria, específicamente un multirrotor, por la flexibilidad en la toma de imágenes a diferentes alturas y con diferentes ángulos, dependiendo de la escena que se pretende captar. Luego se monta la cámara en el dron, junto a ella se dispone de un sistema GNSS (Global Navigation Satellite System) y una IMU (Inertial Measurement Unit) para conocer la posición y orientación de las cámaras en el momento de disparo. En la planificación del vuelo se necesita recubrir el área con fotogramas que se solapen tanto longitudinalmente como transversalmente. A pesar de que los UAVs pueden volar de forma autónoma siguiendo la planificación del vuelo, siempre existe la posibilidad de que algún elemento no funcione correctamente, por lo cual es fundamental que exista un técnico capacitado para tomar el control del UAV y aterrizar en condiciones de seguridad.

<table>
<tr><th colspan="5">Clasificación del UAV según método de sustentación</th></tr>
<tr><th colspan="2">Aerostato</th><th colspan="3">Aerodino</th></tr>
<tr><td>Dirigible</td><td>Globo</td><td colspan="2">Ala fija (avión)</td><td>Ala rotatoria (multirotor)</td></tr>
<tr><th colspan="5">Clasificación del UAV según varios factores generales</th></tr>
<tr><th>Categoría</th><th>Distancia (km)</th><th>Altura de vuelo (m)</th><th>Duración (h)</th><th>MTOW (kg)</th></tr>
<tr><td>Nano (η)</td><td>< 1<</td><td>< 100</td><td>1</td><td>< 0.025</td></tr>
<tr><td>Micro (μ)</td><td>< 10</td><td>250</td><td>1</td><td>< 5</td></tr>
<tr><td>Mini</td><td>< 10</td><td>150-300</td><td>< 2</td><td>150</td></tr>
<tr><td>Close range (CR)</td><td>10-30</td><td>3000</td><td>2-4</td><td>150</td></tr>
<tr><td>Short range (SR)</td><td>30-70</td><td>3000</td><td>3-6</td><td>200</td></tr>
<tr><th colspan="5">Comparación de UAVs</th></tr>
<tr><th>UAV</th><th>Distancia</th><th>Duración</th><th>Influencia del viento</th><th>Operabilidad</th></tr>
<tr><td>Globo</td><td>1</td><td>4</td><td>4</td><td>2</td></tr>
<tr><td>Dirigible</td><td>3</td><td>3</td><td>4</td><td>3</td></tr>
<tr><td>Cometa</td><td>2</td><td>2</td><td>4</td><td>2</td></tr>
<tr><td>Alas fijas</td><td>5</td><td>5</td><td>2</td><td>4</td></tr>
<tr><td>Helicóptero (mini)</td><td>4</td><td>4</td><td>3</td><td>5</td></tr>
<tr><td>Multirotor (con 4-8 hélices)</td><td>4</td><td>3</td><td>2</td><td>5</td></tr>
</table>

Tabla 1: Clasificación y comparación de los UAVs según varios factores. MTOW (Maximun Take-Off Weight) se refiere al peso máximo al despegue. En la comparación de los UAVs (5 indica el valor máximo). Fuente: elaboración propia, datos tomados de (Giordan et al., 2020; UAS Yearbook, 2011).

La superposición suficiente de imágenes es muy importante para generar con precisión el modelo 3D. El valor nominal de solape de las fotografías nadirales depende de la topografía de la superficie, podría ser del 60-80% en dirección longitudinal y 50-80% en dirección transversal (Giordan et al., 2020). En superficies geométricas de fachadas es suficiente tomar el 60% de recubrimiento transversal y 80% de recubrimiento longitudinal. El valor sugerido de la superposición puede alcanzar el 80% si la superficie se caracteriza por un bajo contraste como la nieve o arena (Agisoft, 2018). La adquisición de imágenes oblicuas se basa típicamente en el uso de multirotor (Giordan et al., 2020) pues capturan la escena bajo un ángulo de inclinación mucho mayor que las imágenes nadirales, lo cual mejora la visualización de las estructuras verticales (fachadas, árboles, farolas, etc.) como se muestra en la figura 6. La altura de vuelo estará condicionada por el nivel de detalle que se desee captar, y este a su vez, por la resolución del sensor y la focal del objetivo. En este caso se refiere al GSD (Ground Sample Distance), que es la huella o el tamaño del pixel proyectado sobre el terreno (figura 7) (Cuerno C, Ramirez J, 2015).

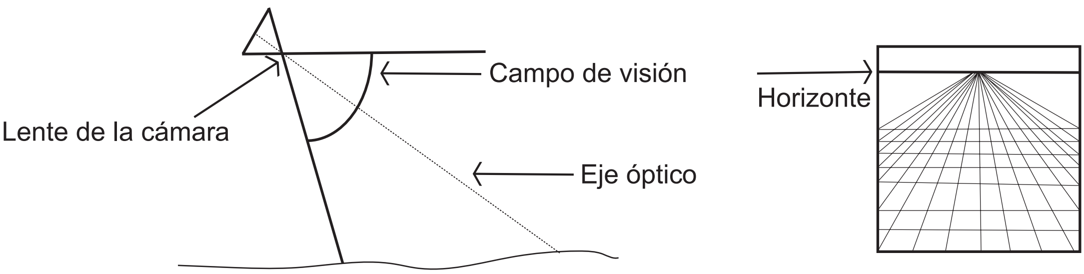


Figura 6. Ejemplo de la orientación de la cámara para la captura de imágenes oblicuas. Fuente: elaboración propia, modificado de (Giordan et al., 2020).

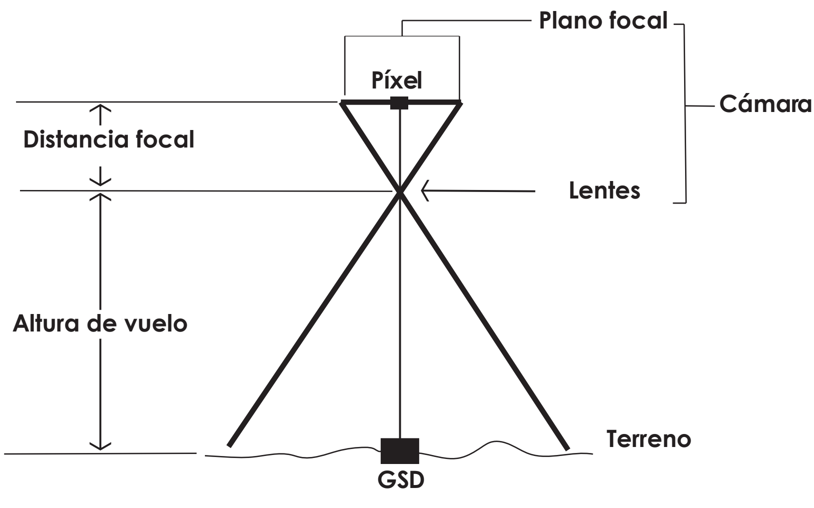


Figura 7. Relación entre GSD y altura de vuelo.
Fuente: elaboración propia, modificado de (Cuerno C, Ramirez J, 2015).

Según el estudio de (Giordan et al., 2020) la precisión real alcanzable dependerá de muchos factores, como:

- Parámetros de vuelo: GSD, área de interés, información de la cámara y objetivos del vuelo.
- Características del UAV disponible: plataforma UAV (duración y almacenamiento de las baterías, distancia máxima desde la estación de control en tierra) y piloto automático.
- Parámetros adicionales como: calibración de la cámara, disponibilidad y distribución de los GCPs (Ground Control Points).

El uso de GCPs es un elemento esencial que podría tener un impacto sustancial en la precisión del SfM (James y Robson 2012; Turner y col. 2015). Se necesitan al menos tres GCPs para georreferenciar el proyecto fotogramétrico, aunque es recomendable aumentar el número de estos puntos para alcanzar mejores precisiones (Martínez Carricondo, 2016; Rosnell & Honkavaara, 2012).

2.1- Procesado fotogramétrico.

El algoritmo SfM permite conocer las propiedades geométricas de un objeto o una superficie mediante información obtenida a partir del solapamiento entre imágenes consecutivas. Se realiza mediante la técnica de estereoscopía (Martínez Carricondo, 2016), y el proceso fotográfico directo y procesado por software. En los últimos años, Agisoft PhotoScan ha ganado popularidad en el ámbito científico, como se evidencia en la figura 8, principalmente debido a la facilidad de su uso. El número de estudios publicados ha aumentado gradualmente en relación con Pix4D, mientras que existe una tendencia lineal constante para el uso de MicMac. Cabe señalar que los resultados de la figura 8 incluyen estudios de UAV de varias comunidades científicas (E. F. Berra & M. V. Peppa, 2020). Estos softwares internamente calculan y procesan las imágenes y finalmente devuelven un modelo 3D del objeto fotografiado.

De las fotografías digitales tomadas por un UAV es posible obtener los datos necesarios para una calibración aproximada, gracias al EXIF (Exchangeable image file format). El EXIF es un estándar creado para almacenar metadatos de las fotografías tomadas con cámaras digitales, que contienen información relativa a la propia imagen y a cómo ha sido tomada. Cuantas más imágenes existan más precisa será la calibración interna. Cada imagen dará una perspectiva del objeto diferente, por lo que habrá que buscar características reconocibles desde diferentes perspectivas. Éstos son los denominados puntos singulares.

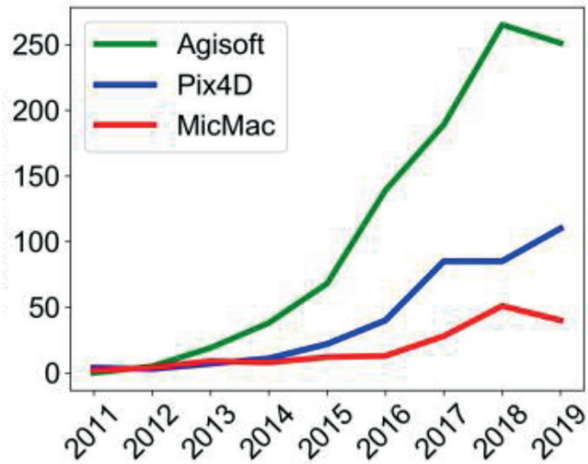


Figura 8. Número de estudios publicados que procesan imágenes de UAV con PhotoScan, Pix4D y MicMac en los últimos ocho años, extraído de Scopus, 2019.

Existen diferentes técnicas para ello, en las que a cada punto singular se le asocia una serie de características que no dependen del lugar de la fotografía. La técnica más conocida es SIFT (Scale-Invariant Feature Transform) (Peña-Villasenín et al., 2020; Gabás Jiménez et al., 2016).

Observando los valores de diferentes puntos singulares en diferentes fotografías, si se encuentran dos con características extraídas con el algoritmo SIFT, en el mismo lugar físico y en imágenes diferentes, se puede considerar que los mismos podrían representar una misma posición física en la escena de captura. Con la información correspondiente a muchos puntos singulares se puede obtener también la localización angular de la cámara con respecto a la escena. Ya se tiene por tanto una estimación de la posición física de la cámara. Por triangulación, si un mismo punto es visto desde diferentes perspectivas espaciales, se puede aproximar su ubicación en un espacio tridimensional. Como resultado, se tendrá la localización en el espacio tridimensional de ese punto. Con todos los puntos posibles ubicados en el volumen, se construye una nube de puntos que representa al objeto fotografiado (Gabás Jiménez et al., 2016). Esta nube de puntos representa, por tanto, la geometría de la escena. La aparición de estas técnicas nos ha permitido trabajar con superficies complejas (Barazzetti et al., 2011) y obtener nubes de puntos, mallas de triángulos y, finalmente, un modelo texturizado tridimensional completo (Westoby et al. 2012).

2.2- De la fotogrametría UAV- SfM a la metodología HBIM.

BIM abarca en un modelo paramétrico la geometría de una edificación, sus características físicas y funcionales, así como información cuantitativa y cualitativa (Smart Building Spanish Chapter, 2018). Se considera a HBIM, como una biblioteca especial de objetos paramétricos BIM que ha sido diseñada como un sistema multidisciplinar y en constante evolución, que se utiliza para administrar, documentar, gestionar y reconstruir digitalmente edificaciones históricas (Carvajal-Ramírez et al., 2019; Capone & Lanzara, 2019; Dore y Murphy, 2012).

La principal diferencia entre BIM y HBIM es el objeto de modelado; mientras que BIM se utiliza en obras de nueva planta y edificios existentes, HBIM aplica la metodología de BIM a un edificio existente histórico para recrear en un mundo digital el edificio como fue construido (Allegra et al., 2020; Hichri et al., 2013). El término "Scan-to-BIM" (figura 9) se refiere al proceso de creación del modelo BIM, a partir de datos de escaneo y fotogrametría (Dore & Murphy, 2017).

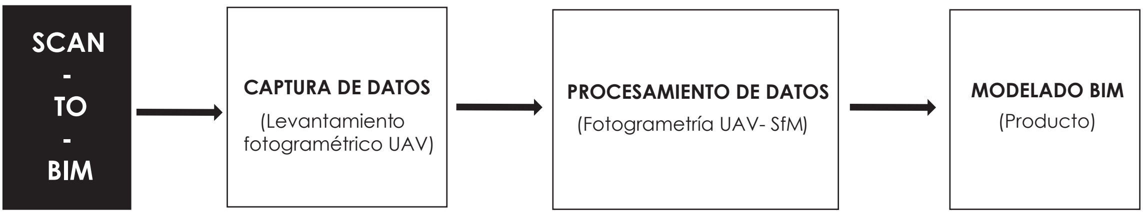


Figura 9. Proceso de trabajo para escanear a BIM. Fuente: elaboración propia.

La nube de puntos 3D, como técnica métrica simplifica las fases de toma, procesamiento y modelado de datos de una edificación, pero siguen siendo superficies poliédricas que necesitan ser exportadas a otros softwares (tabla 2) para dibujar los planos, extraer medidas y proyectar actuaciones sobre ellas.

La tabla 2 ilustra que Autodesk Photo on ReCap 360 permite la exportación de nubes de puntos y se integra mejor con ReCap, la cual es una aplicación inteligente para crear modelos 3D (BIM, AEC, MCAD) desde información escaneada o capturada desde fotos (Rodríguez-Navarro et al., 2016) y se puede utilizar para ver, editar y administrar los archivos de proyecto de nube de puntos. En este caso, habiendo generado la nube de puntos con Agisoft PhotoScan, el archivo que mejor se integra en Revit es el formato (*.las), que guarda la información de color obtenida de las imágenes permitiendo su visualización (Carvajal-Ramírez et al., 2019). Para uso en Revit, este tipo de archivo tiene que ser procesado previamente para ser convertido a un formato (*.rcs) y ello puede hacerse desde la aplicación ReCap.

Software	Importa/Abre (nube de puntos)	Exporta/Guarda	
		Modelo	Nube de puntos
Agisoft PhotoScan		.obj, .3ds, .wrl, .dae, .ply, .dxf, .fbx, .u3d, .pdf, .kmz	.obj, .ply, .txt, **.las**, .u3d, .pdf
Autodesk ReCap	**.rcs**, .fls, .fws,.lsproj, .ptg, .pts, .ptx,**.las**, .zfs, .zfprj, .asc, .cl3, .clr, .e57, .rds, .txt, .xyz, .rcp, .pcg, .xyb, .prj, .xyb		**.rcs**, .pts, .e57, .pcg
Autodesk Photo on ReCap 360		.obj, .rcm, .fbx, .ipm	**.rcs**
Autodesk Revit	**.rcs**, .rcp, .3dd, .asc, .d3, .clr, .e57, .fls, .fws, .ixf,**.las**, .las84, .mpc, .obj, .pcg, .ptg, .pts, .ptx, .rds, .rep, .rxp		

Tabla 2. Compatibilidad de softwares. En color rojo, se destacan los formatos de archivos coincidentes entre diferentes programas. Fuente: elaboración propia.

Revit es el software BIM más utilizado en España, por los profesionales que trabajan con esta metodología colaborativa, según las últimas encuestas realizadas por la comisión *es.BIM* (Esarte Eseverri, 2018). Contiene varias dimensiones (figura 10), logrando la interoperabilidad mediante el uso de diferentes programas y varias disciplinas (Carvajal-Ramírez et al., 2019; Tommasi & Achille, 2017).

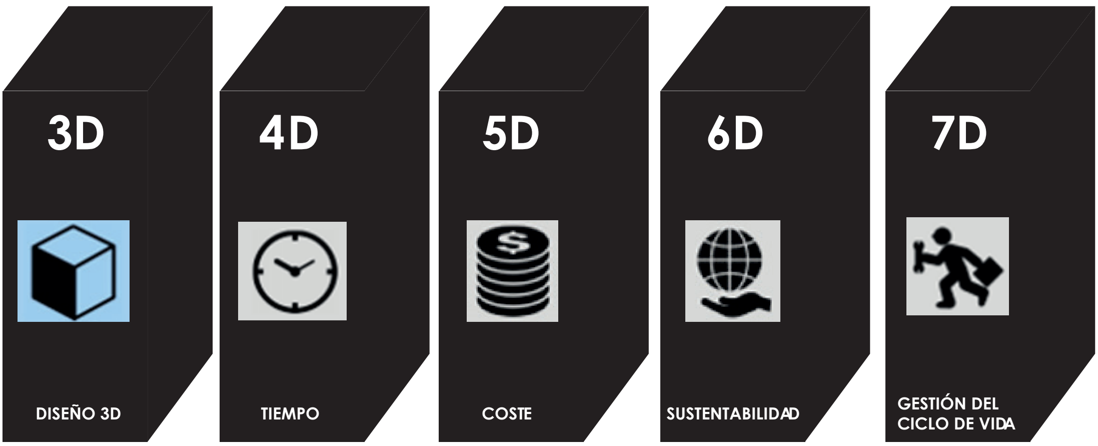


Figura 10. Dimensiones del BIM. Fuente: elaboración propia.

Para la interoperabilidad en BIM se utilizan distintos formatos de archivos como pueden ser los BFC (BIM Collaboration Format), estándar COBIE (Construction Operations Building Information Exchange) o IFC (Industry Foundation Classes). Este último es el más utilizado en el sector de la construcción, ya que es un formato "OpenData", siendo modelos de datos estandarizados y abiertos, desarrollado por buildingSMART (UK BIM Framework, 2020).

El formato IFC es registrado como estándar internacional por la "*International Standardisation Organisation"* en 2013, como ISO 16739 *"Industry Foundation Clasess (IFC) for data sharing in the construction and facility management industries"*. Posteriormente, este estándar ha sido adoptado como Euronorma y está vigente en España desde 2017 como *UNE-EN ISO 16739:2016* (Smart Building Spanish Chapter, 2018). Los elementos de diseño dentro de IFC disponen de distintos atributos como pueden ser tamaño, modelo o propiedades de mantenimiento, etc. Así, es posible exportar elementos en una herramienta de diseño, como por ejemplo Revit, al formato IFC, pudiendo ser luego importada por otro software que admita este tipo de modelo de datos.

El nivel de detalle gráfico debe estar estrictamente relacionado con los objetivos del modelo y con el nivel de precisión del levantamiento métrico (figura 11). Desde un punto de vista puramente gráfico, según (F. Chiabrando, M. Lo Turco, C. Santagati; 2017) los grados de resolución de los modelos identificados se pueden dividir en:

- Grado 1: tosco, un procesamiento 3D con el mínimo detalle posible, escala 1: 200.

- Grado 2: medio, modelo 3D con buen nivel de detalle, tal para identificar sus características topológicas, formales y dimensionales, y en parte también sus características métricas, escala 1:100.

- Grado 3: fino, un modelo 3D igual al del Grado 2 en cuanto a aspectos técnicos e informativos, pero con características gráficas mucho más precisas, con una representación fotorrealista, consistente a escala 1:50, tal y como se muestra en la figura 10.

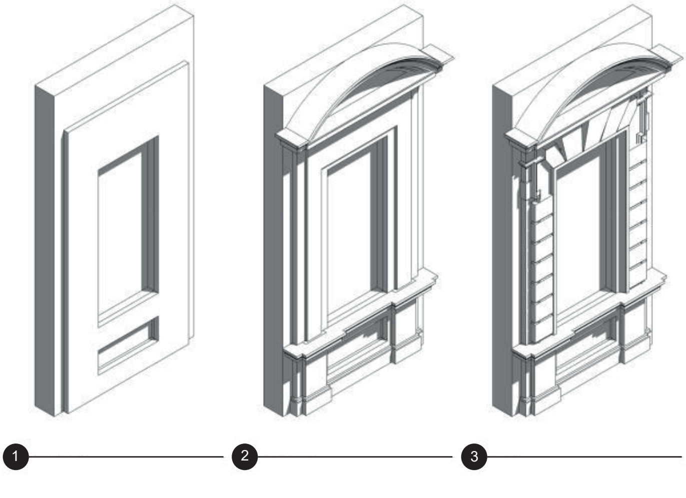


Figura 11. Modelado 3D del mismo componente según varios detalles gráficos, extraído de (Allegra et al., 2020).

Para el proceso de diseño de un modelo HBIM, no es adecuado utilizar geometrías simples, ya que difícilmente describen la forma de estas construcciones históricas. Por ello, hay que recurrir a utilizar plugins o complementos para escanear a BIM. El objetivo de esos complementos consiste en la creación de una biblioteca de elementos paramétricos a partir del procesamiento de datos métricos, mediante la gestión de la nube de puntos.

El mayor desafío del modelado HBIM es la creación de dichos objetos paramétricos inteligentes, a los que asignar la información recopilada, capaces de representar las formas y geometrías únicas y singulares de la arquitectura histórica (Allegra et al., 2020; Tommasi et al., 2016). Posteriormente, se lleva a cabo la identificación de cada objeto paramétrico, como arcos, pilares, vigas, cubiertas, detalles de carpintería y ornamentación, etc, que se completa con los datos geométricos y las propiedades intrínsecas de los elementos en el modelo de información.

En los modelos HBIM, es necesario un adecuado registro de las relaciones estratigráficas y tipológicas del edificio histórico (Smart Building Spanish Chapter, 2018), ya que esta información es útil para conocer su evolución constructiva y contextualización espacial, temporal y social. Es necesario un análisis de todos sus elementos, actividades y procesos constructivos o destructivos, tal y como se muestra en la figura 12. Los materiales se clasifican en constructivos o decorativos, este último puede aportar algún dato de la cronología de la edificación debido a su estilo arquitectónico. Los materiales más empleados en las construcciones históricas son la piedra, la tierra en sus distintos grados de manipulación, la madera y otros elementos vegetales de menor consistencia. Las técnicas y tipologías constructivas poseen un valor cronológico absoluto que facilita la datación de las secuencias estratigráficas (Blanco-Rotea, 2017; Blanco Rotea, 1998). El análisis estratigráfico contribuye a la creación de archivos documentales del patrimonio construido que ayudan a su conservación en caso de pérdida o restauración agresiva, convirtiéndose en un instrumento para la conservación de primer orden. Gracias a este registro de análisis se puede organizar la secuencia de transformaciones de una obra patrimonial al máximo detalle.

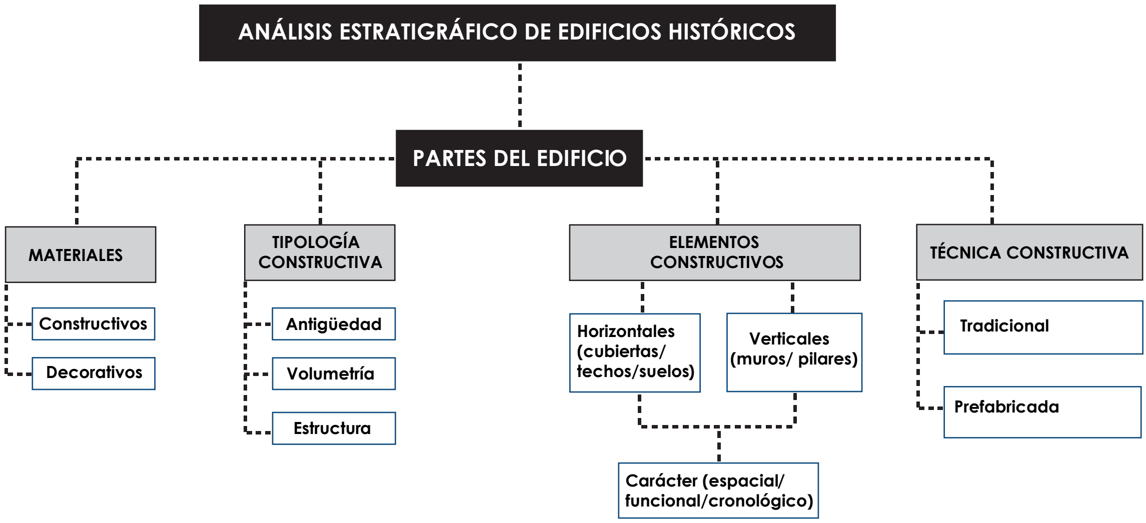


Figura 12. Relaciones estratigráficas y tipológicas de los materiales del edificio. Fuente: elaboración propia.

CAPÍTULO 03 APLICACIÓN PRÁCTICA

3- Embalse de Isabel II en Níjar, Almería.

3.1- Información histórica.

A 6 km de la Villa de Níjar, en Almería, se encuentra el Embalse de Isabel II (figura 13), conocido también como el “Pantano de Níjar”. Su objetivo era dar servicio a las zonas de regadío que se proyectaron en el campo de Níjar. Esta colosal obra forma parte de la “Ruta del Agua”, camino de turismo industrial de 5km que muestra los restos de infraestructuras que canalizaban el agua desde Huebro a Níjar; siendo uno de los elementos de Patrimonio Industrial más espectaculares y a la vez menos conocido de toda Andalucía.

Figura 13. Ubicación del Embalse de Isabell II en Níjar.

Los primeros trabajos de cimentación del muro de la presa datan de 1841, desarrollados por la sociedad privada “Empresa del Pantano”. Este proyecto no contenía planos, ni memorias descriptivas, por lo cual en 1842 se le encarga al arquitecto Gerónimo Ros Giménez el diseño de los planos y un informe sobre el estado actual de las obras. El pantano queda finalmente inaugurado en 1850, aunque faltaban por rematar las obras del muro de la presa, algo que ocurrió en 1851. En 1857 ya estaban terminadas todas las obras, incluido el canal del campo y la casa del pantano. El proyecto fracasó por fallos en los cálculos realizados, por falta de estudios hidrológicos, geográficos y pluviométricos. En la década de los años sesenta, el Embalse de Isabel II, estaba parcialmente anegado y completamente inutilizable. En 1860, el ingeniero francés Maurice Aymard recopila información sobre regadíos, para la publicación *“Irrigations of the south of Spain: studies on the great hydraulic works and the administrative regime of watering of this country”*, por ese motivo viaja hasta Níjar para realizar un informe sobre el pantano.

La figura 14, es la más fiel representación de la realidad construida del embalse, proyectada por Maurice Aymard en 1864, después de su construcción. El Embalse de Isabel II, a pesar de no ser un éxito, fue una construcción avanzada para su época, marcando un hito en la ingeniería hidráulica. Apareció en numerosas revistas internacionales de ingeniería y arquitectura en la segunda mitad del siglo XIX (García Sánchez, 2014).

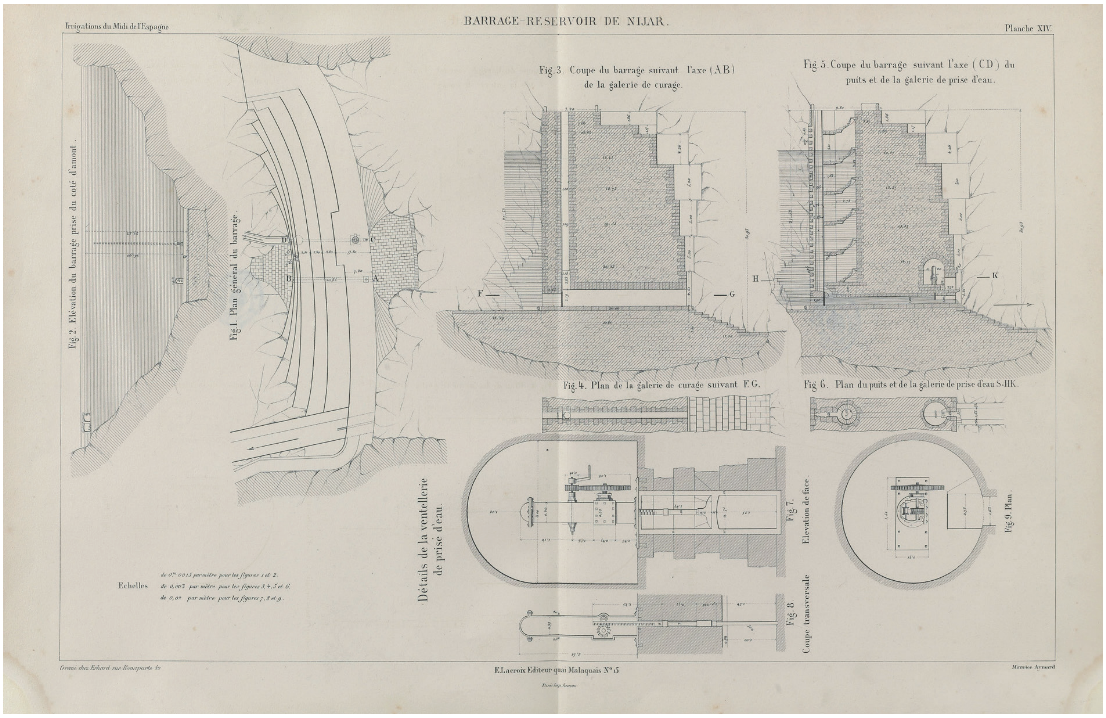


Figura 14. Plano del Pantano de Níjar diseñados por Maurice Aymard in 1864.

3.2- Descripción de la presa.

La presa, construida en el siglo XIX, es una referencia mundial de presas de arco-gravedad construidas en piedra (García Sánchez, 2014). El principal elemento es el muro (figura 15), de aproximadamente 35 metros de altitud y 44 de longitud. En su construcción se utilizaron piedras de sillería caliza en las superficies exteriores y mampostería de cal en el interior. Su llamativa solidez contrasta con la mediana capacidad para la que estaba diseñado. En la parte izquierda de la montaña se encuentra la llamada “Casa del Pantano”, actualmente semiderruida (figura 16) que sirvió como sede para la sociedad que levantó el embalse, desde donde se pueden contemplar excelentes vistas del valle. Ambos elementos son considerados los más representativos del embalse, al estar incluidos en la ruta de turismo industrial de Níjar, por lo que serán el objeto de estudio.

Figura 15.Vista del muro del Embalse de Isabel II.

Figura 16.Vista de la Casa del Pantano.

3.3- Análisis de la presa utilizando el método UAV-SfM.

Levantamiento fotogramétrico.

Para georreferenciar con precisión el proyecto fotogramétrico, es necesario tener una serie de objetivos que sirvan como GCPs. En este sentido, se colocaron 17 objetivos alrededor de la presa, con formato A3 (420 × 297mm) divididos en cuadrantes (figura 17). Las coordenadas 3D de los objetivos se midieron con un receptor del GNSS que opera en modo cinemático de posprocesamiento (PPK) con su base emitiendo correcciones en un punto cerca de la presa, como se muestra en la Figura 17 (B). Tanto los receptores GNSS móviles como los de base eran sistemas Trimble R6. Las coordenadas 3D de la base, corregidas mediante el servicio de posprocesamiento Trimble Centerpoint RTX, fueron 574909.418, 4093250.721 y 372.012m (Sistema de referencia terrestre europeo 1989, modelo de geoide ETRS89 y EGM08). De acuerdo con el estudio de (Martínez-Carricondo, Agüera-Vega, et al., 2020) con estos objetivos es suficiente para que se obtengan resultados con buena precisión tanto en planimetría como en altimetría.

(a) (b)

Figura 17. A) Ejemplo de un GCPs. B) Base de receptor GNSS utilizada.

Captura de Datos.

Para la captura de imágenes se utilizó un UAV DJI Phantom 4 Pro de ala giratoria con cuatro rotores. Para una navegación de precisión, el UAV tiene un GNSS a bordo que usa GPS y GLONASS. También tiene sistemas de visión en la parte delantera, trasera e inferior. Estos sistemas le permiten detectar superficies con un patrón definido e iluminación adecuada y evitar obstáculos con un alcance entre 0,2 y 7 m. La cámara Phantom 4 RGB está equipada con un sensor de una pulgada y 20 megapíxeles (5472 × 3648) y tiene una apertura ajustada manualmente (de f / 2.8 af / 11).

El lente tiene una distancia focal fija de 8.8 mm y un campo de visión horizontal de 84 °. El UAV tomó fotografías en líneas de vuelo paralelas, con un alto porcentaje de superposición longitudinal y transversal, a una altitud de vuelo constante y con un ángulo de cámara vertical de 90 °(Martin et al., 2016).

Planificación del vuelo.

Se realizaron dos vuelos para el levantamiento fotogramétrico. En el primer vuelo se tomaron un total de 207 fotografías nadirales en 13 pasadas mientras estaba en piloto automático usando la aplicación DJI GS Pro. La altitud de vuelo se mantuvo constante a unos 36 metros por encima de la cresta de la presa. La cámara tomó una foto cada dos segundos para obtener una superposición longitudinal del 80%. El segundo vuelo se realizó sin piloto automático, utilizando la habilidad del piloto, con el fin de obtener fotografías oblicuas que mostraran todos los detalles ocultos de la presa. El vuelo se realizó a una distancia de aproximadamente 30 metros sobre el frente de la presa, a siete niveles de altitud diferentes. Se obtuvieron un total de 372 fotografías, incluidas fotografías de la Casa del Pantano y la torre de vigilancia. Al adoptar un ángulo de inclinación de unos 45°, el horizonte quedó fuera de alcance. Por lo tanto, el proyecto fotogramétrico se procesó con un total de 579 fotografías desde diferentes puntos de vista y a diferentes escalas. La figura 18 muestra las superposiciones de imágenes y las ubicaciones de las cámaras durante cada vuelo.

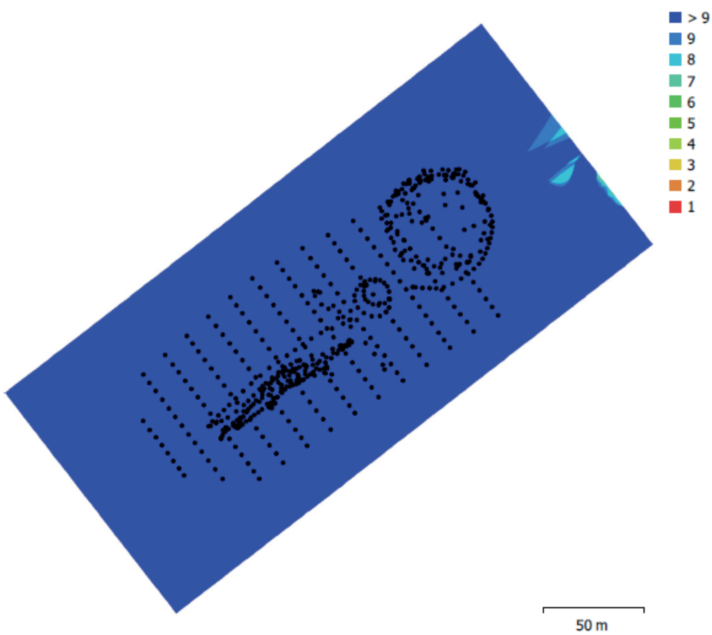


Figura 18. Superposiciones de imágenes y ubicaciones de las cámaras para los vuelos nadirales y oblicuos.

Procesamiento fotogramétrico. Resultados.

El proyecto fotogramétrico se realizó con el software Agisoft Metashape Profesional versión 1.6.1.10009. Este software, basado en el algoritmo SfM, se ejecutó en varios pasos. El primer paso consistió en alinear todas las fotografías identificando y atando los puntos clave. Durante la ejecución de este proceso, el software estimó los parámetros de calibración internos y externos de la cámara, incluidas las distorsiones no radiales, comenzando solo desde la distancia focal de la cámara (este valor se obtiene a partir de los datos EXIF de las fotografías). Una vez ejecutado, el software obtuvo la geometría de la escena, las posiciones y orientación de la cámara y una estimación de los parámetros de calibración de la cámara. Mediante el uso de fotografías con datos de geolocalización, la nube de puntos dispersa resultante fue georreferenciada. Sin embargo, la georreferenciación era de poca precisión y se requerían GCPs para mejorarla. Se puede obtener un ajuste más preciso con tan solo tres GCPs y se puede mejorar aún más aumentando el número de GCPs (Agüera-Vega et al., 2017; Rosnell, T.; Honkavaara, E, 2012). En este estudio, los 17 objetivos se utilizaron para la georreferenciación, utilizando el sistema ETRS89 UTM 30N. En la figura 19 y tabla 3 se muestran los errores obtenidos en los GCPs que se utilizaron para realizar el ajuste fotogramétrico.

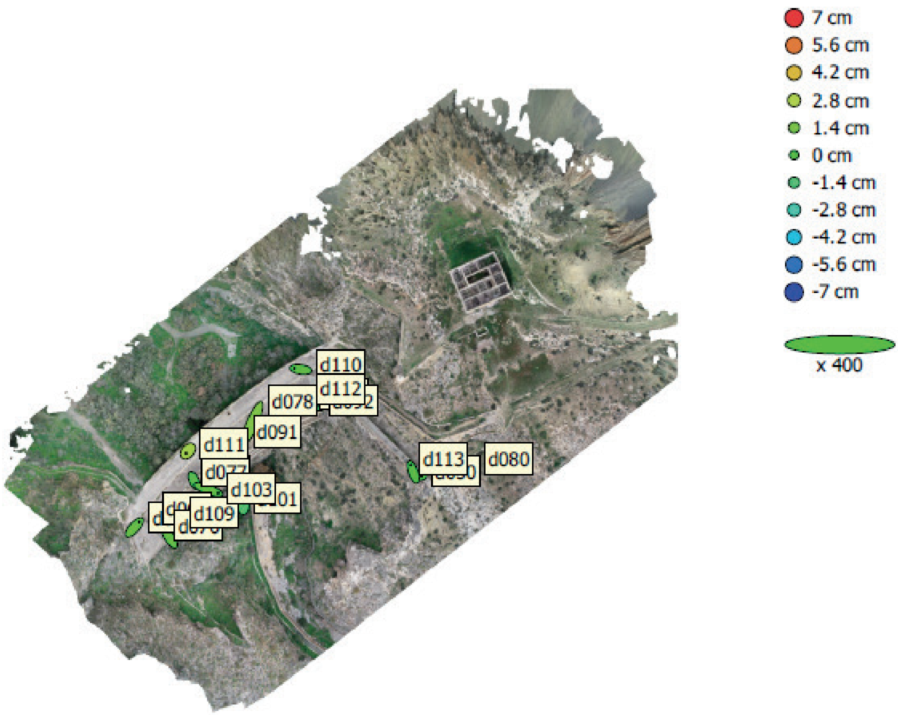


Figura 19. Error de GCPs. El error Z está representado por el color de la elipse. Los errores X, Y están representados por la forma de elipse. Las ubicaciones estimadas de GCP están marcadas con un punto. X (Este), Y (Norte), Z (Altitud).

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
17	1.03573	1.19926	1.83214	1.5846	2.42233

Tabla 3. Puntos de control RMSE. X (Este), Y (Norte), Z (Altitud).

En el siguiente paso, la nube de puntos se densificó a calidad media y se realizó una limpieza manualmente de los puntos que están por fuera del área enmarcada. Como resultado se obtuvo una nube de puntos con alto grado de detalle (figura 20). Según el estudio complementario de (Martínez-Carricondo, Agüera-Vega, et al., 2020), la nube de puntos obtenida tenía una precisión similar a la de un TLS, con un error total inferior a 3 cm. A partir de la gran densidad de puntos creados se puede producir una malla/red de triángulos interpolados para posteriormente generar el modelo final texturizado. En la etapa de texturizado, el programa parametriza la superficie del modelo tridimensional, asignándole a cada triángulo de la malla una sección de la fotografía, creando así un atlas de textura.

Posteriormente se obtiene el DEM (Digital Elevation Models), que son estructuras numéricas que describen las características morfológicas del terreno, también catalogado como una representación de la distribución espacial de la altitud de la superficie del terreno, tal y como se muestra en la figura 21. Una vez obtenida la nube de puntos densa, la malla y textura; se puede construir el "Ortomosaico u ortofoto" (figura 22).

Figura 20. Nube de puntos densa importada en Revit
con aproximadamente 39,801,317 puntos.

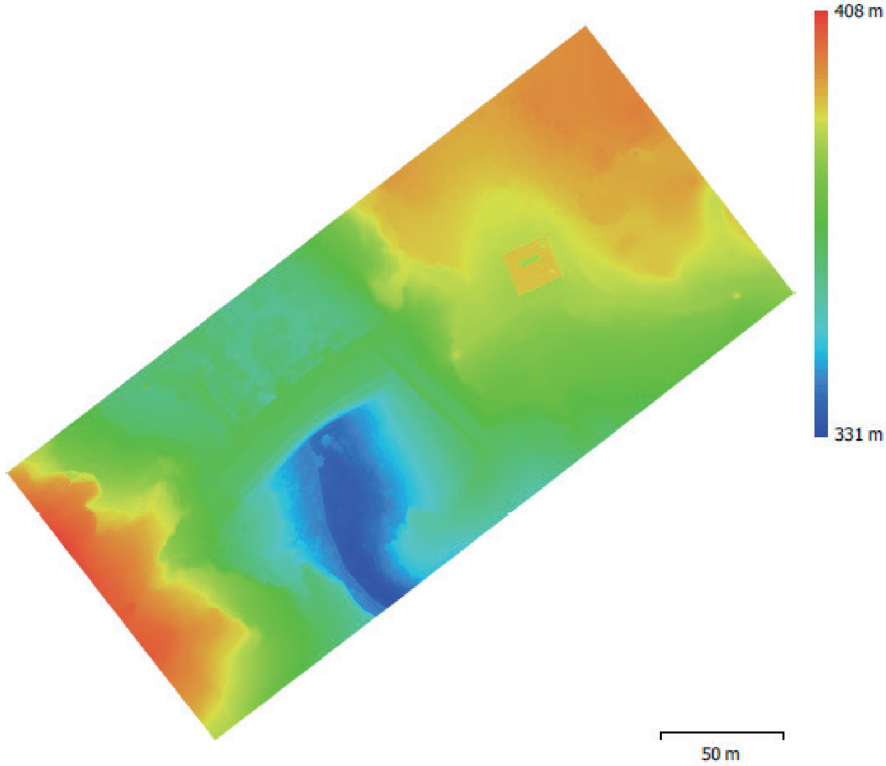


Figura 21. Modelo de elevación digital reconstruido. Resolución: 3,95 cm / pix.
Densidad de puntos: 640 puntos / m²

Figura 22. Ortofoto obtenida del proceso fotogramétrico.

3.4- Aplicación de la metodología HBIM.

Proceso de modelado.

El proceso de modelado HBIM del Embalse de Isabel II parte de la información semántica, tipológica y geométrica, tal y como se muestra en la figura 23. El modelado se realizó utilizando el software Autodesk Revit 2020.

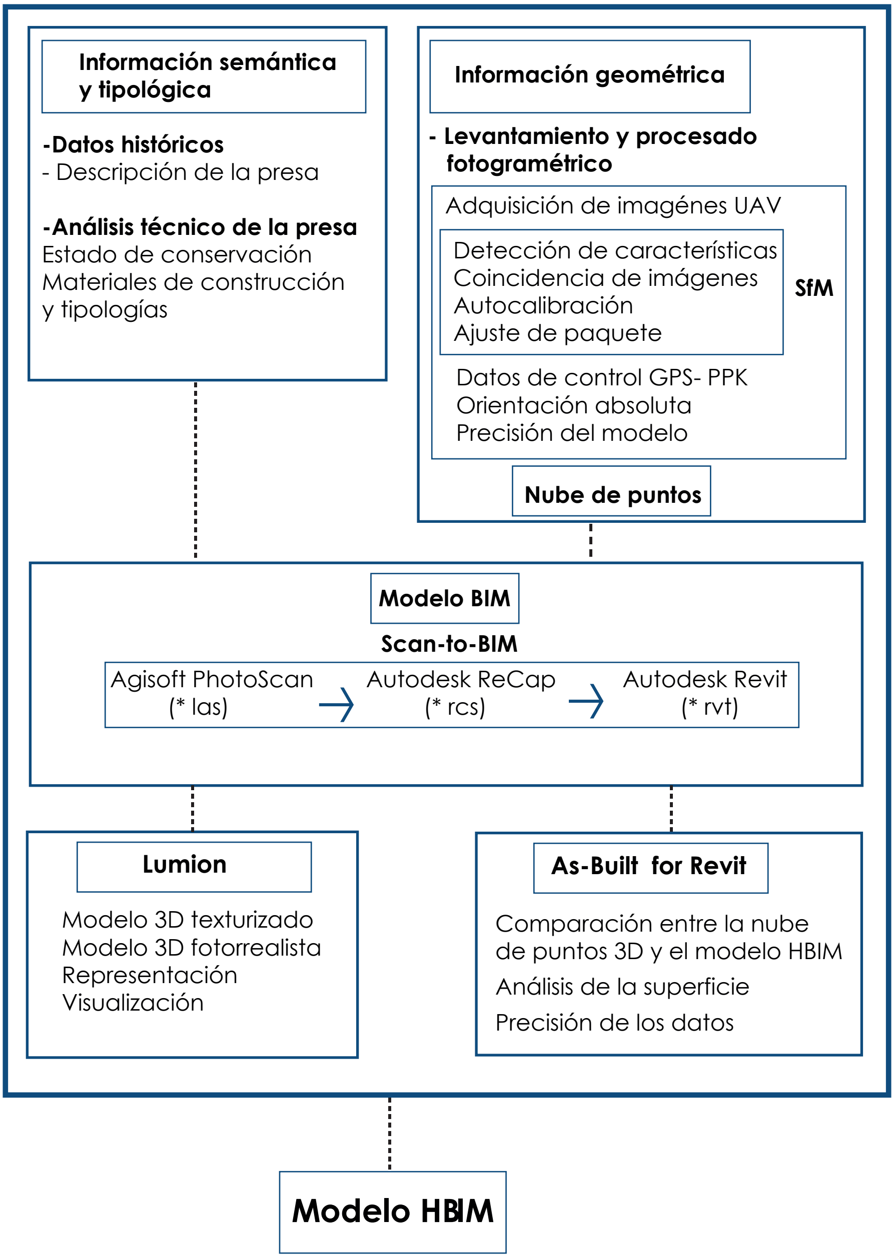


Figura 23. Proceso de modelado completo para la reconstrucción virtual del Embalse de Isabel II. Fuente: elaboración propia.

Utilización del complemento “As-Built for Revit”.

Para la realización del modelo paramétrico se realizó un modelado semiautomático, ajustando las primitivas a las nubes de puntos, utilizando la sección transversal para modelar o hacer extrusión de la superficie. Para el diseño de un modelo HBIM, el enfoque automático que permite reconstruir objetos según la extracción automática de la superficie de la nube de puntos, no es adecuado; ya que difícilmente describe la forma de edificios históricos usando geometrías simples. Por lo tanto, se necesitan utilizar plugins o complementos para escanear a BIM. Su objetivo es la creación de un objeto paramétrico a partir del procesamiento de datos métricos, mediante la nube de puntos. En esta investigación, se utilizó As-Built™ for Autodesk Revit® 2020.1, lanzado por FARO® como complemento perfecto para trabajar con grandes superficies de nubes de puntos, ya que se integra con la interfaz de Revit. Cuenta con una amplia gama de herramientas de evaluación para datos de escaneo láser 3D y fotogrametría, con comandos personalizados para modelar y detallar elementos BIM. La figura 24 muestra el proceso de Scan to BIM con As- Built for Revit. As-Built for Revit amplía significativamente las funciones de la nube de puntos de Revit.

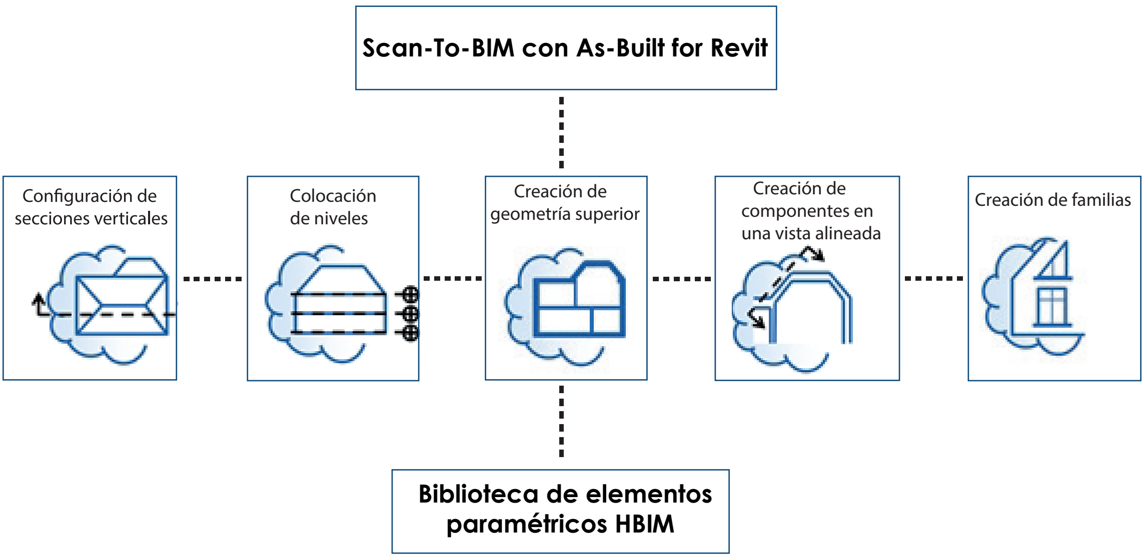


Figura 24. Procedimiento para Scan to BIM mediante “As-Built for Revit”.
Fuente: elaboración propia.

Precisión del modelo HBIM. Resultados.

La precisión y la integridad del modelo 3D, derivado de la fotogrametría UAV, ha permitido desarrollar con éxito el modelo HBIM de la presa, como se muestra en la figura 25. De acuerdo con el procedimiento descrito anteriormente, todos los elementos característicos se modelaron a partir de la nube de puntos. La topografía base del terreno circundante se construyó partiendo del modelo digital de elevación. La figura 26 muestra la superposición de la nube de puntos 3D y el modelo tridimensional HBIM, en Revit.

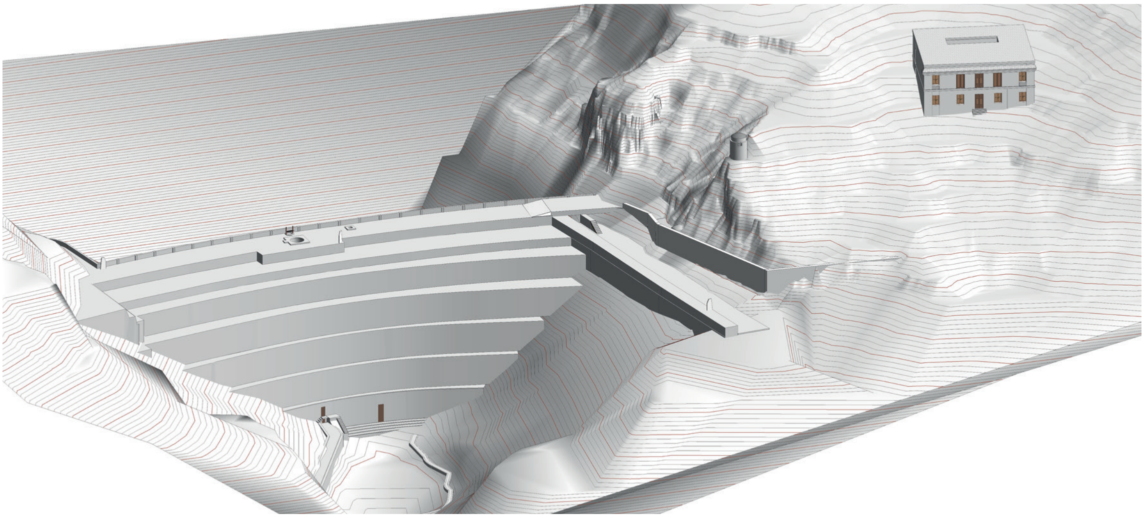


Figura 25. Modelo HBIM creado en Revit.

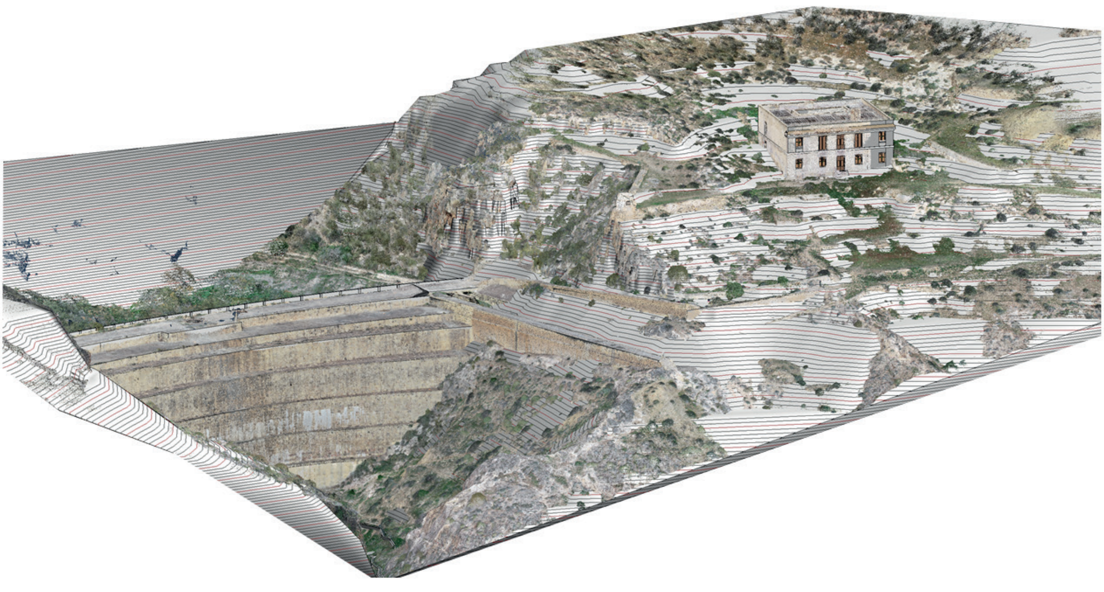


Figura 26. Superposición de modelos 3D
(nube de puntos densa y modelo HBIM) en Revit.

Es imprescindible destacar, que As-Built for Revit permite realizar la comparación entre la nube de puntos y el modelo 3D en Revit, mediante el análisis de la superficie. En este trabajo, el cálculo de la superficie de ambos modelos, se ha calculado y mostrado de forma clara y gráfica (figura 27), donde el valor promedio de diferencias entre el modelo BIM creado y el modelo fotogramétrico es alrededor de 0,05 m; lo cual demuestra que se ha obtenido un modelo 3D de alta precisión haciendo coincidir sus correspondientes alturas y vértices de ambos modelos.

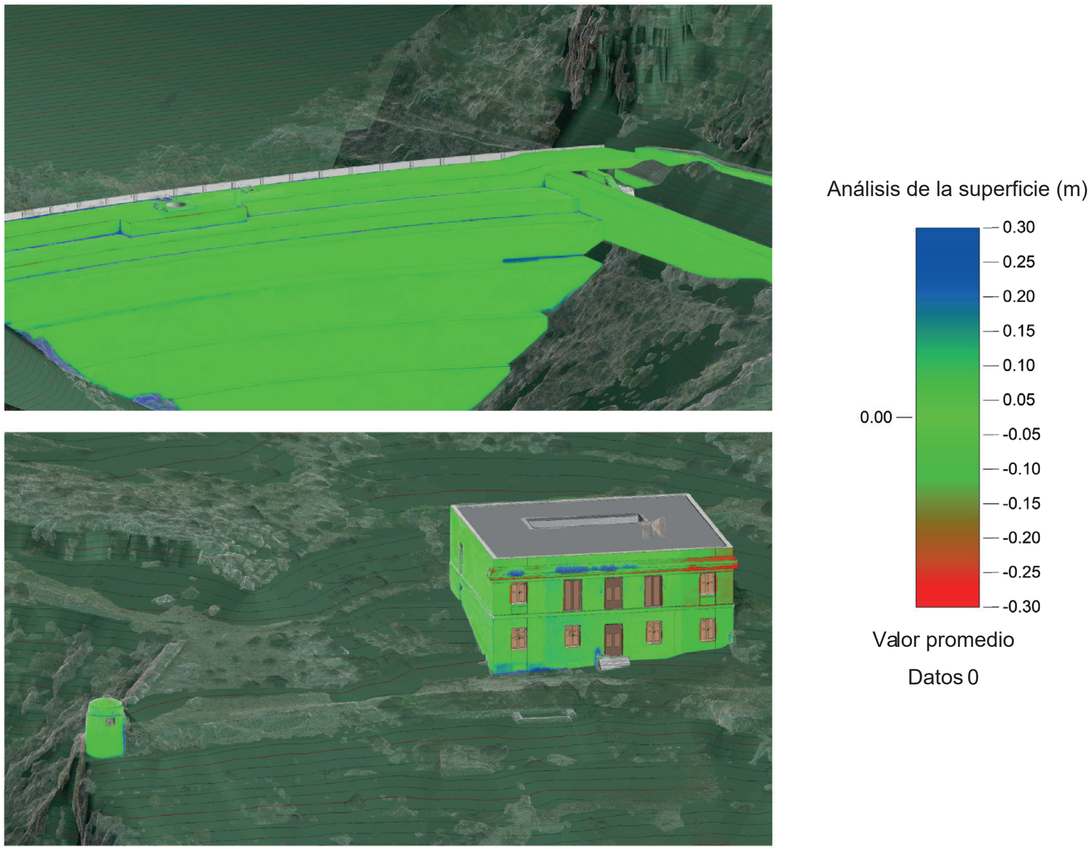


Figura 27. Análisis de superficie del modelo HBIM utilizando el plugin “As-Built for Revit”.

Fotorrealismo. Resultados.

La representación fotorrealista de un modelo 3D, es muy común en el ámbito de la documentación, la conservación y la restauración patrimonial. Toda la información gráfica aplicada sobre el modelo, puede ser utilizada con fines de documentación y difusión del patrimonio, por ejemplo: para realizar visitas virtuales y videos promocionales de edificaciones inaccesibles, desaparecidas o lejanas; para mostrar una simulación de la evolución histórica de un edificio y el entorno mediante la realidad virtual y aumentada, etc. Para este proceso se ha utilizado el software Lumion 8.3, el cual permite convertir rápidamente los diseños 3D BIM en videos, imágenes y presentaciones online 360º. Este software permite aplicar efectos especiales de renderizado, animar los elementos, modelar, y aplicar materiales y texturas. El modelo HBIM en Revit, se ha exportado a Lumion mediante el plugin *"Lumion Plug-in for Revit"*, como archivo tipo *collada (*. dae)*. La figura 28 muestra la representación fotorrealista de la reconstrucción virtual de la presa.

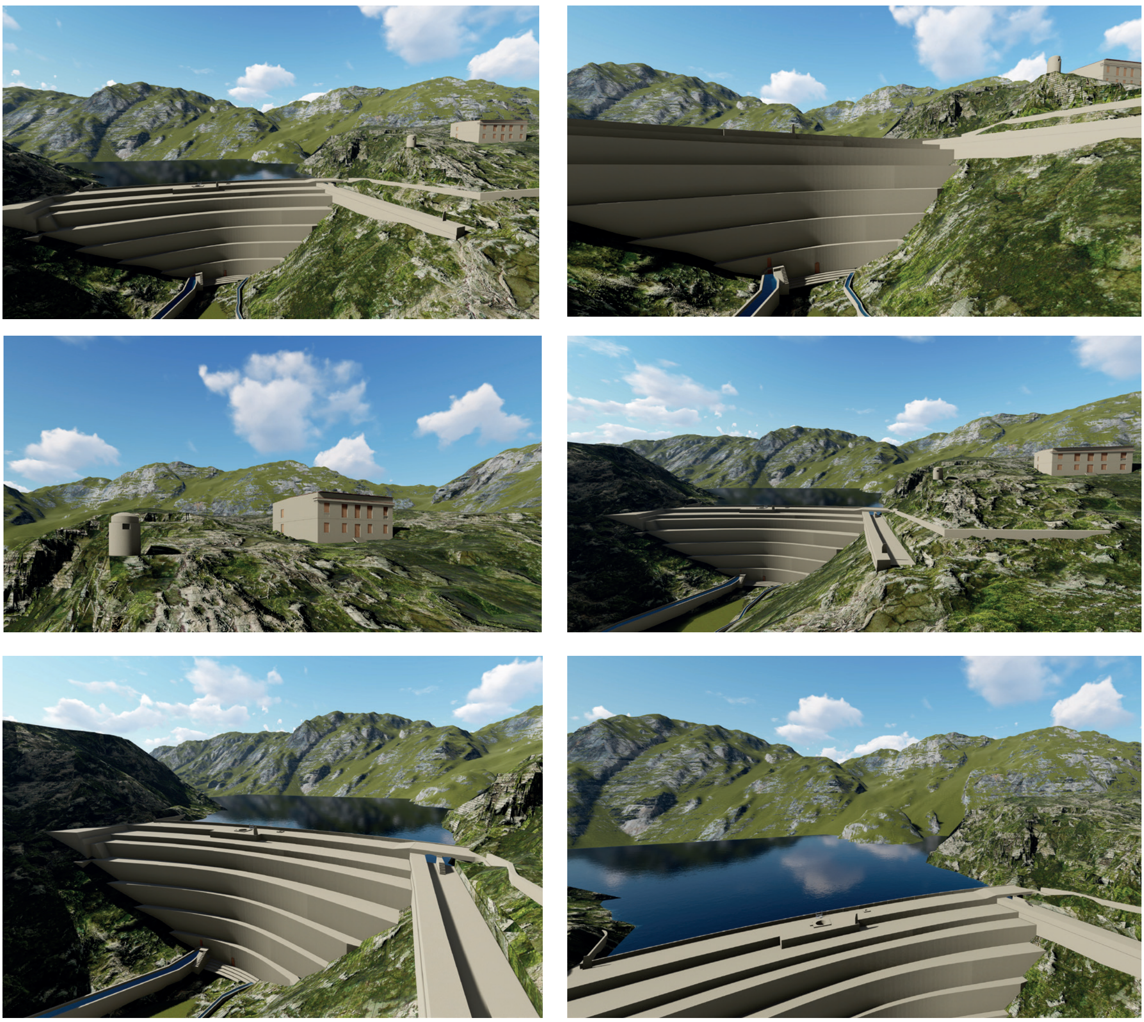
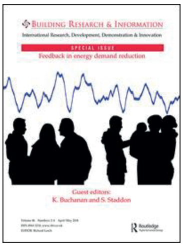


Figura 28. Renderizado en Lumion del Embalse Isabel II.



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Combination of nadiral and oblique UAV photogrammetry and HBIM for the virtual reconstruction of cultural heritage. Case study of Cortijo del Fraile in Níjar, Almería (Spain)

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3.5- Combination of nadiral and oblique UAV photogrammetry and HBIM for the virtual reconstruction of cultural heritage. Case study of Cortijo del Fraile in Níjar, Almería (Spain).

Abstract

Historic Building Information Modelling (HBIM) is the most effective method of rebuilding virtual 3D models of heritage buildings, which constitute a new information management system in the field of cultural heritage interventions. In this study, photogrammetry based on Unmanned Aerial Vehicles (UAV photogrammetry) was applied as an alternative to Terrestrial Laser Scanning (TLS) for the development of HBIM of historical buildings in ruinous state, analysing the case study of the Cortijo del Fraile, in Níjar, Almería (Spain). Based on the analysis of the historical information of the building, a photogrammetric survey is carried out with UAV by means of a combination of nadiral and oblique photographs. In this way, a precise characterization of the object was obtained, avoiding the hidden zones that are characteristic of TLS technology. The generated 3D point cloud served as the basis for the virtual reconstruction of an HBIM model focused on external portion of heritage. Finally, a texturizing process is applied to the HBIM model to achieve a photorealistic finish for visualization, archiving, and recording purposes.

Keywords: UAV photogrammetry; HBIM; cultural heritage; virtual reconstruction; 3D modelling.

Introduction

In recent years, the three-dimensional (3D) models obtained through tools and computer media have become a good source of data for the preservation, reconstruction, and exhibition in museums of emblematic buildings of cultural heritage (El-Hakim, Beraldin, Picard, & Godin, 2004; Galeazzi, 2017; Remondino, 2011). Indeed, virtual reconstruction was one of the proceduresadded to the UNESCO World Heritage list in 1985 for the conservation and preservation of buildings of cultural interest. Likewise, in 2006 the London Charter (Denard, 2016; INITIATIVE, 2006) established the principles of 3D visualization in the field of cultural heritage research and dissemination.

Technological advances have led to important changes in the field of 3D modelling, specifically those related to Terrestrial Laser Scanning (TLS) (Lemmens, 2007; Rüther et al., 2009) and digital photogrammetry (Alshawabkeh & Haala, 2004; Boehler & Marbs, 2004; McCarthy, 2014; Rasztovits, Dorninger, & Scanning, 2013; Yastikli, 2007; Yilmaz, Yakar, Gulec, & Dulgerler, 2007), which today is fully automated using Structure from Motion (SfM) algorithms (Fonstad, Dietrich, Courville, Jensen, & Carbonneau, 2013; Javernick, Brasington, & Caruso, 2014; Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012) and Multi-View Stereopsis (MVS) (Furukawa & Ponce, 2010) through processes derived from computer vision.

The literature shows that improvements in SfM photogrammetry technology allow it to be used as a reliable system in the field of 3D acquisition, with results comparable to those obtained with TLS (Chatzistamatis et al., 2018; Chiabrando, Spanò, Sammartano, & Teppati Losè, 2017; Fryskowska & Stachelek, 2018; Kadobayashi, Kochi, & Furukawa, 2004; Liang et al., 2018; Valenti & Paternò, 2019; Zhihua et al., 2014). The choice of one or another technique depends on the morphology and accessibility of the study zone but also on the assumed costs of carrying out the 3D modelling. In effect, in many cases there are zones that are not accessible or visible through TLS. In this context, Unmanned Aerial Vehicles (UAVs) represent an emerging and economic technology which can be equipped with high-resolution cameras to carry out SfM-based photogrammetry for application to the monitoring and management of historical heritage (Achille et al., 2015; De Reu et al., 2013; Chiabrando, Nex, Piatti, & Rinaudo, 2011; Verhoeven, 2009; Hendrickx et al., 2011; Mesas-Carrascosa, García, De Larriva, & García-Ferrer, 2016; Mozas-Calvache, Pérez-García, Cardenal-Escarcena, Mata-Castro, & Delgado-García, 2012; Ortiz, Gil, Martínez, Rego, & Meijide, 2013; Sauerbier & Eisenbeiss, 2010), especially when there are access restrictions. Another possibility is the integration of the laser scanning on board the UAV, which is called Aerial Laser Scanning (ALS) (Lin, Hyyppä, & Jaakkola, 2011; Roca, Armesto, Lagüela, & Díaz-Vilariño, 2014). However, UAVs also have limitations such as access to the interior of buildings, cavities, hollows or inner parts of arcades. The challenge of autonomous drones flying in an interior space, with no access to GPS is one that is currently being researched by a few research groups (Dupont, Chua, Tashrif, & Abbott, 2017). In turn, the use of oblique photographs improves the results obtained through SfM photogrammetry by allowing visualization of details hidden from the nadiral views (Aicardi et al., 2016; Lin, Jiang, Yao, Zhang, & Lin, 2015; Vetrivel, Gerke, Kerle, & Vosselman, 2015), thus avoiding the use of terrestrial photographs. In all cases, the result obtained is a point cloud or a 3D mesh model that can be used as a basis for the creation of a Building Information Model (BIM), whose mission is to cover the design, construction, and administration processes of a building’s data throughout its life cycle (Merchán, Salamanca, Merchán, Pérez, & Moreno, 2018; Vacanas, Themistocleous, Agapiou, & Hadjimitsis, 2015).

This process is known as ‘scan-to-BIM’ or ‘cloud-to-BIM’ and allows one to get a true view of the locations (Angelini, Baiocchi, Costantino, & Garzia, 2017; Rodríguez-Moreno et al., 2018). Although BIM has its main application in the construction sector (Eastman, 2011), in recent years it has been used successfully in the management of information on architectural heritage and its representation (Biagini, Capone, Donato, & Facchini, 2016; Oreni, Karimi, & Barazzetti, 2017; Quattrini, Malinverni, Clini, Nespeca, & Orlietti, 2015; Quattrini, Clini, Nespeca, & Ruggeri, 2016). In the case of digitizing existing data with artistic and historical significance, this method is referred to as Historic Building Information Modelling (HBIM) (Karachaliou, Georgiou, Psaltis, & Stylianidis, 2019; León-Robles, Reinoso-Gordo, & González-Quiñones, 2019; Saygi, Agugiaro, Hamamcıoğlu-Turan,&Remondino, 2013). However, its implementation in the field of architectural heritage depends on the peculiarities of each building, due to the irregularities they present in terms of morphology and the elements that make it up. Because of this, parametric objects created on BIM platforms cannot be used and new objects and libraries have to be developed. Indeed, it is necessary to develop an HBIM library of prototypes of parametric architectural objects, built from historical data and remote collection of survey data, using TLS or photogrammetry in order to digitally model historical buildings (Capone & Lanzara, 2019; Dore & Murphy, 2012).

The main problem of this reverse engineering process is the amount of time required to parametrize the geometric elements, regardless of the operator’s experience, the manual modelling work, or even the recent developments of automated semantic recognition processes (Armeni et al., 2016). The quality of the model is related to the ‘level of approximation’ or the ‘level of simplification’ applied during the modelling phase. In the case of heritage elements that are in ruinous state, this ‘level of approximation’ depends on the quantity and quality of the historical information collected on the original geometry.

New challenges are currently being posed in 3D digital modelling, relating to the simulation of the structural analysis of the building using a finite element model (FEM), known as Cloud-to-BIM-to-FEM (Barazzetti et al., 2015; Bassier, Hadjidemetriou, Vergauwen, Van Roy, & Verstrynge, 2016). The main goal of the present study is to develop an HBIM model of a singular building of Spanish cultural heritage to carry out its virtual reconstruction, specifically the Cortijo del Fraile in Níjar, Almería, which is in a state of partial collapse.

Due to the impossibility of accessing the interior of the building as it is fenced for security, the point cloud used as a basis for the HBIM modelling has been obtained only by UAV photogrammetry, as an alternative to the use of TLS or any other method. The research is also intended to highlight the importance of combining nadiral and oblique photographs to avoid the grey areas typical of TLS.

Materials and methods

The methods used to carry out this research are summarized in Figure 1. A historical study of the building was carried out to provide us with information on its original state. It was also necessary to know exactly the current state of the building, which was obtained through UAV photogrammetry. From both analyses it was possible to create a BIM that allows the virtual reconstruction of the original state of the building, which can be used for purposes of archiving and visualization.

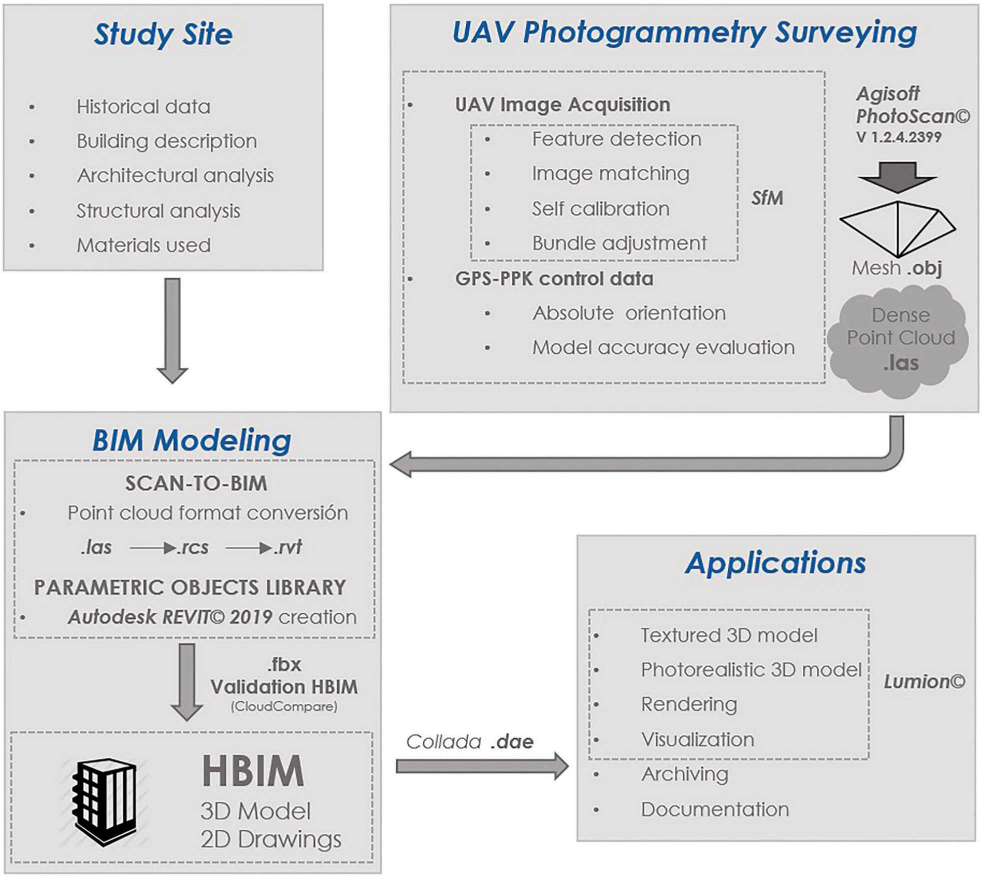


Figure 1. Flowchart of the methodology of this research.

Study site

The Cortijo del Fraile is a building located southeast of Níjar, Almería (Figure 2), within the Natural Park of Cabo de Gata-Níjar, about 6.5 km from the coast of the Mediterranean Sea. It is located in a farm of 730 hectares and surrounded by other smaller farmhouses in the vicinity. The southwest and northeast UTM coordinates (Zone 30, ETRS89) of the study area are (582385, 4080340) and (582515, 4080470), respectively.

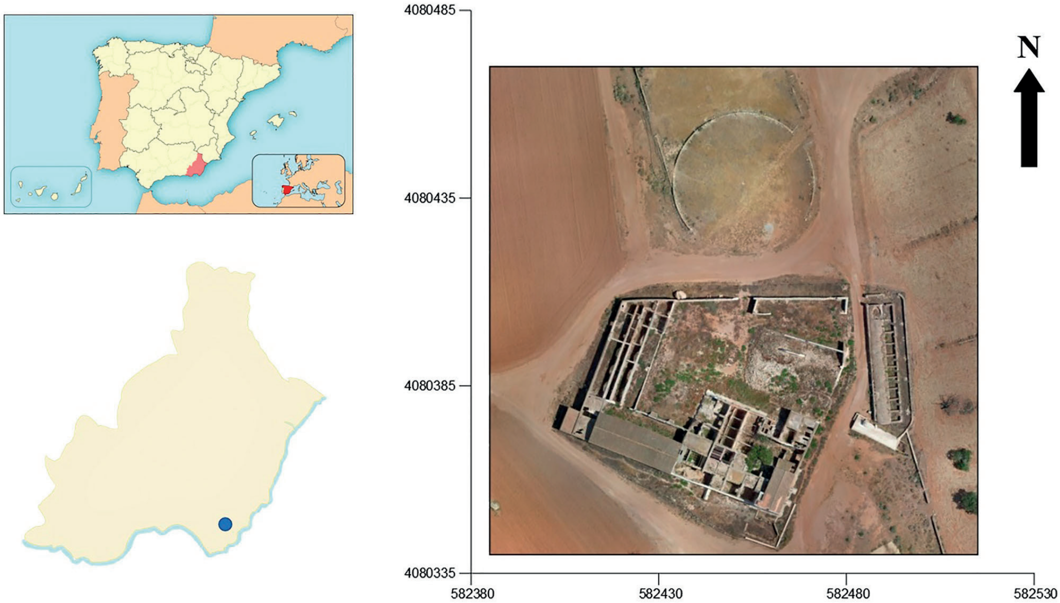


Figure 2. Location of the study area. Coordinates are referred to UTM Zone 30N (European Terrestrial Reference System 1989, ETRS89).

Historic information

The farmhouse was built in the 18th century by the friars of the Convent of Santo Domingo de Almería as an important centre of agricultural exploitation with olive trees and vines. Originally it was known as the 'Cortijo del Hornillo' because it had a large oven for bread making in the central courtyard. This property was probably formed following the process of confiscation of communal lands, which in Níjar gave rise to the consolidation of vast agropastoral complexes that marked the rural economy of the area until the mid-20th century. Originally it belonged to the Acosta family. However, in 1836 the farmhouse passed to the state patrimony, as part of the process of confiscation of, properties of the religious orders, and was later sold at auction.

The Cortijo del Fraile is known for a crime that occurred in its vicinity, the so-called 'crime of Níjar'(Cerezuela, 2018; Torres Flores & Roldán Molina, 2018), which took place on 22 July 1928 and whose protagonist, Francisca Cañadas, lived in the vicinity all his life. The facts were the real events that inspired the plot of Federico García Lorca's dramatic piece Bodas de Sangre (1935) and were also a source of inspiration for the work Dagger of Carnations (1931) by the Almeria writer Carmen de Burgos. It has also been related to cinema, being the scene of numerous films, highlighting those directed by Sergio Leone in the 1960s, which, due to the peculiarity of its climatology and landscape, pretend that the building was located in the American West.

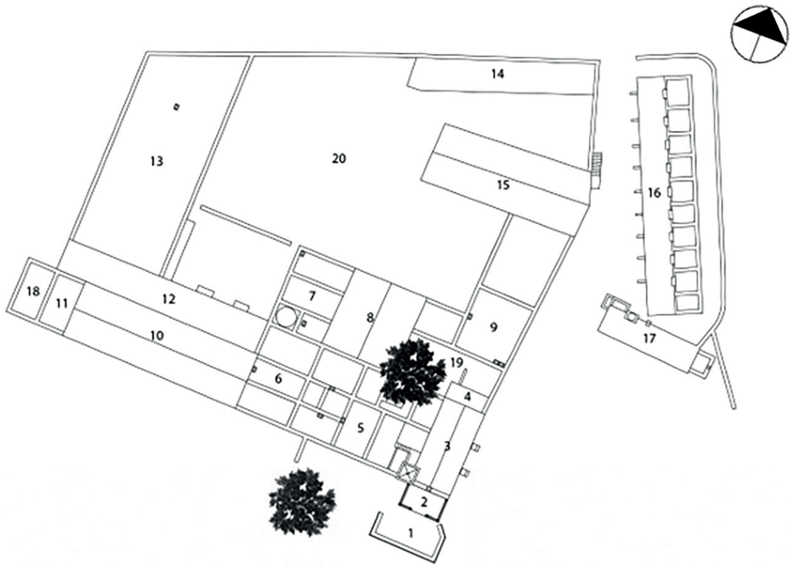
Nowadays there is little documentary information and few photographs about the original image of the farmhouse ('Cortijo del Fraile', 2019; 'Cortijo del Fraile – Lista Roja del Patrimonio', 2012; Jiménez López, 2012; Olmedo Granados, 1999; Pérez-Millán, Yáñez-Pacios, Contreras-García, & Socorro-Picó, 2016). However, there are a large number of films that show images of the original architecture. As an example, the following films stand out: The Good, the Bad and the Ugly and For a Few Dollars More by Sergio Leone in 1966, A Bullet for the General by Damiano Damiani in 1967, Last of the Badmen by Nando Cicero in 1967, and Silbersattel by Lucio Fulci in 1978.

After its abandonment in the 1980s the building has deteriorated and is now in ruins, having spent more than 40 years in constant danger of collapse. On 23 March 2010, a resolution by which the Cortijo del Fraile was declared a 'Property of Cultural Interest' was published in the Official Gazette of the Junta of Andalucía, and the building was enrolled in the General Catalogue of the Andalusian Historical Heritage, categorized as a 'historic site' ('Decreto 44/2011, de 22 de febrero, por el que se inscribe en el Catálogo General del Patrimonio Histórico Andaluz como Bien de Interés Cultural, con la tipología de Sitio Histórico, el Cortijo Fraile, en el término municipal de Níjar (Almería).', 2011). In 2011 some walls suffered damage and collapsed and thus had to be rebuilt and stabilized. Today the farmhouse is privately owned by a company that exploits the farm and its water wells for ecological agricultural production. Figure 3 shows the current status of Cortijo del Fraile.

Figure 3. Actual image of the Cortijo del Fraile.

Architectural analysis and description of structures

Cortijo del Fraile is a building with diverse types of architectural constructions. It is trapezoidal in shape with a plot surface of 3013 m2, of which the constructed surface is estimated to be 1835 m2. The access road to the farmhouse is a dirt track and is delimited with rows of agaves. Its spatial distribution is compact and irregular, formed by a main nucleus and several annexed constructions where almost all the rooms are developed around a large central courtyard. The nucleus consists of housing for the owners, public oratory, houses of the sharecroppers and shepherd, courtyard, corrals, and haystacks and has as annexed constructions two threshing floors, pigsty, wells, and cisterns. Figure 4 shows the architectural plan of the Cortijo del Fraile.



1. Seating area	11. Workers dwelling
2. Entrance atrium to the chapel	12. Entrance of carriages
3. Chapel	13. Barns
4. Access to the crypt	14. Animal drinker
5. Main dwelling	15. Haystack
6. Sharecropper's dwelling	16. Pigsty
7. Stockyards	17. Cattle cistern
8. Stockyards	18. Electric transformer
9. Shepherd's dwelling	19. Inner court
10. Haystack and warehouse	20. Courtyard

Figure 4. Architectural plan of the Cortijo del Fraile.

On the main façade, with large gaps and regular distribution, the chapel, the house of the owners, and the houses of the sharecroppers are aligned. Just in front of the main façade, and following the position of the atrium entrance to the chapel (with wrought iron handrails), it can be recognized that there were several benches separated by walls, which could have been a meeting point. The owner's house has a large window in the facade, and is the only one built with metallic carpentry. It stands out for its superiority with respect to the other houses. The sharecropper's house is a modest dwelling and was directly linked to some work areas; it has access to the courtyards and a big stable, of rectangular plan, with its interior split with diaphragm arches and gabled roof with beams, reeds, mud mortar, and curved tiles.

The housing of the priest located to the East has a different typology, with a single room, compartmentalized into four smaller spaces by vertical walls that do not reach the ceiling at several points in the house. It has a flat cover made with beams, reeds, palm leaves, and lime. It also has access to rooms that correspond with stables and masonry haystacks, which have been practically destroyed. The chapel or oratory stands out for its volume throughout the whole, with a rectangular plant and gable roof of ordinary masonry with lime mixture and plaster. On the outside it is reinforced with two side stirrups and a small bell tower with a square brick base, as shown in Figure 5. The main facade of the chapel, being a religious construction, has characteristic elements such as the rosette with stained glass windows and whose panes are generally built in radial form.

Next to the public access road, two wells with masonry rims are preserved. On the eastern flank of the farmhouse is the pigsty, which is very close to one of the two cisterns. The vertical structure is made up of load-bearing walls of irregular stone masonry with mud, plaster, or lime as agglomerates, garrisoned and bleached externally. In the interior of the load-bearing walls, there is an important concentration of semi-circular arches, something which is not usual in the constructions in the fields of Níjar. These arches are present in the stables located to the west of the complex, whose interior walls are formed by arcades, as shown in Figure 6.

The roofs are mostly flat, resting on wood joists of varying dimensions that are embedded in the loadbearing walls. In the whole group there are three units with gable roofs of two types: the flat tile that appears on the chapel and the curved or Arabic tile present in the other two dependencies, the corrals linked to the housing of the sharecropper and the haystack or warehouse located on the South façade. The top cover of the bell tower is a four-way roof with flat tiles. The carpentry, of which only some examples are preserved, was made of wood, with ironwork being used only in certain places, such as in the atrium and the choir railing of the chapel, in the entrance door, and in the windows of the main house.

Figure 5. Detail of the bell tower.

Figure 6. Perspective of the ensemble showing the semicircular arches in the stables of the Cortijo del Fraile.

Survey of the current state of the building using UAV photogrammetry. Image acquisition.

The images used in this work were taken from a rotatory wing DJI Matrice 600 Pro UAV with six rotors. The UAV was equipped with a DJI Zenmuse X5 motion-compensated three-axis gimbal mounting a digital camera with a lens with a fixed focal length of 15 mm and diagonal FOV of 72 degrees. The resolution of the camera sensor was 16 megapixels (4608 × 3456).

Two different flights were carried out to obtain the images. The first flight was carried out with an autopilot using the DJI GS Pro © application for the purpose of obtaining nadiral photographs. Figure 7 shows some of the parameters configured for the flight execution. Due to the low slope of the surrounding terrain of the building, the flight altitude was set at a constant distance of 50 m above ground level, which implies a surface of 64.7 × 48.5 m2 covered by every photo and an equivalent ground sample distance of 1.1 cm, the reason why this flight height was selected. In accordance with the flight altitude, UAV speed, and light conditions at the time of flight, the shutter speed was adjusted to minimize the effect of blurring on the images taken. The flight plan consisted of 11 passes, and a total of 330 images were selected to carry out the photogrammetric project. The camera was triggered every two seconds and the flight speed was set to obtain forward and side overlaps of 80% and 65%, respectively.

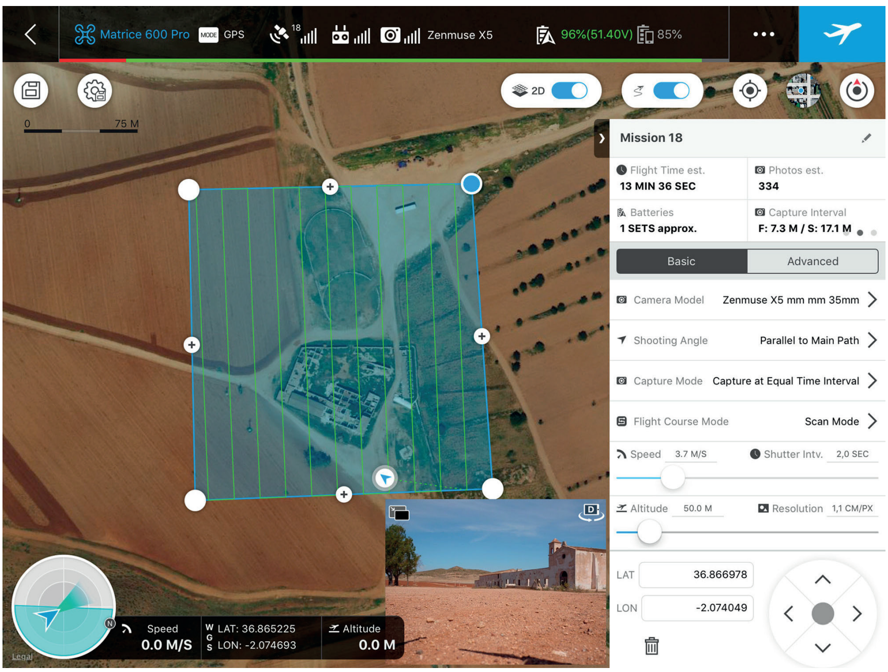


Figure 7. Flight path configuration with DJI GS Pro © software.

The second flight was carried out in manual mode to obtain oblique photographs, with the aim of guaranteeing the photographic capture of the interior of the building and of the four façades of the enclosure. This flight was carried out at an approximate height of 15 m, and a total of 293 photographs were taken. This flight height was selected because the maximum height of the building was 12 m. In this way, the entire study area could be flown over without danger of collision. In addition, due to the FOV of the camera it was possible to cover the whole façade without having to move too far away from it. The angle of inclination of the camera was around 45° to avoid the appearance of the horizon in the photographs. A total of 623 photographs with different points of view and scales were used to carry out the photogrammetric project. Figure 8 shows the camera locations and image overlap.

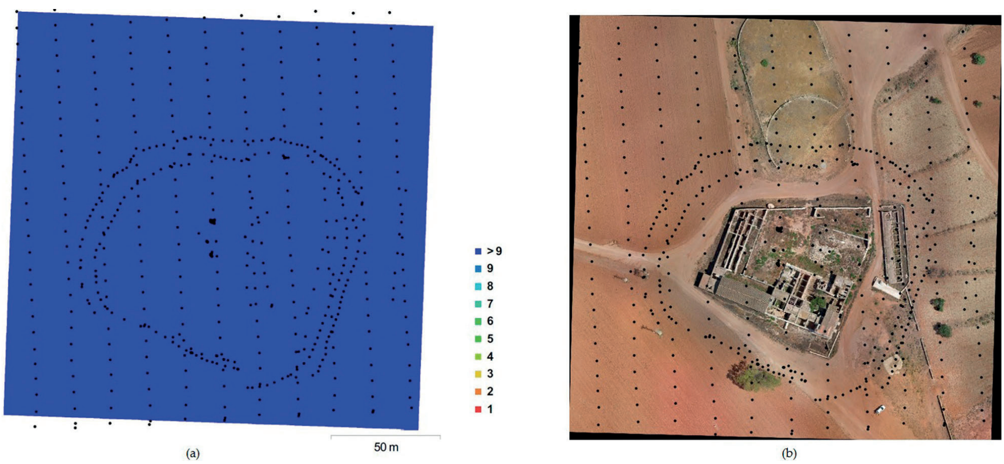


Figure 8. Camera locations and image overlap. Blue colour indicates that the terrain point appears in more than nine photographs.

Survey campaign for georeferencing and evaluating the accuracy of the photogrammetric products

Prior to the image acquisition, eight targets were scattered on the studied surface for the purpose of georeferencing (ground control points, GCPs) and evaluating the accuracy of the photogrammetric project (checkpoints, CPs). Due to the impossibility of entering the interior of the enclosure, the targets were placed on the perimeter of the study zone, as shown in Figure 9a. As in (Martínez-Carricondo et al., 2018). This provision of targets ensured that the results were obtained with good accuracy in both planimetry and altimetry.

The targets consisted of A3 size (420 × 297 mm) red paper on which were two black squares. Figure 9(b) shows a detail of one of these targets. The three-dimensional coordinates of these points were measured with a Global Navigation Satellite System (GNSS) receiver working in Post ProcessedKinematic (PPK)mode,with the base situated at a point near the main facade of the building (Figure 9c). The 3D coordinates of the base, corrected through the Trimble CenterPoint RTX Post-Processing Service, are 582481.520, 4080315.510, and 184.506 m, respectively. Horizontal coordinates are referred to UTM Zone 30N (European Terrestrial Reference System 1989, ETRS89) and the elevation is referred to the Mean Sea Level (MSL) using the EGM08 geoid model. Both rover and base GNSS receivers were Trimble R6 systems. For PPK measurements, these dual-frequency geodetic instruments have a manufacturer’s stated accuracy specification of ±8 mm +1 ppm horizontal RMS and ±15 mm +1 ppm vertical RSM. As the distance between the base station and the study area was approximately 100 m, the horizontal and vertical errors were around 8 and 15 mm.

Figure 9. GCPs used for the georeferencing of the photogrammetric project: (a) distribution of GCPs; (b) example of target; (c) GNSS used in this work.

Photogrammetric processing

The photogrammetric process was carried out using the software packageAgisoft PhotoScan Professional©version 1.2.4.2399. This kind of photogrammetric software based on the SfM algorithm was used because it has been proven to outperform other software applications in terms of accuracy (Sona, Pinto, Pagliari, Passoni, & Gini, 2014). The workflow is a three-step process (Verhoeven, 2011). The first step is the alignment of the images by feature identification and feature matching. While carrying out the image alignment, this software estimates both the internal and external camera orientation parameters, including nonlinear radial distortion. Only an approximate value of the focal length is required, which is extracted automatically from the EXIF metadata. This taskwas carried out with the PhotoScan accuracy set to high. The results of this step are the camera position corresponding to each picture, the internal calibration parameters, and the 3D coordinates of a sparse point cloud of the terrain. In the second step, the sparse point cloud is referenced to an absolute coordinate system (ETRS89 and frames in the UTM, in the case of this study) and densification of the point cloud is achieved with the quality set tomedium, which is based on a pairwise depth map computation. This point cloud needs to be 'cleaned up' to eliminate all of the wild points that do not belong to the model. This process is performed manually. This resulted in a more detailed 3Dmodel. Using the height field method, the mesh is obtained from the dense point cloud. The third step applies a texture to the mesh obtained in the previous step.

Finally, the orthophoto is exported and a grid DSM can be generated from the point cloud. The dense point cloud can also be exported in *.las format, as well as the mesh in *.obj, *.3ds or *.dxf format. The bundle adjustment can be carried out using at least threeGCPs, but more accurate results are obtained if more GCPs are used, and it is recommended that more of them be used to obtain optimal accuracy (Agüera-Vega, Carvajal-Ramírez,&Martínez-Carricondo, 2017; Rosnell & Honkavaara, 2012). In this study, four targets placed in the field around the building were used asGCPs for the georeferencing of the project. The rest of the targets not used in the block adjustment were used as CPs to evaluate the accuracy of the photogrammetric project, according to the formulation of the root mean square error, described in (Agüera-Vega, Carvajal-Ramírez, & Martínez-Carricondo, 2016). The process was completed with about 15 h of cabinet work by a technician with high knowledge of UAV-SfM photogrammetry.

Virtual reconstruction using HBIM methodology

BIM is an intelligent 3Dmodel-based process that involves the generation and management of digital representations of the physical and functional characteristics of places. BIM design tools allow extracting different views from a building model for drawing production and other uses. After the BIM model has been constructed, drawings of the plans, elevations, and sections of the building can be generated directly from the BIM model for purposes of documentation. Also, information such as the material, colour, height, thickness, and so on can be added to each component in the BIM database (Themistocleous, Agapiou,& Hadjimitsis, 2016). TheBIMmodelling was carried out using the software Autodesk Revit © 2019, one of the most used BIM software in the world, which includes a visual programming environment that allows designing with elements of modelling and parametric drawing. The great contribution of this software was to allow the introduction of several dimensions 4D (Time), 5D (Cost), 6D (Sustainability) and 7D (Management and Maintenance) in the building models, achieving interoperability through the use of different software and various disciplines (Tommasi & Achille, 2017), communicating with each other through compatible formats, with the Industrial Foundation Classes (IFC) data exchange format being the most widely used, as it is an open and neutral standard maintained by BuildingSMART®.

The Cloud-to-BIM process continues to import the dense point cloud in *.las format generated byUAV photogrammetry and converting it to Revit format *.rcp or by using Autodesk ReCap®. The information received from the dense cloud is thousands of colorimetric points of information that show the details of the current state of the building, for example, irregularities in a wall, different finishes, and even whether a wall has an inclination. In this way it is possible to visualize the dense point cloud for use as a guide to establish the levels in the section and the axes of the plan (Donato, Biagini, Bertini, & Marsugli, 2017; Chiabrando, Lo Turco, & Rinaudo, 2017; Chiabrando, Lo Turco, & Santagati, 2017; Oreni et al., 2017; Rodríguez-Moreno et al., 2018). It is also possible to import the mesh obtained from Agisoft using the plugin ‘Mesh Import from OBJ Files’ (‘Mesh Import from OBJ Files – Revit App – truevis.com’, 2019), which allows you to study the facial properties of every wall and roof. The modelling of all the walls, holes, windows, and doors as well as the roofs starts from the dense point cloud generated by UAV photogrammetry. All of this modelling is based on the historical information gathered in the previous phase as well as in the research work carried out in the field. To carry out this process it is necessary to create a library of parametric objects. Each of these objects is created manually as Revit does not have an automatic geometry recognition option. Themost recent scientific literature shows that great efforts are being made to generate 3D geometries in automatic recognition, but this lacks the details that would be valid for application in the heritage area (Dore & Murphy, 2017).

As an example, Figure 10 shows the Tuscan portico attached to the inside of the chapel, created from other objects (entablature, capital, shaft and base of Tuscan order) tomodify its values and dimensions according to the scale, thus being able to obtain infinite combinations depending on the alphanumeric parameters. This process is applicable to all the historical parametric objects created that make up the model. Figure 10 also shows the objects created to develop the barrel vault inside the chapel. Metadata is entered for each component created. So, for example, if performing a structural calculation is wanted, entering the parameters that define the resistance of the materials used will be required.

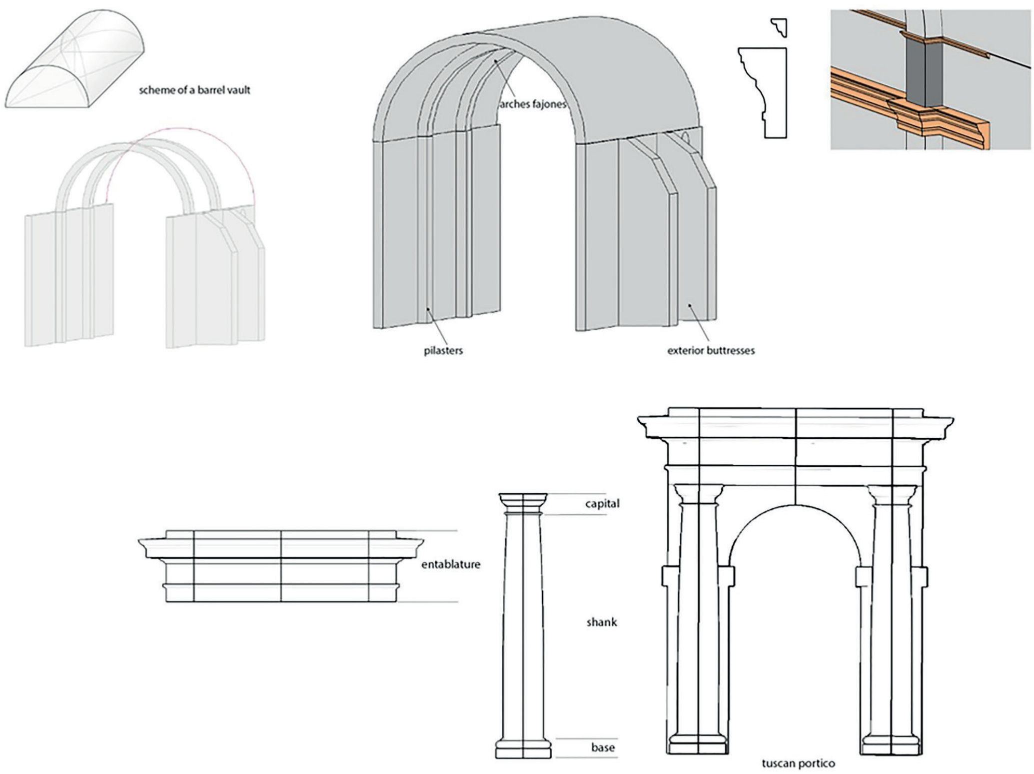


Figure 10. Some examples of parametric objects created to develop the HBIM model.

In turn, from the point cloud it is possible to obtain a cartographic representation of the digital terrain model (DTM) on which to support the 3Dmodel of the building. Once the 3D model has been developed, it is necessary to add materials and textures to achieve a photorealistic finish. Revit is not a software designed for rendering, since working with different materials is complex, and external elements such as trees are not very sophisticated. On the other hand, Lumion© is a software based on the rendering engines of videogames that is revolutionizing the current panorama due to the speed with which it allows rendering videos, as well as images, being one of the most used nowadays.

It has vegetation libraries, and standard natural environments, which allow giving greater realism to the model and creating images with very high resolution (De Kleijn, De Hond, & Martinez- Rubi, 2016; Meini, Felice, & Petrella, 2018). The best way to export 3D models from Revit to Lumion is through 'Lumion Plug-in for Revit'. It includes two functionalities: as an exporter for LiveSync, which makes it possible to visualize the model in Lumion in real time, and to export it as a file type Collada (*.dae) of Revit and to load or recharge it constantly in Lumion.

Validation of the HBIM model

Each of the parametric objects created to develop the HBIMmodelmust be validated bymeasuring the distances between the mesh of the photogrammetric model and the mesh of the created parametric object. In order to do this, the parametric objectmust be exported fromRevit in *.fbx format and the photogrammetric model must be exported from Agisoft in *.obj format. Both files must be imported from CloudCompare (Girardeau-Montaut, 2017), where the 'Cloud to Mesh Distance' command can be used to compute the distance between the parametric object created in Revit and the model created in Agisoft.

In the absence of a criterion adopted by the scientific literature for the validation of a parametric object (Adami, Scala, & Spezzoni, 2017), in this research the criterion has consisted in obtaining an average difference around 0 (between −0.05 and 0.05 m) and a standard deviation of less than 0.10 m.

Results and discussion

Table 1 shows the accuracy obtained in the photogrammetric project. RMSEXY shows the error differences obtained between the X and Y coordinates measured by GNSS and those obtained in the orthophoto, and RMSEZ shows the error difference obtained between the Z coordinate measured by GNSS and that obtained in the Digital Surface Model (DSM). RMSET shows the total error.

Label R	MSEXY (m)	RMSEZ (m)	RMSET (m)
P2	0.026 0	.040 0	.047
P5	0.101 0	.158 0	.189
P7	0.106 0	.028 0	.110
P8	0.222 -	0.048 0	.227
Total	0.133 0	.086 0	.159

Table 1. Accuracy obtained in the CPs of the photogrammetric project

The results were RMSEXY = 0.133 m, RMSEZ = 0.086 m and the total error or vector sum of 0.159 m. Figure 11 shows the point cloud imported into Revit obtained by UAV photogrammetry using Agisoft PhotoScan, where the point cloud had a total of 27,046,199 points. The mesh obtained had a total of 1,801,780 faces and 901,504 vertices. From this point cloud, the reconstruction of the original state of the building was carried out based on the historical information collected. Figure 12 shows the superimposition of high-precision 3D models based on the dense point cloud and the HBIM model made in Revit, matching its corresponding heights and each vertex of both models. There are also some details of the rosette of the main facade and the belfry.

Figure 11. Point cloud imported from Autodesk Revit.

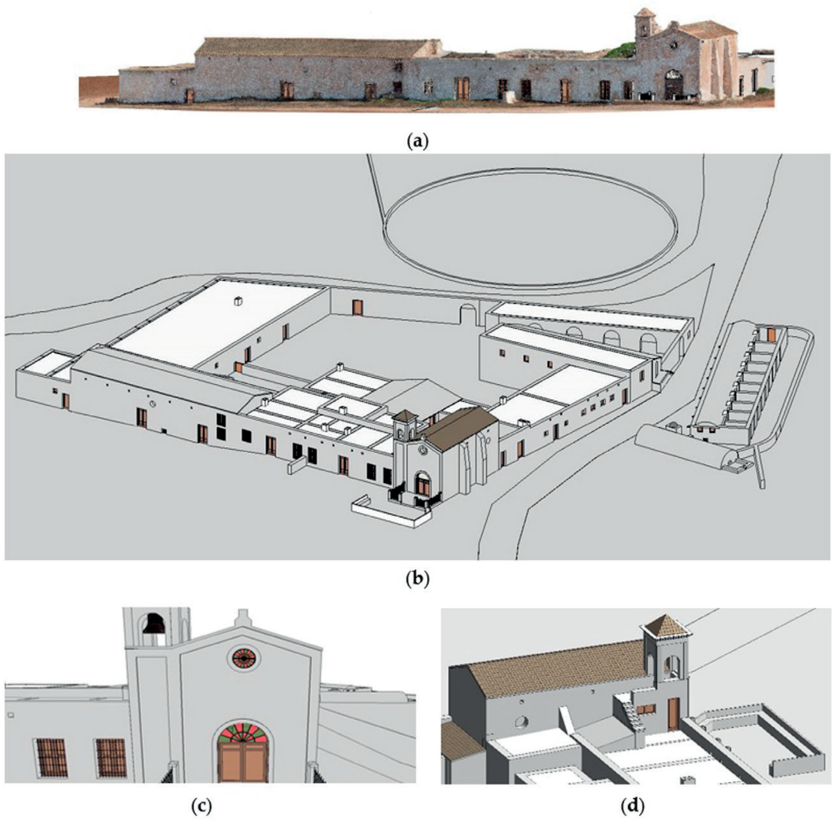


Figure 12. HBIM model of the building made in Revit: (a) detail of the superimposition between the point cloud and the HBIM model;(b) overall perspective; (c) detail of the rosette of the main facade; (d) detail of the bell tower.

Figure 13 shows an example of the validation carried out for the roof of the chapel, where the average differences between the created object and the photogrammetric model are around 0 with a standard deviation of less than 0.05m. The results are represented by a false colour which describes the differences. Using Revit, plans were generated, including floor plans, elevation, and sections of the building. Different views were also generated in perspective of the built complex. Figure 14 shows some of the renderings obtained with Lumion © of the 3D model of the virtual reconstruction of the Cortijo del Fraile, with the aim of achieving a photorealistic finish and preservation for archival and documentation purposes.

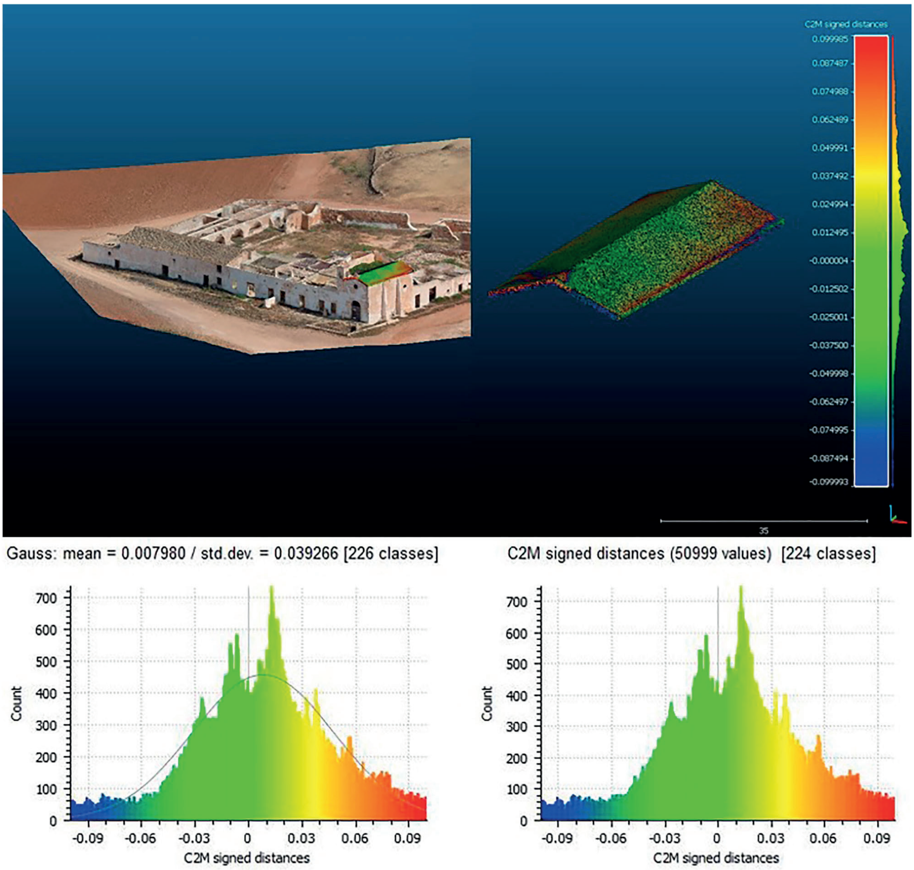


Figure 13. Example of the validation carried out for the roof of the chapel.

Accuracy of the photogrammetric project

The values obtained in the photogrammetric project are in accord with several applications studied by (Clapuyt, Vanacker, & Van Oost, 2016), who compared 10 cases of 3D topographic reconstructions based on the SfM algorithm with similar conditions to those in this archaeological site.

Figure 14. Renders obtained with Lumion © software.

In all the cases, the accuracy of measurements was on the order of centimetres. In this research, the total error obtained in the georeferencing of the model is 0.159 m, which is considered more than sufficient for this kind of intervention. Although this reference is not focused on the field of cultural heritage, the other studies consulted in this research do not evaluate the absolute precision of the photogrammetric model or the point cloud obtained by TLS, but are limited to making comparisons between the results obtained by different methods.

Comparison between TLS and UAV photogrammetry

Many authors have conducted studies performing comparisons between point clouds obtained by laser scanner and by UAV photogrammetry. Among them, (Koutsoudis et al., 2014) processed 183 nadiral and 469 terrestrial images using PhotoScan software for modelling the state of a building, in particular an Ottoman monument located in the region of Xanthi (Greece). The objective of that study was to compare the results with those generated by a laser scanner, and an average difference of 1.4 cm was obtained. They concluded that, although there are advantages and disadvantages regarding the use of laser scanners, it is possible to obtain models and highquality digitalizations from software based on SfM photogrammetry. (Barrile, Bilotta, Lamari, & Meduri, 2015) obtained a point cloud to model a fifteenth to 16th-century masonry castle in southern Italy (Marina di Gioiosa Jonica, Reggio Calabria) called Torre Galea.

This point cloud was obtained with different software applications and it was concluded that the point cloud obtained with PhotoScan showed smaller differences (2 cm) than that obtained by laser scanner. In this research it has been impossible to carry out a survey with a TLS, as there is a fence on the perimeter of the building that prevents access to the interior for security reasons. Regardless of the accuracy obtained by each method (TLS or UAV photogrammetry), both are complementary and, in many cases, the only way to achieve a complete HBIM model, both interior and exterior faces of the building.

Height of the photogrammetric flight and use of oblique and terrestrial images

(Grenzdörffer, Naumann, Niemeyer, & Frank, 2015) carried out a survey of the Cathedral of St Nicholas in the City of Greifswald. For this, they combined the use of laser scanners and nadiral and oblique images obtained by means of UAV. Once the point clouds were obtained, they performed a comparison, obtaining differences between 2.5 and 8.8 cm. They concluded that UAVs are an excellent tool for those places that are not accessible to a laser scanner but that in some cases may require the use of terrestrial photographs for zones adjacent to the ground. In our study, it was not necessary to use terrestrial photographs, due to the use of low-altitude oblique aerial photographs (<15 m) with different pitch angles. This has been possible due to the peculiarities of the building studied, as there are no prominent projections along the façade, and the ability of the UAV to move along all elements of the building. The major limitation found for the use of the UAV in this study has been for the survey of the lower areas of the semi-circular arches. In this case, the only solution would have been to enter the interior of the building.

(Aicardi et al., 2016) carried out a survey of S. Maria's Chapel, which is part of the Novalesa Abbey, a Benedictine monastery in Val Susa (Piedmont, Italy) using oblique aerial photographs at short distance (20 m) and processed the model using software based on SfM, concluding that in all cases high precision point clouds were obtained, in accordance with the results obtained in this study.

(Karachaliou et al., 2019) developed an HBIM model of Averof's Museum of Neohellenic art located in Metsovo, Greece. In this case the flight was performed in three strips (two nadiral and one oblique), without the use of terrestrial images, as in our study. The main difference between the two pieces of research and ours is that they had the architectural designs of the exterior and interior in order to extract information regarding its dimensions. In our case most of the interior information was captured from the air because most of the rooms had a collapsed roof, and from other historical information sources.

Accuracy of the HBIM model

The 'level of accuracy' of information has to be chosen, related to the type of intervention and as homogenous as possible, in order to obtain a model that is easy to manage and understand (Biagini et al., 2016). For this reason, there are no quantitative records to establish the permitted precision limits. (Adami et al., 2017) makes a comparison between the objects created and the point cloud, but does not set the permissible limits of precision either. In this study, some limits have been used that may be indicative for other studies and which have given good results, as the whole parametric model has been adjusted in a reasonable time. In most of the cases of this study, the differences found are due to surface irregularities and deformations over time.

Conclusions

UAV photogrammetry has been shown to give results that are competitive with those obtained through surveys carried out by TLS. In this sense, both the increase in the number of photographs and the combination of nadiral and oblique photographs significantly improves the quality of the dense points cloud obtained through the photogrammetric process, as well as avoiding the emergence of potential grey areas. This dense point cloud is obtained with centimetre accuracy and is the best possible basis for modelling the existing architecture. It is therefore essential in the case of carrying out virtual reconstructions of buildings in a dilapidated state. During the modelling process, it is very important to adopt a validation procedure that ensures maximum compatibility between the parametric object and the ground truth. In this research, references have been established that can serve as a basis for other authors who carry out similar projects. In addition, in order to successfully complete an HBIM model, it is necessary to complement this technology with a thorough and exhaustive study of existing historical documentation that provides information on the original geometry and architecture. This method represents a viable option in those cases in which access is restricted for security reasons, or where TLS does not have a direct line of sight, since it allows to obtain precisions on the order of centimetres with a very high efficiency in cost and time. However, UAVs also have limitations such as problems accessing the interiors of buildings, so as long as there is no progress in that field, this methodology is especially limited to exterior HBIM.

This study has shown that it is possible to use a method based exclusively on images obtained from UAV in order to obtain a reconstructed model that allows visualization as well as the archiving and registration of documentation with a view to carrying out future restoration projects.

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CAPÍTULO

04 CONCLUSIONES GENERALES

Con la combinación de la fotogrametría UAV-SfM y la metodología HBIM es posible obtener resultados muy precisos, manteniendo la legitimidad del inmueble. Estos modelos son el núcleo contenedor de toda la información gráfica, y son extraordinarias formas de reconstruir virtualmente edificaciones históricas.

Dada la presencia de numerosas variables y peculiaridades en el estudio de la arquitectura histórica, la toma de datos utilizando la fotogrametría UAV representa una opción viable en aquellos casos en los que el acceso al edificio está restringido por razones de seguridad, por encontrarse en ruinas o ser inaccesible y también, en los casos donde el TLS no tiene una línea de visión directa. Los UAV son una herramienta muy eficaz por la velocidad en la toma de datos y su eficiencia en la adquisición de imágenes. Son una buena solución debido a su bajo coste; pero requieren una buena capacidad del piloto para la gestión de la misión de vuelo, en particular en un entorno complejo (Giordan et al., 2020). La literatura dedicada al uso de UAV y el procesamiento de datos es muy amplia y variada. Solo para citar algunos artículos más representativos (Nex & Remondino; 2014) hacen referencia al uso de UAV para mapeo 3D y (James et al., 2017) describieron cómo es posible optimizar el proceso SfM.

La fotogrametría UAV-SfM ofrece resultados de mapeo fotorrealistas en forma de ortomosaicos, nubes de puntos y mallas texturizadas. Debido a su precisión y calidad, se pueden identificar y medir datos fácilmente. En cambio, el TLS ofrece una nube de puntos donde se pueden identificar formas y contornos, pero no ofrece detalles contextuales (Drone Photogrammetry vs. LIDAR: What Sensor to Choose for a given Application | Wingtra, n.d.). Los resultados de los dos casos de estudio que se han analizado en esta tesis, han demostrado que con el método UAV-SfM, es muy importante el número y distribución de los GCPs, porque permiten tener mejor control de la calidad del modelo final en términos de precisión y exactitud; y permiten corregir algunos puntos de deformación local. Es imprescindible, además, la cantidad y secuencia de imágenes tomadas (tanto en términos de posicionamiento geográfico como de resolución), y la superposición entre imágenes para obtener una nube de puntos densa con precisión centimétrica. En ambos casos la precisión obtenida fue con un error total inferior a tres centímetros, lo cual permite obtener un levantamiento métrico de alta resolución, para la gestión y reconstrucción de modelos 3D, convirtiéndose de forma rápida y automática en modelos HBIM inteligentes.

Para completar con éxito un modelo HBIM, es necesario integrar esta metodología con un estudio minucioso y exhaustivo de la documentación histórica existente que proporcione información sobre la geometría y arquitectura original del inmueble. Para la generación de los modelos 3D paramétricos en Revit, es imprescindible utilizar complementos como *As-Built for Revit*, ya que permite trabajar con mayor facilidad y precisión grandes superficies de nube de puntos.

Las precisiones de ambos modelos deben ser validados midiendo las distancias entre la malla del modelo fotogramétrico y el modelo paramétrico creado. En este estudio se ha demostrado por diferentes vías, mediante la utilización del software *CloudCompare* y el pugin *As-Built for Revit*, que el valor promedio de diferencias entre ambos modelos es alrededor de 0,05 m; lo cual demuestra que se ha obtenido un modelo 3D de alta precisión.

En esta investigación se ha confirmado que la metodología HBIM es muy eficiente para la gestión de información heterogénea sobre edificios patrimoniales, como sus geometrías y propiedades, diversas construcciones (sistema de bóvedas, muros, ventanas, etc.) (Previtali et al., 2020) y tecnologías decorativas (Bruno et al., 2019). En los últimos años, las investigaciones han mostrado que un modelo HBIM es el punto de partida para la interpretación de la evolución histórica del edificio y la creación de proyectos de mantenimiento y restauración (Pocobelli et al., 2018). El uso de HBIM en el campo del patrimonio cultural es una excelente solución para una mayor coordinación, gestión y conservación eficiente (Karachaliou, Georgiou, Psaltis y Stylianidis, 2019).

A su vez, en el proyecto HBIM se pueden elaborar tablas de cantidades y planificación, ya que incorpora un listado de todos los elementos del proyecto y puede vincularse a bases de datos de costos en el mismo software o exportarse a programas de administración de tiempo y costos (4D y 5D, respectivamente) para obtener el presupuesto de restauración. Además un modelo HBIM puede tomarse como base en cualquier proyecto de intervención del patrimonio (historia, arqueología, arquitectura, arte, etc.) así como al tipo de trabajos que se desarrollan (investigación, protección, conservación y difusión) (Smart Building Spanish Chapter, 2018), ya que permite la interoperabilidad de varias disciplinas mediante un modelo común, como el formato IFC, pudiendo ser importado por otros softwares; siendo, además, un modelo flexible que admite prolongadas transformaciones en la intervención. De este modo, toda la información quedará ordenada de un modo coherente con la propia naturaleza de los bienes culturales, siendo más sencilla, lógica y eficiente la gestión de dicha información (Smart Building Spanish Chapter, 2018). La calidad gráfica de la información obtenida, desde el nivel planimétrico hasta el fotorrealista, ha demostrado ser una herramienta muy potente para la reconstrucción virtual de obras patrimoniales abandonadas.

Futuras líneas de investigación.

Las propuestas de líneas de investigación futuras que se proponen desarrollar a partir de esta investigación son las que se mencionan a continuación.

1- Investigar respecto al acceso de los UAV en espacios interiores de edificaciones patrimoniales que se encuentren en desuso, ruina o prácticamente inaccesibles. Proponer una nueva metodología para poder documentar al máximo detalle los interiores de los estos inmuebles con la ayuda de los drones.

2- Profundizar en el tema referente a los plugins o complementos para “Scan-to-BIM”, donde se propone diseñar nuevos complementos, o mejorar los existentes, para modelar y reconocer automáticamente los objetos paramétricos y facilitar aún más, la creación de los mismos.

CAPÍTULO 05 ANEXOS

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UAV PHOTOGRAMMETRY AND HBIM FOR THE VIRTUAL RECONSTRUCTION OF HERITAGE

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Keywords: UAV photogrammetry, HBIM, cultural heritage, virtual reconstruction, 3D modelling

Abstract. Three-dimensional (3D) models have become a great source of data for the conservation, reconstruction, and documentation of emblematic buildings of cultural heritage. In this study, photogrammetry based on Unmanned Aerial Vehicles (UAVs) was applied to perform a photogrammetric survey of a dilapidated cultural heritage building. On the basis of this survey and the historical information gathered from the building, its virtual reconstruction has been carried out using a Historic Building Information Modeling (HBIM); applying realistic materials and textures in order to document it.

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UAV PHOTOGRAMMETRY AND HBIM FOR THE VIRTUAL RECONSTRUCTION OF HERITAGE

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KEY WORDS: UAV photogrammetry; HBIM; cultural heritage; virtual reconstruction; 3D modelling.

ABSTRACT:

Three-dimensional (3D) models have become a great source of data for the conservation, reconstruction, and documentation of emblematic buildings of cultural heritage. In this study, photogrammetry based on *Unmanned Aerial Vehicles (UAVs)* was applied to perform a photogrammetric survey of a dilapidated cultural heritage building. On the basis of this survey and the historical information gathered from the building, its virtual reconstruction has been carried out using a *Historic Building Information Modeling (HBIM)*; applying realistic materials and textures in order to document it.

1. INTRODUCTION

The methods of digitization or 3D virtualization based on images, today, are a very useful technique in the area of cultural heritage; specifically related to the *Unmanned Aerial Vehicles (UAVs)*, which represent an emerging and economic technology in the data collection of photogrammetric surveys; and can be equipped with high resolution cameras, obtaining nadiral images and oblique during low altitude flights with greater security for the operator. The use of oblique photographs improves the results obtained by *Structure from Motion (SfM)* Photogrammetry, by allowing the visualization of hidden details of the nadiral views (Aicardi et al., 2016), thus avoiding the use of terrestrial photographs.

The processing of these images with SfM algorithms can provide very accurate 3D models (Chatzistamatis, Kalaitzis, Chaidas, Chatzitheodorou, Papadopoulou, Tataris and Soulakellis, 2018), obtaining as a result a three-dimensional mesh model that can be used as a reference for the creation of a *Building Information Modeling (BIM)* model, whose methodology covers the design, construction and administration processes of a building's data throughout its life cycle (Merchán, Salamanca, Pérez, Moreno, 2018). Its implementation in patrimonial works depends on the irregularities of each building. Because of this, parametric objects created on BIM platforms can not be used; having to create new objects and own libraries, slowing down the modeling process. For this reason, new challenges arise in 3D digital modeling (Barazzetti et al., 2015), such as *Historic Building Information Modeling (HBIM).*

HBIM as a plug-in for BIM is a novel library of prototypes of parametric architectural objects; constructed from historical data and remote collection of survey data, using TLS or photogrammetry; to digitally model historic buildings (Capone and Lanzara, 2019; Dore and Murphy, 2012). More and more intervention works in the architectural heritage are based on an HBIM model based on the geometric information provided by the scanning and photogrammetry equipment (Dore, Murphy, and Dirix, 2017). The main objective of this study is to reconstruct virtually through an HBIM model, the Cortijo del Fraile, in Níjar, Almería, Spain; patrimonial work that is in a ruinous condition.

2. CASE STUDY

The Cortijo del Fraile (Fig.1), is a building built in the eighteenth century, located southeast of Níjar, Almería; inside the Natural Park of Cabo de Gata-Níjar. It is located on an estate of 730 hectares, in an arid landscape of volcanic lands and rising elevations towards the coast. The southwest and northeast UTM coordinates (Zone 30, ETRS89) of the study area are (582385, 4080340) and (582515, 4080470), respectively.

The Cortijo del Fraile is famous for the crime that occurred in its vicinity in 1928, the so-called *"Crime of Níjar"* (Torres Flores and Roldán Molina, 2018), whose protagonist, Francisca Cañadas (Luis Antonio de Villena, 1998), lived in the surroundings all his life. This real story inspired Federico García Lorca for the plot of his tragedy *"Bodas de Sangre"* (1931); also the dramatic and poetic vision *"Puñal de Claveles"* (1931) by Almeria writer Carmen de Burgos (Cabañas Alamán, 2009). Bearing in mind that little information is available regarding the original image of the Cortijo (Cortijo del Fraile, 2019), the graphic proposal of films like *"The Good, the bad, the ugly"* and others inspired by Sergio Leone in the sixties, show images of their original architecture. The Cortijo del Fraile was declared *"Property of Cultural Interest"* and inscribed in the General Catalog of the Andalusian Historical Heritage, with the typology of *"Historic Site"* (DECRETO 44/2011, de 22 de Febrero).

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Fig. 1. Actual image of the main façade of Cortijo del Fraile

2.1 Description of the building

The built-up area, as shown in figure 2, has a trapezoidal-shaped floor plan, with a plot area of 3,013 m² and a built-up area (main house, sharecroppers and shepherd, chapel, stables, and corrals) is estimated at 1,835 m2. The building responds to the typology of *"Vernacular Architecture"* (Cortijo del Fraile, Lista Roja del Patrimonio, 2012), where several units are distributed on a single floor around a central courtyard. The nucleus consists of housing for the owners, chapel, houses of the sharecroppers and the shepherd; central courtyard, corrals, barns, pigsties, wells, and cisterns.

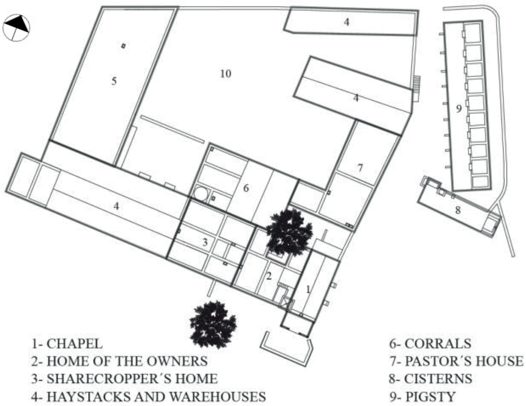

Fig. 2. General scheme of the Cortijo del Fraile.

The Cortijo del Fraile is a typical example of scattered buildings, on one level, with buildings of solid character, flat roofs compartmentalized by the vertical extension of the load-bearing walls and where the chimneys of the various kilns stand out as isolated elements in the predominant horizontality of the whole. The Cortijo is considered one of the best examples of large houses, combining the use of housing with other dependencies of agricultural work; leading to a complex building.

The chapel has a rectangular floor plan and a gable roof with flat tile, standing out for its volume in the whole, having a small bell tower with a square base of bricks and a hipped roof with a flat tile. The interior of the chapel has a barrel vault, with pointed arches resting on pilasters, and an altarpiece in the presbytery. Under the altar, there is a funerary crypt with twelve niches and on the ground the entrance to an underground chamber. The vertical structure of the building is formed by stone masonry load-bearing walls with mud, plaster or lime as binders. At the same time, many of the load-bearing walls are made up of semicircular arches, which are not usual in the immediate constructions of the site. The roofs are generally flat, with the exception of the corrals linked to the dwelling of the sharecropper and the haystack, which have a gable roof made of Arabic tiles. After its definitive abandonment in the eighties, the current state of construction is one of ruin (Fig. 3), having been in a state of abandonment for more than 40 years and in constant danger of collapse. Today, it is the private property of a company that exploits the farm and its wells for ecological agricultural production in the open air.

Fig. 3. Current state of ruin of the facilities of Cortijo del Fraile

3. APPLICATION OF UAV TECHNOLOGY

To perform the photogrammetric survey; firstly, 8 targets were placed around the building (Fig. 4), due to the inability to access the interior to be able to georeference *Ground Control Points (GCPs)* and evaluating the accuracy of the photogrammetric project *Checkpoints (CPs).* The targets consisted of A3 size (420 × 297 mm) red paper on which were two black squares. The three-dimensional coordinates of these points were measured with a *Global Navigation Satellite System (GNSS)* receiver working in *Post Processed Kinematic (PPK)* mode, with the base situated at a point near the main facade of the building. Horizontal coordinates are referred to as UTM Zone 30N (European Terrestrial Reference System 1989, ETRS89) and the elevation is referred to the Mean Sea Level (MSL) using the EGM08 geoid model. The GNSS base receivers were from the Trimble R6 system. Once the support points were placed, the photographic shot was taken with a UAV DJI MATRICE 600 PRO with six rotors; was equipped with a digital camera with a lens with a fixed focal length of 15 mm and diagonal FOV of 72 degrees. The resolution of the camera sensor was 16 megapixels (4608 × 3456).

Fig. 4. Distribution of GCPs for the georeferencing of the photogrammetric project, overlapped to orthoimage obtained from photogrammetric project

Two flights were made; the first at a height of 50 m above ground level, with an autopilot using the DJI GS Pro © application to obtain nadiral photographs. The flight plan consisted of 11 passes. The camera was triggered every two seconds, the flight speed was set to obtain forward, and side overlaps of 80% and 65%, respectively. The second flight was established at a height of 15 m above the ground level because the height of the building is 12 m. This flight was made manually to obtain oblique photographs of the four facades and the interior of the building. Figure 5 shows the locations of the camera and the overlapping of the images, where the blue color indicates that the point of the terrain appears in more than nine photographs. A total of 623 photographs were taken, used to perform the photogrammetric process. In table 1, the details of the cameras are shown.

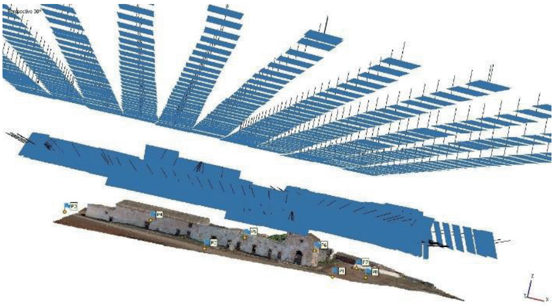

Fig. 5. Camera locations grouped in two flying heights

Number of images	623
Flying altitude	49.2 m
Ground resolution:	1.16 cm/pix
Coverage area:	3.49e+04 sq m
Camera stations:	623
Tie points:	298,321
Projections:	2,216,716
Reprojection error:	2.3 pix

Table 1. Detail of cameras

3.1 Photogrammetric process

The photogrammetric process was carried out using the software package *Agisoft PhotoScan Professional © version 1.2.4.2399* (Agisoft PhotoScan, 2015). This photogrammetric software is based on creating high-quality 3D models from images, using *3D Multivision* reconstruction technology (Furukawa and Ponce, 2010) and the *SfM algorithm* (Javernick, Brasington, and Caruso, 2014); and it has been used because it has been proven to outperform other software applications in terms of accuracy (Sona, Pinto, Pagliari, Passoni and Gini, 2014). The software processing part of selecting the nadiral and oblique images that are going to be used in the process. Agisoft PhotoScan is able to adjust the calibration parameters of the camera automatically during the calculation of the orientations of the images, starting from the initial values extracted from the image data. Then the images are aligned by calculating the internal orientation and a scattered 3D point cloud with correspondence between images. In the process of alignment, the program uses several algorithms that detect the points and obtain the orientation and position of the images. In this study, the model has been georeferenced indirectly through the topographic survey carried out with the Trimble R6 GNSS. Then you get the cloud of dense points that serves as the basis for the construction of the three-dimensional mesh. From the high density of points created, the mesh/network of interpolated triangles is produced to subsequently generate the final texturized model. Then I applied to texture to the mesh obtained in the previous step. Finally, the orthophoto is exported and a DSM grid can be generated from the cloud point. The dense point cloud can also be exported in *(* .the)* format, as well as the mesh in *(* .obj)*, *(* .3ds)* or *(* .dxf)* format. The bundle adjustment is carried out at least three GCPs, but more accurate results are obtained if more GCPs are used, and it is recommended that they are used to obtain optimal accuracy (Agüera-Vega, Carvajal-Ramírez, and Martínez -Carricondo, 2017).

4. APPLICATION OF THE HBIM METHODOLOGY

Virtual reconstruction involves the attempt of visual recovery, from a virtual model, at a specific moment of construction or object manufactured by the human being in the past based on the existing physical evidence (Carta de Londres, 2009). HBIM is the possible solution for the three-dimensional parametric representation, which allows the user to draw models and manage data on historical architectural elements, within a common software environment (Icon.Net Pty Ltd 2009), being the data exchange format *Industry Foundation Classes (IFC)* the most used, since it is an open and neutral standard maintained by *BuildingSMART®*. BIM modeling was carried out using the software *Autodesk Revit © 2019*, today, one of the most used BIM software, which contains several dimensions *4D (Time), 5D (Cost), 6D (Sustainability) and 7D (Management and Maintenance)* in building models, achieving interoperability through the use of different programs and several disciplines (Tommasi and Achille, 2017). In this study, the modeling procedure performed (Fig. 6), part of the data captured using the UAV-Photogrammetry technology, described in the previous section.

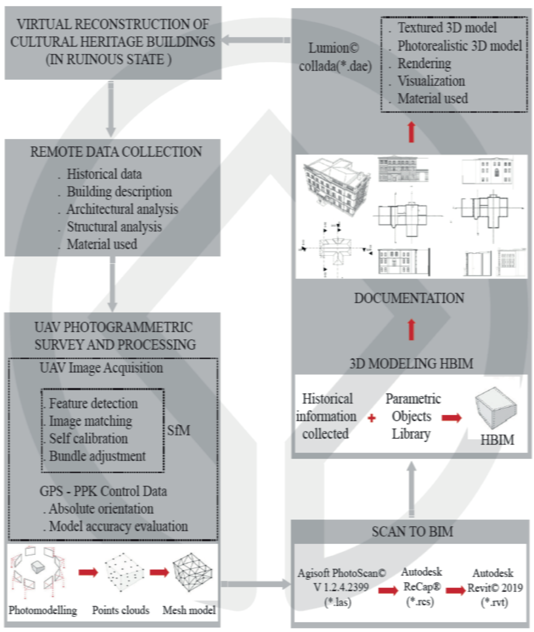

Fig. 6. Modeling procedure performed.

4.1 Scan to BIM

The term Scan to BIM incorporates the exploration process, by scanning data in the form of *Point Cloud Data (PCD)* point clouds that contain geospatial information about the building and its surroundings (Hajian and Becerik-Gerber, 2010). Revit® can link the point cloud from its own interface or through the *Autodesk ReCap®* application with the format *(* .las)* that stores the color information obtained from the images, allowing their visualization. The procedure that has been used for *Scan to BIM is: PhotoScan (* .las) -> ReCap (* .rcs) -> Revit (* .rvt).*

Based on the scanty historical information collected from the building, as archive images of films showing their original architecture, historical parametric objects can be reconstructed. The parametric character of Revit® allows for a certain constructive element; for example, in this study: the Tuscan portico attached to the interior of the chapel (Fig. 7a); take as a base created objects such as the entablature, the capital, the shaft and the base of Tuscan order, to modify the values of their dimensions according to the scale; infinite combinations can be obtained depending on the alphanumeric parameters.

This process would be applicable for all created historical parametric objects that make up the model (Fig. 7). Another of the parametric objects created is the barrel vault inside the chapel (Fig. 7b), which is made of reinforced concrete and has two semi-circular arches, which rest on pilasters by the corresponding abutments.

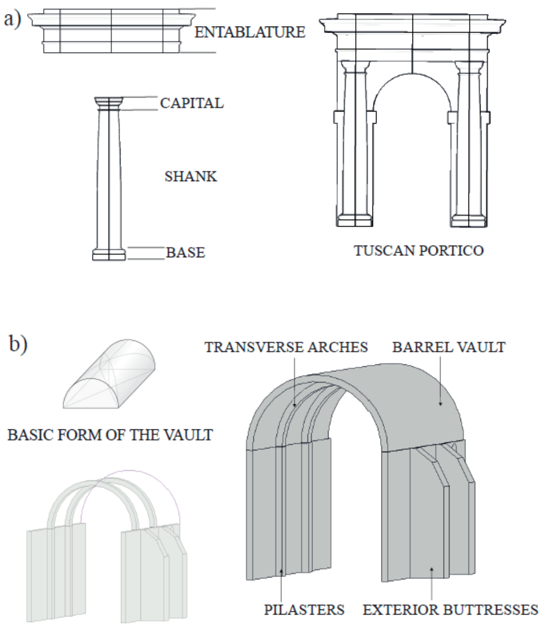

Fig. 7. Parametric objects library; a) Tuscan portico; b) barrel vault

To each created component the metadata is introduced. For each element in a scene, the necessary characteristics are introduced; For example, of the barrel vault (Fig. 8), you can obtain information about its materials, geometric data on the architecture of the elements and their structure.

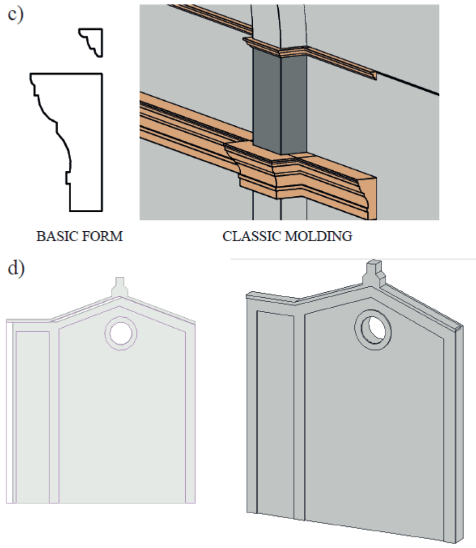

Fig. 7. Parametric objects library; c) set of moldings (listel, strips, half bocel and caveto) that are basic elements of classical architecture; d) Striped pediment where the upper part is interrupted by an ornamental motif

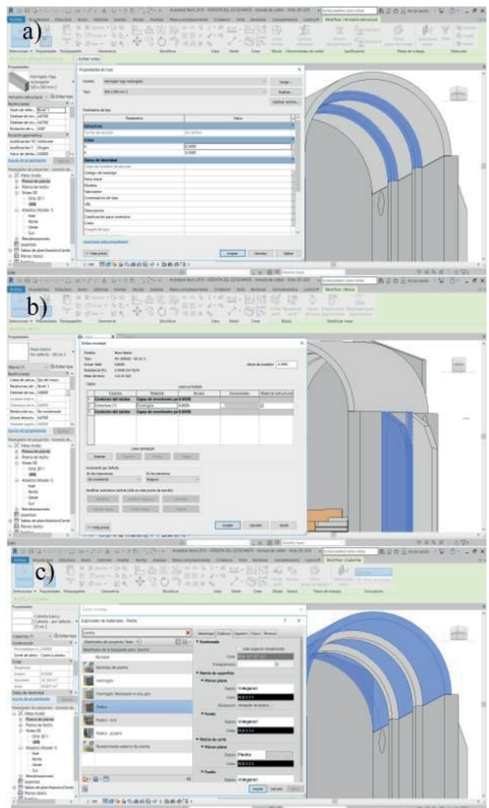

Fig. 8. Metadata. Barrel vault; a) geometric data of the arcs fajones; b) characteristics of the structural elements of the abutments, such as the resistance of the materials; c) characteristics of the materials of the barrel vault

4.2 Modeling Process

Starting from the three-dimensional mesh, 3D modeling is done manually of all the elements that make up the model; because Revit®, as a BIM software, does not have an automatic geometry recognition option. The most recent scientific literature states that great efforts are being made in automatic recognition to generate 3D geometries, but this lacks the valid details to be applied in the heritage area (Dore and Murphy, 2017). The complete modeling process was carried out in approximately 48 hours of work. The information received in Revit® is thousands of colorimetric points of information that show details of the property, such as, for example if a wall has an inclination. In this way it is possible to visualize the cloud of dense points to use as a guide to establishing the levels in section, the axes in plant (Chiabrando, Lo Turco, and Rinaudo, 2017, Oreni, Karimi, and Barazzetti, 2017, Rodríguez-Moreno et al., 2018), and later, modeling the entire building.

To obtain photorealistic images, it is necessary to add materials and textures to the 3D model. Revit is not software designed to render, on the other hand, *Lumion ©* is a software-based on video game rendering engines that is revolutionizing the current outlook. Both software has data exchange format; therefore, the 3D model can be exported from Revit® to Lumion © to add materials and textures (Meini, Felice, and Petrella, 2018) and perform the rendering process. The best way to export them is through *"Lumion Plug-in for Revit"*. The plug-in includes two functionalities: exporter for LiveSync which allows visualizing the model in real-time, and also export it as a type file *Collada (* .dae)* of Revit and load or reload it constantly in Lumion.

4. RESULTS

4.1 Accuracy of the photogrammetric project

Table 2 shows the precision obtained, for each of the GCPs, in the adjustment of the photogrammetric block. By not having more additional points *Checkpoints (CPs)* to evaluate the accuracy of the 3D model obtained, this was obtained as indicated in (Sanz-Ablanedo et al., 2018). In this way, the accuracy of the model can be estimated based on the precision obtained during the photogrammetric block adjustment. Thus, in our study, a total of 8 GCPs and 330 zenith photographs were used, so the number of GCPs per 100 photos is around 2.5, which shows an overestimation of the accuracy of the block adjustment with respect to the of the factor 3.6 model. Therefore, in our study, we can estimate that the 3D model was obtained with an approximate precision of 0.36 m. In figure 4, the orthophoto generated as a result of the photogrammetric process is observed.

On the other hand, (Grenzdörffer, Naumann, Niemeyer, and Frank, 2015) in their experiment, combined the use of laser scanners and nadiral and oblique images obtained by UAV, resulting in differences between 2.5 and 8.8 cm in the point clouds. They came to the conclusion that UAVs are an excellent tool for those places that can not be accessed with a laser scanner, but that in some cases may require the use of terrestrial photographs for areas adjacent to the ground. In our study, it was not necessary to use terrestrial photographs, due to the use of oblique low-altitude aerial photographs (<15 m) with different inclination angles. This has been possible due to the peculiarities of the building studied since there are no prominent projections along the façade, and the ability of the UAV to move along all the elements of the building.

Label	XY error (m)	Z error (m)	Error (m)	Error (pix9
P1	0.0759695	0.039759	0.0857447	0.723
P2	0.024946	0.0360585	0.0438465	0.548
P3	0.0458986	- 0.0925971	0.103348	0.603
P4	0.0634247	0.0416442	0.0758745	0.623
P5	0.0731339	0.102679	0.126062	0.802
P6	0.102097	- 0.0957468	0.139969	0.756
P7	0.0430949	0.0131652	0.045061	0.507
P8	0.148894	-0.045183	0.155598	0.581
Total	**0.0808717**	**0.0662522**	**0.104545**	**0.626**

Table 2. Accuracy obtained on each GCP during photogrammetric bundle adjustment

Figure 9 shows the point cloud obtained by UAV photogrammetry using Agisoft PhotoScan, where the point cloud had a total of 27,046,199 points. The mesh obtained had a total of 1,801,780 faces and 901.504 vertices.

Fig. 9. Dense point cloud obtained from the photogrammetric project

4.2 Accuracy of the HBIM model

Each of the parametric objects created to develop the HBIM model must be validated by measuring the distances between the mesh of the photogrammetric model and the mesh of the parametric object created. Due to this, the parametric object must be exported from Revit in format *(* .fbx)* and the photogrammetric model must be exported from Agisoft in format *(* .obj)*. Both files must be imported from CloudCompare (Girardeau-Montaut, 2017), where you can use the *"Cloud to Mesh Distance"* command to calculate the distance between the parametric object created in Revit and the model created in Agisoft. In the absence of a criterion adopted by the scientific literature for the validation of a parametric object (Adami, Scala, and Spezzoni, 2017), in this research, the criterion has been to obtain an average difference of around 0 (between -0.05 m and 0.05). m) and a standard deviation of less than 0.10 m.

Figure 10 shows the HBIM model realized in Revit, which coincides in position and dimensions with the real element, so that, if a detailed study of it is wanted, this could be the basis. From the 3D model with its associated metadata, the planimetry (planes, sections, and elevations) was obtained; as well as the calculation memories.

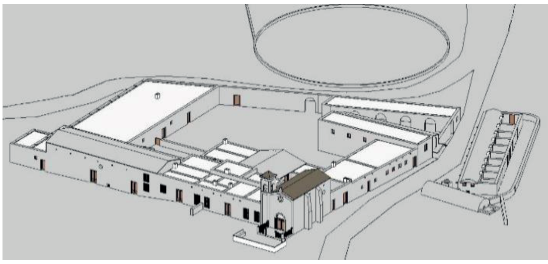

Fig.10. HBIM model of the building made in Revit

Figure 11 shows some of the representations obtained with Lumion © of the 3D model of the virtual reconstruction of Cortijo del Fraile, with the aim of achieving a photorealistic finish for conservation, archiving and documentation purposes.

Figure 11. Renders obtained with Lumion © software

Several authors have used the HBIM methodology to model buildings of cultural heritage. Specifically, (Oreni et al., 2017) developed an HBIM model to represent The Ice House of Filarete's Ospedale Maggiore in Milan (Italy). For this, they used two different parametric modeling tools, Revit®, and ArchiCAD®. The study showed the limitations and advantages in the workflow of each of them but concluded that the HBIM process allowed the integration of documented historical data with the existing physical state, in order to obtain a baseline for preventive maintenance, monitoring, and future conservation. It is, therefore, an ideal tool also for virtual reconstruction in those cases in which the current state is weakened or in a state of ruin, as has been done in this study. (Biagini, Capone, Donato, and Facchini, 2016) applied the HBIM modeling to the SS. Nome di Maria church in Mantua (Italy) concluding that this methodology allows representing the old building, the design ideas and the intervention phases, all from the parametric modeling based on a digital point cloud of the current state. (R. Quattrini, Malinverni, Clini, Nespeca, and Orlietti, 2015) developed an HBIM of the Church of Santa Maria at Portonovo, an abbey from the Romanesque period emphasizing that this model serves as the basis for a set of data for all disciplines, in particular for restoration and conservation.

On the other hand, (Karachaliou, Georgiou, Psaltis, and Stylianidis, 2019) developed an HBIM model in the Revit® software of the "Averof's Museum of Neohellenic art" located in Metsovo, Greece, using the orthoimages of the facades produced with photogrammetry processes UAV generated in PhotoScan and exterior and interior designs of the building, as has also been shown in this work. In addition, they made measurements in situ of the interior places of the building; instead, it is this study, because the Cortijo del Fraile is totally in ruins and access to the interior is prohibited; most of the inside information was captured from the flight with the drone, since most of the spaces had the roof collapsed; and also, with the support of data found together with archive photographs; obtaining the same results in terms of accuracy and quality of the information.

5. CONCLUSIONS

The cloud of points turns out to be the best possible base for the survey and subsequent modeling of patrimonial buildings in dilapidated condition. It is necessary to complement this technology with a thorough and exhaustive study of the existing historical document that provides information about the original geometry and architecture. Recent experimentation in the field (Bruno and Roncella, 2018) indicates that there is a lot to overcome in terms of costs, training and processing times, the use of HBIM in the cultural heritage field is a good solution and a potential for more coordinated and efficient management and preservation (Karachaliou, Georgiou, Psaltis, and Stylianidis, 2019).

Although sometimes this fundamental premise is left aside, we believe that adequate graphic documentation can be one of the most effective means for the conservation of cultural heritage, thanks to the relatively small resources that are needed and the high amount of information recorded and safeguarded. In an extreme case, a building could disappear, leaving its material cultural values conveniently preserved through complete graphic documentation (Talaverano, 2014). This study has shown that it is possible to successfully implement this method of work and obtain, therefore, a reconstructed model that allows the visualization, as well as the archiving and recording of the documentation with a view to future restoration and conservation projects.

The result of the HBIM model achieved in this work allows obtaining data from different materials and construction techniques, as well as its zoning within the building, to perform stratification and chronological studies depending on the materials and techniques used. Also, pathologies can be detected, especially for the calculation of the deformations of a constructive element; installing deformation control sensors that will send the information to the HBIM system, taking information on this type of pathologies in real-time. The control of dampness by means of a sensor system is also very useful, especially in large walls that are affected by different types of humidity. On the other hand, by means of the different construction phases of the project, the different historical phases of the project can be obtained. In addition, you can manage the entire project, like any BIM system, which allows the preparation of different projects, as well as implement it as a maintenance tool, especially for economic calculation.

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