sustainability

Review

Unmanned Aerial Vehicles (UAV) Integration with Digital Technologies toward Construction 4.0: A Systematic Literature Review

Titi Sari Nurul Rachmawati and Sunkuk Kim *

Department of Architectural Engineering, Kyung Hee University, Yongin-si 17104, Korea; titisari.nurul@khu.ac.kr
* Correspondence: kimskuk@khu.ac.kr; Tel.: +82-31-201-2922

Abstract: Unmanned Aerial Vehicles (UAVs) have been employed in the construction industry in the last decade for various purposes such as progress monitoring and building inspection. Recently, there has been a rising trend of employing UAVs with other digital technologies (DTs), such as Building Information Modeling and Extended Reality. The integration of these technologies encourages automation and digitization toward better project performance. However, little is known about the implementation of UAVs in conjunction with other DTs. Therefore, this study performs a systematic literature review to determine application areas and technology trends regarding UAVs' integration with other DTs. The search yielded 287 articles, of which 36 satisfied the established inclusion criteria and formed the foundation of this systematic review. Seven application areas of UAV integration with other DTs were identified: progress monitoring, historic building conservation, information management, construction safety, construction education, structural and infrastructure inspection, and transportation. This study also revealed UAV technology trends encouraging automation and digitization: automated progress monitoring, automated UAV inspection planning, real-time video streaming, and parametric model development of historicbuildings. This study is expected to be a starting point of future in-depth research by providing a general understanding of the current applications of UAVs integration with other DTs.

Keywords: systematic literature review; unmanned aerial vehicle; digital technology; Building Information Modeling; construction management

check for updates

Citation: Rachmawati, T.S.N.; Kim, S. Unmanned Aerial Vehicles (UAV) Integration with Digital Technologies toward Construction 4.0: A Systematic Literature Review. *Sustainability* **2022**, *14*, 5708. https://doi.org/10.3390/su14095708

Academic Editor: Ali Bahadori-Jahromi

Received: 8 April 2022
Accepted: 5 May 2022
Published: 9 May 2022

1. Introduction

The construction industry has gradually shifted toward digitalization in the last decade. Wide-ranging digital technologies (DTs) have enabled the digitization, automation, and integration of the construction process throughout the construction life cycle [1]. Such technologies comprehensively and profoundly transform the construction management process and assist decision-making in construction firms [2]. This circumstance is labeled Construction 4.0, a term derived from the phrase Industrial Revolution 4.0.

Wong et al. [3] categorized four major types of DTs in the construction domain: Building Information Modeling (BIM), Geographic Information Systems (GIS), the Internet of Things (IoT), and Unmanned Aerial Vehicles (UAVs). IoT includes radio frequency identification (RFID) and sensing technology. UAV technologies include points cloud, photogrammetry, and 3D laser scanning. In addition, Perrier et al. [4] studied Extended Reality (XR), or combined real-and-virtual environments and interactions generated through computer technology. XR comprises augmented, virtual, and mixed reality (AR, VR, and MR, respectively).

BIM denotes the shared digital representation of infrastructure/buildings to facilitate design, construction, and operation processes for the foundation of reliable decision-making of stakeholders [5]. BIM functions pivotally in building management and is thus considered focal to Construction 4.0 technologies. BIM has been integrated with GIS, where the BIM model is blended into the layers of geospatial context. Contractors and owners can obtain the geospatial data pertaining to a project, for instance, surrounding areas, disaster risk potential, site selection, or on-site material layout. These details can help stakeholders to judge construction circumstances accurately [6].

UAVs, or unmanned aerial systems, or drones, are remote vehicles equipped with onboard sensors and are controlled by a pilot on the ground [7]. UAVs are used in varied construction processes, such as earthwork surveying [7,8], on-site management [9], progress monitoring [10,11], safety inspections [12,13], and damage assessment [14,15]. In general, UAVs take images or videos that can later be processed via photogrammetry to create 3D objects as required. UAVs are advantageous compared to traditional data collection because their technology is faster and more efficient at a lower cost. In addition, UAVs can reach areas deemed inaccessible or dangerous for human workers. UAV-collected data can be independently processed and analyzed but can also be used as an input for BIM. Tan et al. [14] studied UAV integration with BIM for building inspection, comparing real-time UAV-collected data to as-planned 4D BIM to monitor progress. In addition to BIM, data accumulated via UAVs may also serve as input for GIS to monitor building-related activities [11].

The construction industry has also adopted XR, although it is still in the beginning stage. XR includes VR, AR, and MR. VR generates full virtual content within a computer-generated artificial 3D environment for the users [16]. AR integrates real-world and digital content by overlaying digital content on the user’s real-world environment [17]. MR is similar to AR but differs in its potential to allow interactions between digital content and the real world, making it more realistic for the users [18]. Several researchers have investigated the integration of UAVs as reality-based data capturing technologies in conjunction with BIM and XR. A 3D as-built model acquired from UAVs is compared to as-planned models from BIM [19]. The comparison is then visualized in the XR environment that stakeholders can access off-site using various gadgets. This integration improves communication and assists stakeholders, who can understand the project’s progress and make informed decisions.

Adopting these emergent technologies is expected to improve productivity and communication, reduce costs, and support reliable decision-making. A few researchers have published review papers regarding these technologies: Perrier et al. [4] presented an overview of DTs in the Construction 4.0 era, and Khan et al. [20] conducted a literature review on BIM integration with other immersive technologies [20]. However, no prior reviews have examined the integration of UAVs with other DTs. Whereas knowing UAV integration with other DTs can assist researchers and professionals in improving the project performance even more. Therefore, the aim of this paper is to systematically review peer-reviewed academic studies on the integration of UAVs with other DTs. By providing a general understanding of current application areas and technology trends of UAV integration with other DTs, this study can serve as a starting point for future, in-depth studies. Specifically, this study seeks to answer the following research questions. (1) What are the construction-related application areas of UAV integration with other DTs? (2) What is the most extensively used construction-related application area for UAV integration with other DTs? (3) What are the construction-related technology trends of UAV integration with other DTs?

2. Materials and Methods

This study applied the systematic literature review method, defined as “identifying, evaluating, and interpreting all research relevant to a particular research question, topic area, or phenomenon of interest” [21]. Publications were searched using several databases: Scopus, Science Direct, Web of Sciences, Taylor and Francis Online, American Society of Civil Engineers (ASCE) Library, and Wiley Online Library. Additionally, the keywords were also searched via Google Scholar.

To answer the research objectives of this study, the search terms comprised combinations of three main keywords. The first keyword represented the UAVs are “unmanned aerial vehicle”, which included numerous synonyms, such as “unmanned aerial system” and "drone". The second keyword, "construction management", was equated in this study with "construction industry" and "construction 4.0". Lastly, the third keyword encompassed other 4.0 technologies in the construction industry: "Building Information Modeling", "Geographic Information System", "Internet of Things", "Mixed Reality", "Virtual Reality", "Augmented Reality", "information and communication technology", and "sensing technology". The keywords for other DTs were gained based on preliminary studies about various technologies currently implemented in the construction industry. The keywords were searched using the Boolean operator "AND" to extract discrete keywords that were required to be present in the records and "OR" to connect two or more similar terms in keywords. Table 1 summarizes the search results for each database.

Table 1. Search by keywords in the literature databases.

Literature Database	Records
Google Scholar	8960
Scopus	287
Science Direct	276
ASCE Library	174
Web of Science	90
Taylor and Francis Online	47
Wiley Online Library	9

Records were extracted from Scopus rather than other databases because (a) Scopus includes a broad range of scientific journal publications, and most records from other databases are also found in Scopus, (b) the extraction results from Scopus can be integrated into VOSviewer software, which enables the construction and visualization of bibliometric networks, and (c) previous systematic literature reviews have used Scopus [4,20].

The records were filtered using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines displayed in Figure 1. The PRISMA 2020 guideline provides a flow diagram that assists scholars in transparently filtering publications [22]. This flow diagram contains four stages: identification, screening, eligibility, and inclusion. A reliable final database on the desired topic of a literature review is attained after filtering is performed at each stage.

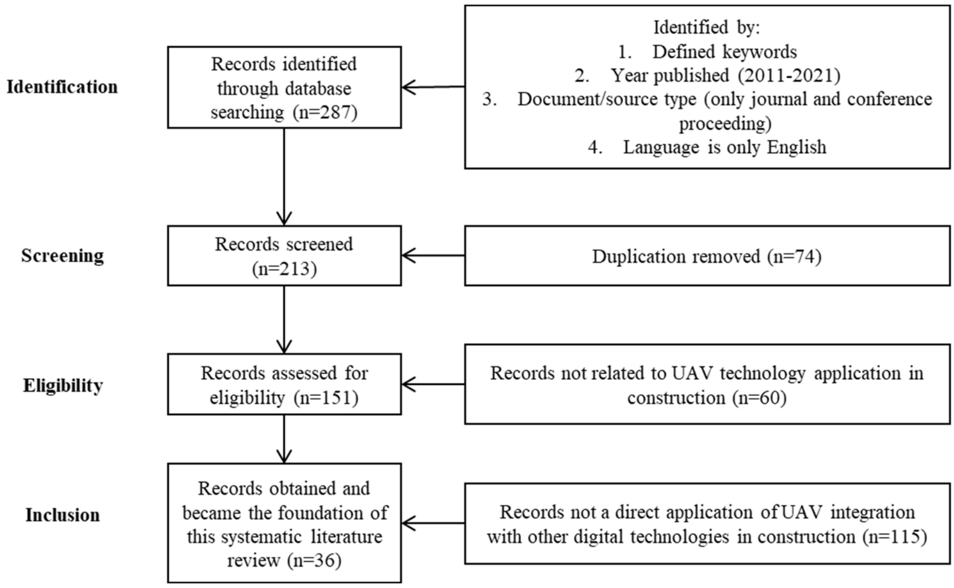


Figure 1. Flow diagram of the literature review and the analysis process.

The records were identified in the following ways at the identification stage: (1) defined keywords, (2) the time of publication was restricted and only studies published in the last decade (2011–2021) were included, (3) the type of documents was specified as the inclusion of only peer-reviewed journal publications and conference proceedings, and (4) the language was stipulated as only English. An aggregate of 287 records was identified through this database search.

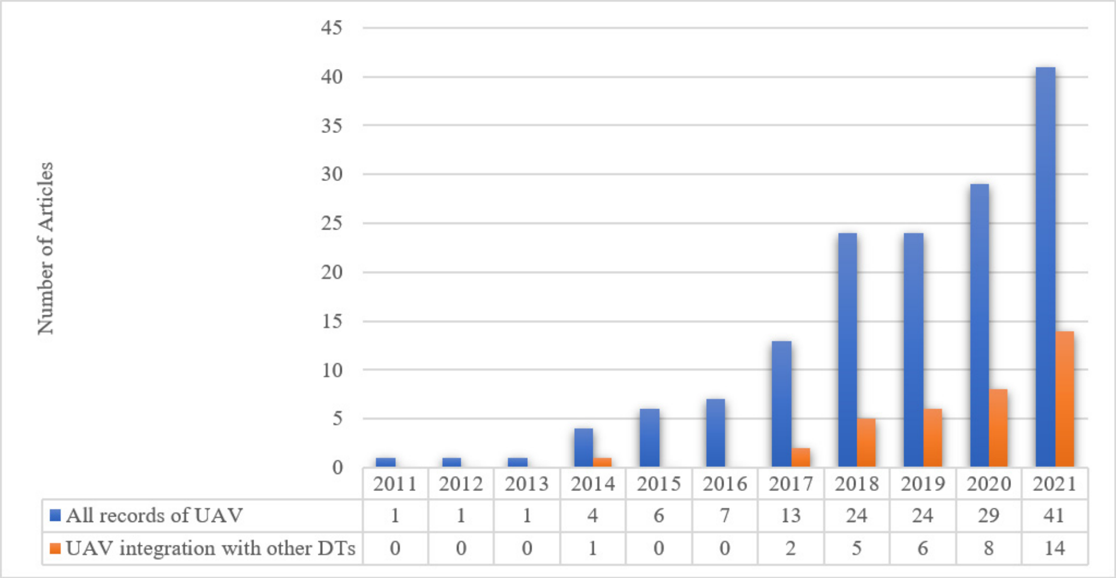
Of these results, seventy-four duplicates were removed at the screening stage, and 213 records remained. Next, the type of the records was filtered according to the established eligibility criteria. The publications were then screened based on the following conditions: (1) UAV application in construction, (2) varied DT applications in construction, and (3) the integration of UAV with other DTs in construction. A total of 151 records passed the above eligibility criteria.

The title and abstracts of 151 records were subsequently inspected at the inclusion stage to determine whether the record satisfied the inclusion criteria. To be included in the review, the publications were required to focus on UAV integration with other DTs in the construction domain. Studies such as literature reviews and dissertations were excluded. Finally, 36 records became the basis of this systematic literature review.

3. Results

3.1. Time-Series Analysis

Figure 2 exhibits the annual publications on UAV applications in construction over the last decade (2011 to 2021). The publications were divided into two types following the PRISMA guideline. First, the blue bar was computed from the eligibility stage and represents UAV applications as stand-alone technology as well as integrated with other DTs. Second, the orange bar was processed from the inclusion stage and only indicates UAV integration with other DTs.



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
■ All records of UAV	1	1	1	4	6	7	13	24	24	29	41
■ UAV integration with other DTs	0	0	0	1	0	0	2	5	6	8	14

Figure 2. Number of published articles by year.

Seven or fewer articles were published annually between 2011 and 2016, revealing the preliminary nature of this research domain. A rising trend was noted in 2017, during which 13 papers were published. The number of articles then increased rapidly up to 2021. Most records from the early 2000s referenced exploratory studies on the general potential of UAVs in construction or their specific applications in safety inspection [23,24]. One 2014 record related to UAV integration with other DTs pioneered UAV integration with

AR [25]. No research initiative was undertaken in the next two years (2015–2016) on UAV integration with other DTs. Such efforts have increased significantly since 2017.

The research in the late 2000s developed into varied categories such as simulation studies [26–28], case studies [29], and the interoperability of UAVs with other DTs [14,30]. A more in-depth literature study was also accomplished on the application of UAV technology in construction [31,32]. Nevertheless, the number of publications is not as high as studies published on other technologies such as BIM, suggesting ample potential for future research on UAVs.

3.2. Country Analysis

Table 2 displays 36 publications on UAV employment with other DTs classified by the country of the lead author's affiliation as stated in the paper. The United States of America (USA) leads this research domain with 12 published articles, followed by China with six articles. Four countries, including Korea, have published two articles each. Finally, ten countries, including Japan, have published one article each.

Table 2. Number of published articles by country.

Country	Number of Articles	Remarks
USA	12	
China	6	
Germany, Italy, Korea, Spain	8	Four countries presented two articles each
Brazil, Chile, France, Japan, Malaysia, Mexico, Philippines, Poland, Romania, Singapore	10	Ten countries presented one article each
Total	36	

3.3. Journal Allocation Analysis

Of the 36 publications on the deployment of UAVs with other DTs reviewed in this study, 17 were peer-reviewed journal papers. Most of the reviewed papers were published in internationally certified Science Citation Index or Science Citation Index Expanded journals. Table 3 summarizes the list of most popular journals and includes the journal impact factors (JIF) based on the Journal Citation Reports of 2021. As Table 3 demonstrates, Sensors and Applied Science ranked first and second with three papers each. Automation in Construction and Construction Innovation took third and fourth place with two papers each. Notably, some papers were also published in high JIF journals such as Automation in Construction, Journal of Management in Engineering, and Building Research and Information.

Table 3. List of the most popular journals.

Journal Title	Number of Papers	JIF 2021
Sensors	3	3.576
Applied Sciences	3	2.679
Automation in Construction	2	7.700
Construction Innovation	2	2.667
Journal of Management in Engineering	1	6.853
Building Research and Information	1	5.322
Journal of Computing in Civil Engineering	1	2.979
Heritage Science	1	2.517
Smart and Sustainable Built Environment	1	2.054
Advances in Civil Engineering	1	1.924
International Journal of Occupational Safety and Ergonomics	1	1.601
Total	17	

3.4. Co-Occurrence Keywords Analysis

The co-occurrence network of a keyword maps the relationships between keywords in the studied field [33]. Every keyword is visualized in terms of nodes that are linked, and each link is weighted. The bigger the node, the higher the occurrence frequency of the keywords. The thicker the links and the closer the positions between keywords, the stronger the relationships between those keywords.

This study created the networks using VOSviewer software. The options "author keywords" and "full counting" were checked using VOSviewer analysis for the co-occurrence networks of the keywords to obtain a holistic visualization landscape of this research field. Keywords conveying the same meaning were manually equated. The minimum occurrences of each keyword were set to 5, resulting in 21 keywords that met this threshold. Table 4 presents a detailed analysis of the co-occurrence of keywords along with their number of occurrences and their total link strength.

Table 4. Top keywords of UAV integration with other DTs in construction.

Keywords	Occurrences	Total Link Strength
unmanned aerial vehicles	128	212
building information modeling	52	113
construction industry	27	65
3d modeling	23	60
safety inspection	22	49
photogrammetry	16	41
augmented reality	11	29
virtual reality	9	29
construction management	12	27
point cloud	10	23
remote sensing	11	22
digital technology	9	20
progress monitoring	10	20
construction safety	7	17
aerial photography	6	16
project management	5	15
geographic information system	5	13
laser scanning	5	13
construction monitoring	6	12
internet of things	5	11

Figure 3 exhibits the co-occurrence network of keywords extracted from 151 records assessed at the eligibility stage of the PRISMA protocol. UAVs with a total link strength of 212 are the center of the network and are strongly connected to the construction industry and BIM as DTs. Further, UAVs demonstrate the most robust connection with BIM than other DTs. This result aligns with BIM's strategic position: BIM is highly interoperable with diverse DTs in the construction industry [34].

Three clusters were observed in the network and are summarized in the following sections.

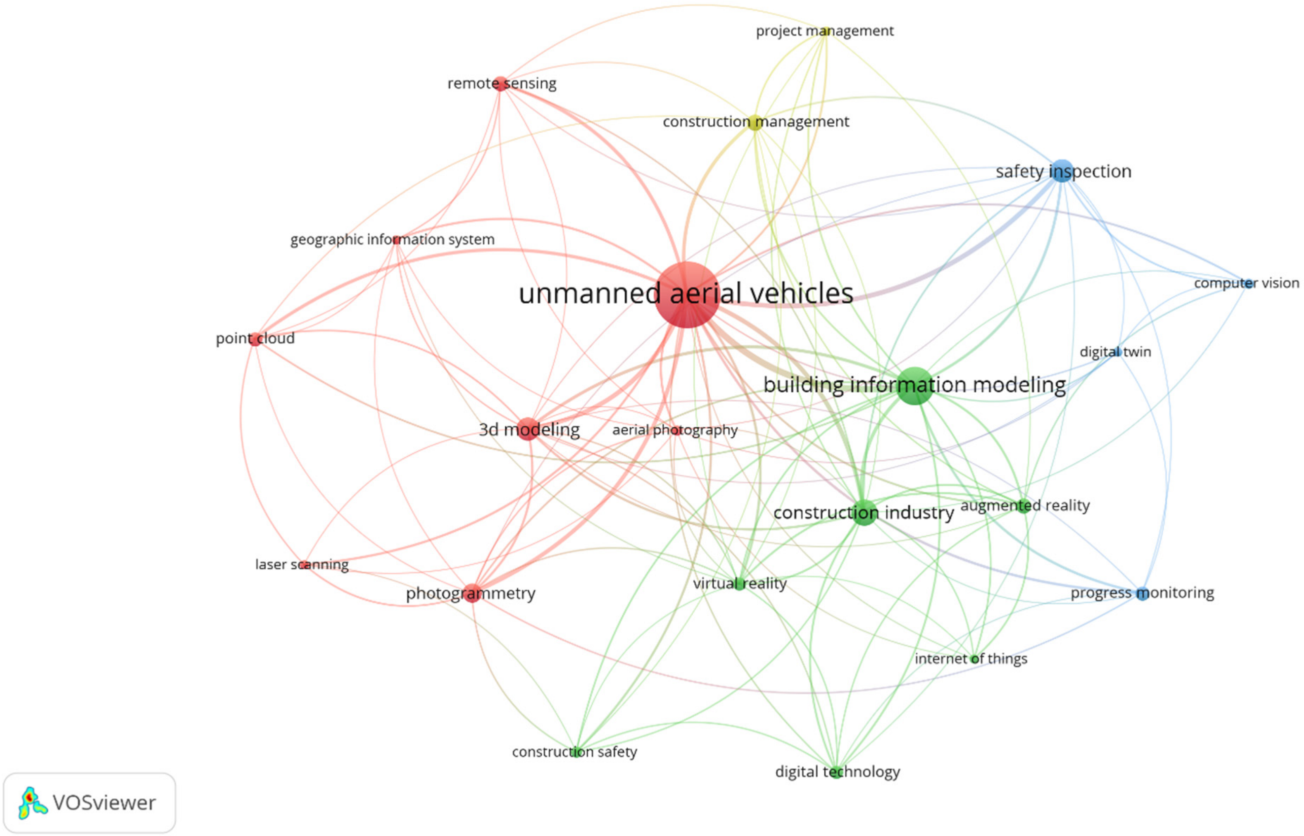


Figure 3. Co-occurrence network of UAV based on authors' keywords.

3.4.1. UAV Technology Cluster

UAVs denote the center of the red cluster and are firmly integrated with the point cloud, photogrammetry, remote sensing, and 3D modeling. They are less robustly connected with laser scanning, GIS, aerial photography, and structure-from-motion (SFM). This cluster concerns UAV technology as stand-alone equipment and the methods of processing data acquired from UAVs. The primary process of UAV implementation comprises data collection, reconstruction, simulation, and visualization [34]. UAVs obtain data by taking aerial images at different heights and tilt angles. The images must be overlapping for conversion into 2D/3D models [35]. This method is popularly labeled SFM photogrammetry. SFM has become more prevalent than traditional photogrammetry because it generates a point cloud using overlapping images without the need for predefined ground control points (GCPs) [36]. However, the 3D model should still be georeferenced via known GCPs to increase accuracy. In addition, this cluster evidences a correlation between remote sensing, GIS, and UAV. Freimuth et al. [36] have reported that the UAV is an established remote sensing and mapping tool. The acquired data can be used in GIS to create a digital elevation model (DEM) or a digital surface model (DSM) for spatial analysis [37,38].

3.4.2. Other Digital Technologies Cluster

This cluster reveals that UAVs have been integrated with other DTs, including BIM, AR, and VR. UAVs show the most established integration with BIM, and this outcome corresponds to BIM's stature as the pivotal software used in the construction industry [34]. Two approaches to UAV integration with other DTs are elucidated in this cluster: (1) UAVs are only integrated with BIM/XR/IoT, and (2) BIM functions as an intermediary between UAVs and XR (AR/VR). Using the first approach, UAVs visualize site conditions, and the acquired data were subsequently processed to construct an as-built 3D model. This model is then compared to an as-planned model generated from BIM [39,40]. A study by Wen and Kang [25] also developed a virtual construction in a real field environment captured in real-time by UAVs.

This novel approach can assist site planners, who can observe simulated projects on real sites. The second approach denotes an extension of the first type. The comparison of as-built and as-planned models is visualized as AR/VR and can be accessed in real-time through various devices by stakeholders [19]. This integration improves project performance in many aspects, including control, documentation, productivity, and communication between stakeholders.

3.4.3. Construction Management Cluster

This cluster combines yellow and blue clusters. UAVs have evolved in the last decade from being used for military purposes to equipment meant for civilian applications [41]. UAVs are used throughout the lifecycle of construction projects and are equipped with sensors (camera, GPS, or thermal sensor) and backend software. In the pre-construction phase, UAVs assist site planners in surveying site conditions [7,8]. At the construction stage, UAVs assist in tracking progress [10,11], performing safety inspections [12,13], tracking material movement, and improving communication between stakeholders. Finally, UAVs can perform building or bridge assessments in the post-construction phase, specifically in unreachable and unsafe areas [14,15]. Overall, UAV usage improves construction automation processes so that projects can progress more precisely and efficiently. This network analysis concludes that UAVs are most used in the application areas of safety inspection and construction monitoring.

3.5. UAV Integration Type Analysis

Figure 4 shows the percentage of integration of UAVs with other DTs based on 36 studied publications. Most studies (20 articles, 56%) integrated UAVs only with BIM. For example, the 3D as-built model obtained from UAV photogrammetry was compared to the 4D as-planned model in a BIM environment [34,42]. UAV integration with XR for purposes such as smart historic tourism [30], flight training simulators [43], and virtual site visits [44,45] followed, with eight articles (22%). BIM acted as an intermediary between UAVs and XR technologies, taking the third position with four articles (11%). To cite an example, off-site progress monitoring was conducted using MR technologies in one study to visualize a 3D model from UAVs and a 4D model from BIM [39,46]. UAV integration with GIS ranked fourth with three articles (8%) and was primarily used for spatial analysis [47]. IoT demonstrated minor integration with UAVs, with only one article (3%) regarding integrated UAVs with RFID to accomplish material tracking [48].

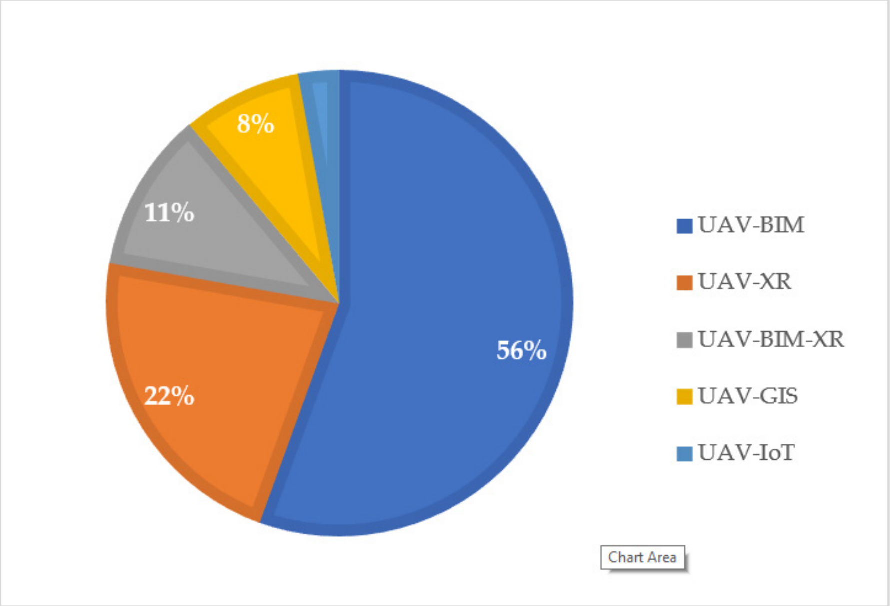


Figure 4. UAV integration with other DTs based on integration type.

3.6. Application Areas of UAV Integration with Other DTs

This literature review identified seven distinct application areas of UAV integration with other DTs in the construction domain, as presented in Table 5. These application areas denote the interpretations of the authors of this paper based on 36 studied publications. These application areas encompassed progress monitoring, historic building conservation, information management, construction safety, construction education, structural and infrastructure inspection, and transportation.

Table 5. Application areas of UAV integration with other DTs.

Application Area	Examples from Articles	Reference
Progress monitoring	Progress monitoring Tracking material on sites	[11,19,34,36,39,42,46,48–51]
Historic building conservation	3D modeling of historic building Spatial analysis Tourism potential analysis	[30,47,52–55]
Information management	Data collection of real-time as-built structure Real-time video streaming Decision-making assistance	[25,44,56–58]
Construction safety	Identification of potential hazard locations Construction safety inspection	[31,40,59,60]
Construction education	Virtual site visit Training simulation for inspection	[43,45,61,62]
Structural and infrastructure inspection	Building inspection Bridge inspection Post-earthquake building inspection	[14,63–65]
Transportation	Earthwork volume calculation Heavy equipment planning	[66,67]

Figure 5 elucidates that progress monitoring constituted the largest share of the 36 articles, with 11 papers (31%). Historic building conservation and information management came in second and third place with six (17%) and five (14%) articles, respectively. Four studies each were published on construction safety, construction education, and structural and infrastructure inspection and shared the same proportion at 11%. The transportation sector was positioned last with only two articles (5%).

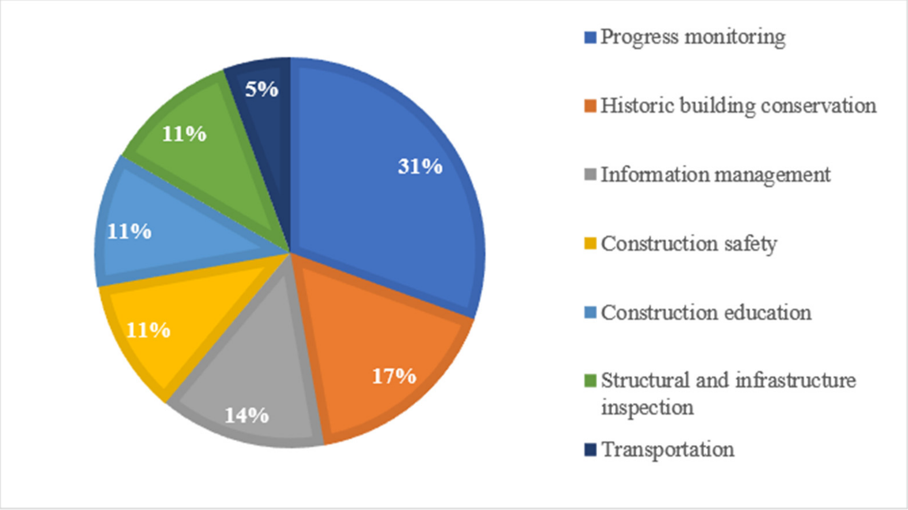


Figure 5. Flow diagram of the literature review and the analysis process.

3.6.1. Progress Monitoring

Eleven of the 36 evaluated articles (31%) studied UAV integration with other DTs to monitor construction progress. Conventional supervision is labor-intensive and requires a lot of time to collect and process data. Meanwhile, integrating UAVs with other DTs offers increased efficacy of time, accuracy, safety, and cost.

Most articles on progress monitoring reported similar procedures. First, the UAV acquired aerial images, then processed using photogrammetry software to create a 3D point cloud and a 3D as-built model. Subsequently, the 3D as-built model was compared to the 4D as-planned model in a BIM environment [34,42]. However, unlike other studies, Bognot et al. [11] used GIS to generate the as-planned model instead of BIM. The 3D as-built model was later aligned with the 4D as-planned model of the building formed from the extrusion of building elements for comparison.

After comparing as-built and as-planned structures, Alizadehsalehi and Yitmen [19] and Raimbaud et al. [46] developed progress monitoring visualizations for stakeholders in an MR environment, enabling the off-site supervision of construction. However, Alvares and Costa [39] asserted the limitations of progress monitoring through UAVs, citing the requirement of significant initial investments in developing monitoring procedures and training project teams on the procedures.

Four other studies focused on automation and optimization during progress monitoring using UAVs. Hamledari et al. [49] proposed a framework that utilized a 4D building information model and Swarm Intelligence to automatically generate UAV inspection mission plans that yielded complete coverage of inspection targets while minimizing flight duration. In congruence with a previous study, Freimuth and König [36] proposed automatic inspection planning to avoid obstacles near the inspected building. These last two studies employed 4D BIM semantic information to generate precise as-planned geometric models [50,51]. These models render a building from all points of view during the monitoring phase and offer more accurate element detection.

Unlike other investigations, Zhang et al. [48] addressed equipped UAVs with RFID to track construction material. UAVs were flown to detect the material construction dimensions at construction sites. The detected construction material dimensions were compared with previously obtained data to monitor the material supply chain.

3.6.2. Historic Building Conservation

A total of six papers (17%) discussed the preservation and reconstruction of historic building conservation. It analyzed their tourism potential by encompassing the 3D modeling of heritage buildings and the spatial analysis of the surrounding areas.

A study by Templin and Popielarczyk [30] proposed UAV usage to generate a 3D reconstruction model for the inventory of the historic Modlin water tower in Poland. Subsequently, the 3D model was utilized to build smart tourism services based on Web/AR/MR technology. Users can access information and attend virtual tours of the historic building. The Hatfaludy Mansion in Romania was also surveyed using UAVs [47]. The data acquired from UAVs formed the basis for a 3D model constructed in BIM to serve conservation and restoration purposes. The DEM and DSM of the mansion's surrounding areas were used for GIS's spatial analysis (terrain and accessibility analysis).

Four studies introduced Heritage Building Information Modeling (HBIM). First, Barrile et al. [52] surveyed the Sant Antonio Abate Church using UAV photogrammetry to reconstruct a 3D as-built model. Subsequently, the 3D model was segmented into individual elements and imported into Industry Foundation Classes (IFC) files to the BIM software. The technical geometry information, material description, and historical information were added to each element. The data becomes the basis of the building's conservation efforts. A similar procedure was also performed to build a 3D model of the Royal House of Bourbon Cellar in Italy [53] and Cortijo del Fraile's historic farmhouse in Spain [54]. Martínez-Carricondo et al. [54] extended this usage by developing the exterior and interior of the farmhouse. One study employed UAVs to survey Spain's large historic Isabel II dam [55]. The 3D points cloud was combined with historical information to generate an HBIM containing all relevant graphical, structural, and archaeological data.

3.6.3. Information Management

Of the 36 articles, five (14%) were related to information management. A study by Wen and Kang [25] designed an interface that mix scene of real views from UAVs and virtual views using AR technology. The interface provides access to real-time image streams from multiple devices. This proposed UAV-AR system can assist decision-makers and site planners in observing simulated projects at real sites. Yan et al. [44] performed a similar procedure, using AR technology to visualize real-time video from UAVs for off-site participants. The simulation system uses an AR algorithm named Simultaneous Localization and Mapping (SLAM) to render virtual building models in real-time and real-world environments. To et al.'s study [56] also highlighted the importance of UAVs for real-time structure scanning to serve data collection purposes for information management constructed on the Digital Twin Framework. Finally, Wang et al. [57] combined the 3D model from BIM and the terrain model obtained from UAV to generate an integrated model in a VR environment to present construction sites to stakeholders. However, Kim et al. [58] noted a gap hindering the use of UAV technology in the decision-making process. Their investigations elucidated the need for clear roles and responsibilities for key decision-makers (operators, observers, and inspectors) in UAV applications.

3.6.4. Construction Safety

Four of the 36 articles (11%) described UAV integration with other DTs for construction safety. According to Chen et al. [59], there are two approaches of UAVs and BIM incorporation in the domain of construction safety. First, UAVs may be used to visualize current site conditions in BIM to facilitate safety experts in identifying potential hazard locations. Second, BIM may be used to map construction sites and identify locations posing potential hazards. UAVs may then be deployed to inspect the implementation of safety management at construction sites. Alizadehsalehi et al. [40] applied the first approach in their study, using images acquired from UAVs to generate a 3D model in BIM. They then used this model to evaluate and redesign the safety system. Patel et al. [31] employed the second approach, comparing data captured by UAVs with the established safety rules based on BIM and Occupational Safety and Health Administration. Safety experts then analyzed the comparison results to generate mitigation strategies. Manzoor et al. [60] also utilized the second approach, using BIM for UAV flight planning and performing a safety inspection. They scheduled UAV flights on the construction site regularly to monitor and detect construction workers who were not wearing safety hats and belts.

3.6.5. Construction Education

The employment of UAVs in conjunction with other DTs for construction education was the subject of four of the 36 retrieved publications (11%). Massive UAV usage is anticipated in the Construction 4.0 age. It is thus crucial that civil engineering students are equipped with knowledge and skills regarding UAVs at universities. Vega et al. [61] presented an instructional design to teach UAV technology to university students. By the end of the course, students can: (1) fly UAVs, whether in simulation or the real field, (2) connect UAVs with computers to display flight variables, and (3) use a mathematical model to process the data acquired from UAVs.

In addition to teaching activities, some studies have developed learning tools that integrate UAVs with VR/AR. Albeaino et al. [43] explored a VR-based flight training simulator named DroneSim as an alternative to real-world drone-based building inspection training. DroneSIM was employed to improve construction students' UAV operation and flight training skills. Olayiwola et al. [45] developed a real-time virtual site visit that connected site personnel on construction sites and students in classrooms to enhance students' field knowledge and skills. These virtual site visits deployed UAVs to capture real-time conditions at the construction site and employed an AR device to communicate the images to students. Nevertheless, Sakib et al. [62] emphasized the need to understand better the effectiveness of flying UAVs in a VR environment. They contemplated the differences in the physiological conditions (performance, mental workload, and stress) of UAV operators flying UAVs in the real world and in a VR environment using wearable devices.

3.6.6. Structural and Infrastructure Inspection

Four of the 36 articles (11%) reported on UAV usage with other DTs for structural and infrastructure inspection. Three investigations mentioned in this study performed a structural inspection at the post-construction stage. Nguyen et al. [63] formulated a bridge inspection and maintenance framework comprising four major elements: data acquisition, data processing, BIM-based system, and MR-based inspection. Chen et al. [64] proposed an uncommon integration of UAVs with GIS to inspect building facades. Tan et al. [14] developed an automatic inspection method using UAVs and BIM to enhance automation in construction. They generated the coverage path planning using a Genetic Algorithm that optimized the UAV flight time. The fourth assessed article for this application area specifically conducted a structural inspection in post-earthquake conditions. Levine and Spencer [65] used UAV imagery, component identification, and damage evaluation available as tools on the BIM platform to analyze the post-earthquake safety of a designated building. The identified damage was then compared to its pre-earthquake structural conditions.

3.6.7. Transportation

Two of the 36 articles (5%) were related to transportation. One study conducted earthwork planning for excavators, while the other performed a productivity analysis of cable crane transportation. Kim et al. [66] integrated a UAV-based point cloud and BIM to review earthwork design and plan the earthwork for excavators. This method reduced the need for redesigning due to design errors and assisted site planners in developing an automated earthwork planning system. Wang et al. [67] developed an automated vision-based method of productivity analysis for cable crane transportation. The UAV-based 3D reconstruction of a crane bucket model was superimposed on a realistic scene using AR for vision-based model training at a construction site.

3.7. Technology Trends of UAV Integration with Other DTs

Based on 36 articles from the inclusion stage of the PRISMA protocol of this study, the authors interpreted the main technology trends of UAV integration with other DTs. The technologies were identified based on their contributions to encouraging automation and digitization toward the Construction 4.0 era. The identified technology trends included automated progress monitoring, automated UAV inspection planning, real-time video streaming, and the parametric model development of historic buildings.

3.7.1. Automated Progress Monitoring

Initially, UAVs were used to obtain an as-built 3D model that was later compared to an as-planned 4D model in a BIM environment. However, the automatic comparison of as-built 3D models acquired from UAVs into 4D BIM is still limited [68]. This matter discourages industry practitioners from implementing the integration of UAVs and BIM to monitor progress. Some of the evaluated papers developed a framework of automated progress monitoring based on a 3D model from UAVs in a BIM environment to resolve this issue.

Hamledari et al. [51,69] undertook a series of research initiatives to develop automated progress monitoring using the IFC format to integrate an as-built 3D model acquired from UAVs with an as-planned 4D model from BIM. The images taken by UAVs were processed into an IFC-based 3D model using the semantic information of building components from BIM. The model was then input into the BIM environment on which the comparison was made with as-planned 4D BIM. A 4D BIM updating technique developed by Hamledari et al. [69] was used to integrate the progress data into IFC-based 4D BIM. Braun et al. [50] created an identical principle for automated progress tracking, where a C#-based Windows Presentation Foundation software tool was specifically built for the 4D BIM updating technique. Progress can be documented regularly if automated progress monitoring is successfully applied. In turn, such consistent inputs can assist stakeholders in analyzing progress and making informed decisions.

3.7.2. Automated UAV Inspection Planning

Initially, UAVs were used to inspect defects in building surfaces. Phung et al. [70] investigated UAV usage to inspect building and bridge surfaces, and Jung et al. [71] presented UAV coverage path planning to inspect high-rise structures. However, such inspections were inefficiently implemented and were insufficiently automated as a pilot would manually operate the UAV to capture the Point of Interest.

Therefore, some scholars developed UAV flight path planning algorithms to advance automation. Such algorithms can generate a collision-free path in the targeted inspection areas. Some examples include the Genetic Algorithm [14], Firefly Algorithm [36], and Swarm Intelligence [49]. These algorithms plan UAV flights by taking into account flight paths that are non-repetitive and free from collisions, safe flying distances, limited UAV flight times, and camera specifications [14].

BIM strategically provides the primary input to these algorithms, such as inspection objectives and areas. BIM offers numerous advantages as the data source for the UAV flight planning algorithms. First, BIM offers geometric and semantic information about the structures. Inspectors can use this information to define their inspection objectives [72]. Inspectors can then extract the inspection target by filtering out non-inspected components from the BIM model [14]. Second, BIM provides spatial data of the structure so the algorithm can generate non-repetitive and collision-free flight paths and define UAVs' take-off and landing positions [14]. Third, BIM provides structure information based on time, commonly named the 4D model [36]. The algorithm can automatically generate discrete UAV flight plans according to the 4D BIM data every time an inspection is conducted.

Few case studies have implemented and validated the automatic UAV inspection method. Tan et al. [14] utilized BIM to obtain the areas requiring inspection and employed a Genetic Algorithm to generate UAV flight plans. The method was implemented in a laboratory building at Shen Zhen University. Freimuth and König [36] generated automatic inspection plans to avoid collisions using Dronecode Foundation's Software-in-the-Loop framework. Finally, Hamledari et al. [49] developed an automated inspection plan using 4D BIM and Swarm Intelligence to ensure the complete coverage of inspection targets and minimize flight time. The procedures and the software used by these studies differ, but their principal method is identical. Overall, UAV flight planning based on BIM encourages automation in inspection and delivers more time-efficient, accurate, and high-quality scrutiny compared to manual inspection [14].

3.7.3. Real-Time Video Streaming

Some studies have integrated UAVs with XR technology for simulation and communication purposes. For example, Wang et al. [57] created an integrated VR model of a construction site using BIM and a terrain model obtained through UAVs. Ji et al. [73] used AR technology to improve the UAV operator experience, previously limited to 2D displays. However, the process in these studies was not real-time: a time difference remained between UAV data collection and VR visualization.

Some studies have tackled this limitation by integrating UAVs and XR to develop real-time video streaming, which can offer many benefits. First, it allows more users to participate in simulations by transmitting the simulated scene to off-site devices in real-time [44]. Second, off-site users can interact with on-site construction workers and make informed and quick decisions [25]. Yan et al. [44] stated that three technologies must be integrated to actualize real-time video streaming: (1) SLAM for the real-time rendering of virtual building models in the real-world environment, (2) UAVs to capture real-world environments, and (3) telecommunications for the real-time data transmission of AR images to multiple devices (smartphones, tablets, and computers). Lastly, Olayiwola et al. [45] served an educational purpose by creating a real-time virtual site visit between engineering students in a classroom and on-site construction workers.

3.7.4. Parametric Model Development of Historic Building

In 1985, UNESCO established a conservation and preservation procedure for historic buildings [54]. One such process concerns a virtual reconstruction of a historic building. However, the absence of blueprints and complex architectural features make conservation efforts difficult [52]. A combination of UAV and BIM may be utilized to generate a 3D model encompassing graphical, structural, and archaeological data about the historic building to overcome this issue.

The first step involves capturing images using UAVs and conducting global-navigation satellite system surveys of GCPs. Nadiral and oblique photographs are obtained to improve the levels of detail and accuracy. Nadiral images capture the entire area, and oblique photographs display the fine details of the historic buildings [74,75]. Next, the captured images are processed through photogrammetry software using the SFM algorithm [76,77]. The generated point cloud is georeferenced using image geolocation data GCPs to increase accuracy [78]. Next, a mesh is built, and texture is applied to the mesh. Finally, the definitive point cloud is exported in the *.las format to BIM [55].

The point cloud in the *.las format is exported in BIM, using Autodesk ReCap. The point cloud is employed as a guide to creating objects for the parametric model [79]. Ultimately, the parametric objects are identified and archived in a library. The identification is manually performed because most historic building objects represent complex and non-standardized components [80]. This entire process is named HBIM. Once the 3D model is completed in HBIM, it is validated by comparing it with the dense point cloud obtained from UAV photogrammetry [81]. The 3D model may be textured at the next stage using specialized software such as Lumion to create a photorealistic appearance [55].

The parametric model has been developed, implemented, and validated with several historic buildings. For example, researchers reconstructed 3D exterior models of Sant Antonio Abate Church [52] and the House of Bourbon Cellar [53] in Italy. Martínez-Carricondo et al. [54] developed both the exterior and interior of a farmhouse. One study integrated UAV and BIM to build a 3D model of Spain's large and historic Isabel II dam [55].

4. Discussion

This section presents the predominant results of this systematic literature review. Figure 6 shows that the literature review yielded seven application areas and four technology trends of UAV integration with other DTs.

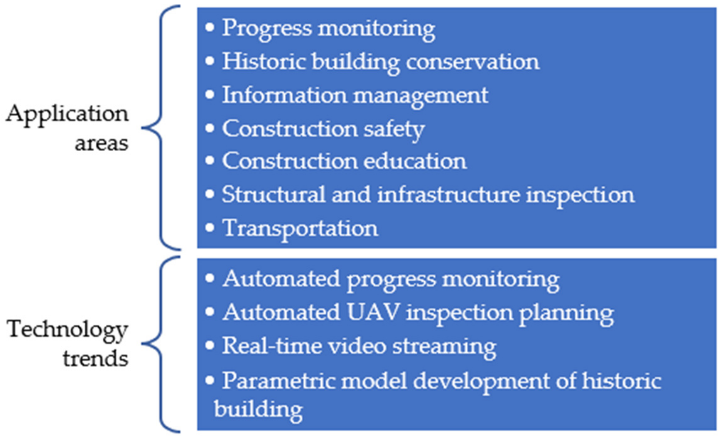


Figure 6. Identified application areas and technology trends of UAV integration with other DTs.

As Figure 6 elucidates, UAV technology has been integrated with other DTs for varied application areas in construction: progress monitoring, historic building conservation, information management, construction safety, construction education, structural and infrastructure inspection, and transportation. Progress monitoring (31%) represents the most used application area: eleven of the 36 articles investigated integrations of UAV and other DTs to monitor construction progress.

The literature review clarified the varied integration of UAVs with other DTs. UAVs are most frequently integrated with BIM and least integrated with IoT (RFID and sensing technologies). This outcome is in accordance with the BIM as focal technology that is highly interoperable with other DTs in the construction industry. Some studies visualized the results of UAV-BIM in the XR environment for visualization purposes. Finally, some studies integrated UAVs with GIS, primarily for the spatial analysis of a project's environment.

Time-series analyses revealed that UAV applications were launched in the construction industry over the last decade (2011–2021). The initial studies began in 2011 and were principally exploratory. Pioneering investigations of UAV integration with other DTs were introduced in 2014, and research in this domain increased significantly from 2017. Consequently, the leading technology trends of combining UAVs with other DTs were identified, including automated progress monitoring, automated UAV inspection planning, real-time video streaming, and the development of parametric models of historic buildings (Figure 6).

Most research has addressed the development of frameworks, procedures, and tools applied to specific case studies or simulations. The integration of UAVs with other DTs presents great potential for better data collection, processing, analysis, and visualization than traditional methods. It also fosters collaboration and communication between stakeholders. However, increased research initiatives are necessary (i.e., case study research) to validate existing frameworks, procedures, and tools. Most existing studies have used similar frameworks; however, their methods and tools have differed, and construction workers may be confused about methods that should be used in real-world scenarios. Hence, best practices and standardized procedures must be instituted for all application areas for the actual field implementations of UAV and other DT integrations.

Most existing studies have focused on the technical aspects. Only a few articles have addressed non-technical aspects such as communication, stakeholders, and human resources. These facets function pivotally in the successful integration of UAVs and other DTs. Some challenges of such non-technical factors include low familiarity of construction workers and no clear role and responsibilities of stakeholders in managing data acquired from the integration of UAVs and other DTs. In addition, construction workers must be equipped with knowledge about DTs to understand how to employ UAVs with other DTs. Finally, further research is required to determine the legal and financial aspects of integrating UAVs with other DTs at the national and construction firm levels.

5. Conclusions

This paper presented a comprehensive systematic literature review of the integration of UAVs with other DTs in anticipation of the emergent Construction 4.0 era. Unlike other reviews, this literature review grouped UAV integration with other DTs under application areas and further identified technology trends based on Construction 4.0 features (automation, digitization, interoperability, and real-time simulation). Based on the article selection using the PRISMA 2020 guidelines, 36 articles focusing on the integration of UAVs with other DTs became the foundation of this study. The outcomes of this study are expected to be the starting point in assisting construction researchers and professionals for further advancement of UAV usage in the construction domain.

A time-series analysis evidenced the significant increase in UAV research in the construction sector over the last decade (2011–2021). It started with exploratory studies of general UAV usage and UAV application as a stand-alone technology. Subsequently, research on UAV integration with other DTs for various application areas is rapidly growing. The country analysis revealed that the USA ranks first in this research domain with 12 articles (33%), followed by China with six articles (17%).

The statistical analysis of 36 articles that were obtained following the inclusion stage of the PRISMA protocol corresponded to seven of the application areas. In this context, progress monitoring received the most significant attention (31%), followed by historic building conservation (17%) and information management (14%). The evaluated articles identified two main approaches to UAV integration with other DTs: (1) UAVs are only integrated with BIM/GIS/XR/IoT, and (2) UAVs are integrated with BIM, and the result from BIM are visualized in XR. Most studies integrated UAVs with BIM (56%), followed by XR technologies (22%). Only one study investigated the integration of UAVs with RFID. Hence, the research field of UAV integration with IoT (RFID and sensing technologies) is still wide open for future research.

Regarding the technology trends of UAV integration with other DTs, automated progress monitoring, automated UAV inspection planning, real-time video streaming, and parametric model development of historic buildings were identified. The existing studies encompassing these technology trends focused on developing novel frameworks, procedures, and tools. These studies reveal the immense potential of the integration of UAVs with other DTs: productivity, accuracy, and documentation are enhanced for data management (collection, processing, analysis, and visualization), and collaboration and communication are encouraged between stakeholders. Nonetheless, further research is required to validate the postulated frameworks, procedures, and tools (i.e., case studies research). Accordingly, the standard procedures for UAV integration with other DTs at the national and construction firm levels can be established.

Most of the existing studies have focused on the technical aspects of the examined integrations. Further studies on the non-technical aspects of UAV integration with other DTs are necessary. For example, qualitative studies on construction workers' acceptance, preparedness, and abilities to use UAVs with other DTs are not yet explored. A comparison study on the integration of UAVs and other DTs with conventional methods has not yet been conducted. Likewise, the legal and financial aspects of UAV integration with other DTs at the national and company levels must also be examined.

Author Contributions: Conceptualization, T.S.N.R. and S.K.; methodology, T.S.N.R. and S.K.; validation, T.S.N.R. and S.K.; formal analysis, T.S.N.R. and S.K.; investigation, T.S.N.R.; resources, T.S.N.R.; data curation, T.S.N.R.; writing—original draft preparation, T.S.N.R.; writing—review and editing, T.S.N.R. and S.K.; supervision, S.K.; project administration, S.K.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MOE) (No. 2022R1A2C2005276).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ASCE	American Society of Civil Engineers
AR	Augmented Reality
BIM	Building Information Modeling
DEM	digital elevation model
DSM	digital surface model
DTs	digital technologies
XR	extended reality
GCPs	ground control points

GIS	Geographic Information System
IFC	Industry Foundation Classes
IoT	Internet of Things
MR	Mixed Reality
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RFID	radio frequency identification
SFM	structure from motion
SLAM	Simultaneous Localization and Mapping
UAV	Unmanned aerial vehicle
USA	United States of America
VR	Virtual Reality

References

1. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [CrossRef]
2. Dallasega, P.; Rauch, E.; Linder, C. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Comput. Ind.* **2018**, *99*, 205–225. [CrossRef]
3. Wong, J.K.W.; Ge, J.; He, S.X. Digitisation in facilities management: A literature review and future research directions. *Autom. Constr.* **2018**, *92*, 312–326. [CrossRef]
4. Perrier, N.; Bled, A.; Bourgault, M.; Cousin, N.; Danjou, C.; Pellerin, R.; Roland, T. Construction 4.0: A survey of research trends. *J. Inf. Technol. Constr.* **2020**, *25*, 416–437. [CrossRef]
5. Azhar, S. Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadersh. Manag. Eng.* **2011**, *11*, 241–252. [CrossRef]
6. Ma, Z.; Ren, Y. Integrated Application of BIM and GIS: An Overview. *Procedia Eng.* **2017**, *196*, 1072–1079. [CrossRef]
7. Siebert, S.; Teizer, J. Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system. *Autom. Constr.* **2014**, *41*, 1–14. [CrossRef]
8. Kwon, S.; Park, J.-W.; Moon, D.; Jung, S.; Park, H. Smart Merging Method for Hybrid Point Cloud Data using UAV and LIDAR in Earthwork Construction. *Procedia Eng.* **2017**, *196*, 21–28. [CrossRef]
9. Jiang, W.; Zhou, Y.; Ding, L.; Zhou, C.; Ning, X. UAV-based 3D reconstruction for hoist site mapping and layout planning in petrochemical construction. *Autom. Constr.* **2020**, *113*, 103137. [CrossRef]
10. Asadi, K.; Suresh, A.K.; Ender, A.; Gotad, S.; Maniyar, S.; Anand, S.; Noghabaei, M.; Han, K.; Lobaton, E.; Wu, T. An integrated UGV-UAV system for construction site data collection. *Autom. Constr.* **2020**, *112*, 103068. [CrossRef]
11. Bognot, J.R.; Candido, C.G.; Blanco, A.; Montelibano, J.R.Y. Building Construction Progress Monitoring Using Unmanned Aerial System (Uas), Low-Cost Photogrammetry, And Geographic Information System (GIS). *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *IV-2*, 41–47. [CrossRef]
12. Narumi, T.; Aoki, S.; Muramatsub, F. Indoor Visualization Experiments at Building Construction Site Using High Safety UAV. In Proceedings of the International Symposium on Automation and Robotics in Construction, Banff, AB, Canada, 21–24 May 2019; pp. 961–966. [CrossRef]
13. Gheisari, M.; Rashidi, A.; Esmaeili, B. Using Unmanned Aerial Systems for Automated Fall Hazard Monitoring. In *Construction Research Congress 2018*; American Society of Civil Engineers: New Orleans, LA, USA, 2018; pp. 62–72. [CrossRef]
14. Tan, Y.; Li, S.; Liu, H.; Chen, P.; Zhou, Z. Automatic inspection data collection of building surface based on BIM and UAV. *Autom. Constr.* **2021**, *131*, 103881. [CrossRef]
15. Aliyari, M.; Ashrafi, B.; Ayele, Y.Z. Hazards identification and risk assessment for UAV–assisted bridge inspections. *Struct. Infrastruct. Eng.* **2022**, *18*, 412–428. [CrossRef]
16. Zhou, J.; Lee, I.; Thomas, B.; Menassa, R.; Farrant, A.; Sansome, A. In-Situ Support for Automotive Manufacturing Using Spatial Augmented Reality. *Int. J. Virtual Real.* **2012**, *11*, 33–41. [CrossRef]
17. Hou, L.; Wang, X.; Bernold, L.; Love, P.E.D. Using Animated Augmented Reality to Cognitively Guide Assembly. *J. Comput. Civ. Eng.* **2013**, *27*, 439–451. [CrossRef]
18. Chi, H.-L.; Kang, S.-C.; Wang, X. Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Autom. Constr.* **2013**, *33*, 116–122. [CrossRef]
19. Alizadehsalehi, S.; Yitmen, I. Digital twin-based progress monitoring management model through reality capture to extended reality technologies (DRX). *Smart Sustain. Built Environ.* **2021**. [CrossRef]
20. Khan, A.; Sepasgozar, S.; Liu, T.; Yu, R. Integration of BIM and Immersive Technologies for AEC: A Scientometric-SWOT Analysis and Critical Content Review. *Buildings* **2021**, *11*, 126. [CrossRef]
21. Kitchenham, B.; Charters, S. *Guidelines for Performing Systematic Literature Reviews in Software Engineering*; Version 2.3; EBSE Technical Report EBSE-2007-01; School of Computer Science and Mathematics, Keele University: Keele, UK; University of Durham: Durham, UK, 2007.

22. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, 105906. [CrossRef]
23. Gheisari, M.; Irizarry, J.; Walker, B.N. UAS4SAFETY: The Potential of Unmanned Aerial Systems for Construction Safety Applications. In *Construction Research Congress 2014*; American Society of Civil Engineers: Atlanta, GA, USA, 2014; pp. 1801–1810. [CrossRef]
24. Irizarry, J.; Gheisari, M.; Walker, B.N. Usability assessment of drone technology as safety inspection tools. *J. Inf. Technol. Constr. (ITcon)* **2012**, *17*, 194–212. Available online: http://www.itcon.org/2012/12 (accessed on 23 February 2022).
25. Wen, M.-C.; Kang, S.-C. Augmented Reality and Unmanned Aerial Vehicle Assist in Construction Management. In *Computing in Civil and Building Engineering*; American Society of Civil Engineers: Orlando, FL, USA, 2014; pp. 1570–1577. [CrossRef]
26. Kim, H.; Lee, J.; Ahn, E.; Cho, S.; Shin, M.; Sim, S.-H. Concrete Crack Identification Using a UAV Incorporating Hybrid Image Processing. *Sensors* **2017**, *17*, 2052. [CrossRef] [PubMed]
27. Entrop, A.G.; Vasenev, A. Infrared drones in the construction industry: Designing a protocol for building thermography procedures. *Energy Procedia* **2017**, *132*, 63–68. [CrossRef]
28. Tomita, H.; Takabatake, T.; Sakamoto, S.; Arisumi, H.; Kato, S.; Ohgusu, Y. Development of UAV Indoor Flight Technology for Building Equipment Works. In Proceedings of the International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, 28 June–1 July 2017; pp. 452–457. [CrossRef]
29. Mustaffa, A.A.; Hasmori, M.F.; Sarif, A.S.; Ahmad, N.F.; Zainun, N.Y. The Use of UAV in Housing Renovation Identification: A Case Study at Taman Manis 2. *IOP Conf. Series: Earth Environ. Sci.* **2018**, *140*, 012003. [CrossRef]
30. Templin, T.; Popielarczyk, D. The Use of Low-Cost Unmanned Aerial Vehicles in the Process of Building Models for Cultural Tourism, 3D Web and Augmented/Mixed Reality Applications. *Sensors* **2020**, *20*, 5457. [CrossRef] [PubMed]
31. Patel, T.; Suthar, V.; Bhatt, N. Application of Remotely Piloted Unmanned Aerial Vehicle in Construction Management. In *Recent Trends in Civil Engineering*; Pathak, K.K., Bandara, J.M.S.J., Agrawal, R., Eds.; Lecture Notes in Civil Engineering; Springer: Singapore, 2021; Volume 77, pp. 319–329. [CrossRef]
32. Melo, R.; Costa, D.B.; Álvares, J.; Irizarry, J. Applicability of unmanned aerial system (UAS) for safety inspection on construction sites. *Saf. Sci.* **2017**, *98*, 174–185. [CrossRef]
33. van Eck, N.J.; Waltman, L. *Visualizing Bibliometric Networks, In Measuring Scholarly Impact: Methods and Practice*; Ding, Y., Rousseau, R., Wolfram, D., Eds.; Springer: Cham, Switzerland, 2014; pp. 285–320.
34. Duarte-Vidal, L.; Herrera, R.F.; Atencio, E.; Rivera, F.M.-L. Interoperability of Digital Tools for the Monitoring and Control of Construction Projects. *Appl. Sci.* **2021**, *11*, 10370. [CrossRef]
35. Fernández-Hernandez, J.; Gonzalezaguilera, D.; Rodríguez-Gonzálvez, P.; Mancerataboada, J. Image-Based Modelling from Unmanned Aerial Vehicle (UAV) Photogrammetry: An Effective, Low-Cost Tool for Archaeological Applications: Image-Based Modelling from UAV Photogrammetry. *Archaeometry* **2015**, *57*, 128–145. [CrossRef]
36. Freimuth, H.; Müller, J.; Konig, M. Simulating and Executing UAV-Assisted Inspections on Construction Sites. In Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 28 June–1 July 2017; pp. 647–654. [CrossRef]
37. Hugenholtz, C.; Brown, O.; Walker, J.; Barchyn, T.; Nesbit, P.; Kucharczyk, M.; Myshak, S. Spatial Accuracy of UAV-Derived Orthoimagery and Topography: Comparing Photogrammetric Models Processed with Direct Geo-Referencing and Ground Control Points. *Geomatica* **2016**, *70*, 21–30. [CrossRef]
38. Sestras, P.; Salagean, T.; Bilasco, S.; Bondrea, M.V.; Nas, S.; Fountas, S.; Spalevic, V.; Cimpeanu, S.M. Prospect of a Gis Based Digitization and 3d Model for a Better Management and Land use in a Specific Micro-Areal for Crop Trees. *Environ. Eng. Manag. J.* **2019**, *18*, 1269–1277. [CrossRef]
39. Álvares, J.; Costa, D.B. Construction Progress Monitoring Using Unmanned Aerial System and 4D BIM. In Proceedings of the 27th Annual Conference of the International. Grupo para Construção Enxuta (IGLC), Dublin, Ireland, 3–5 July 2019; pp. 1445–1456. [CrossRef]
40. Alizadehsalehi, S.; Yitmen, I.; Celik, T.; Arditi, D. The effectiveness of an integrated BIM/UAV model in managing safety on construction sites. *Int. J. Occup. Safe. Ergon.* **2020**, *26*, 829–844. [CrossRef]
41. Zhou, S.; Gheisari, M. Unmanned aerial system applications in construction: A systematic review. *Constr. Innov.* **2018**, *18*, 453–468. [CrossRef]
42. Tian, J.; Luo, S.; Wang, X.; Hu, J.; Yin, J. Crane Lifting Optimization and Construction Monitoring in Steel Bridge Construction Project Based on BIM and UAV. *Adv. Civ. Eng.* **2021**, *2021*, 5512229. [CrossRef]
43. Albeaino, G.; Eiris, R.; Gheisari, M.; Issa, R.R. DroneSim: A VR-based flight training simulator for drone-mediated building inspections. *Constr. Innov.* **2021**. [CrossRef]
44. Yan, L.; Fukuda, T.; Yabuki, N. Intergrating UAV Development Technology with Augmented Reality Toward Landscape Tele-Simulation. In Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia, Osaka, Japan, 22–24 April 2019; Volume 1, pp. 423–432.
45. Olayiwola, J.; Akanmu, A.; Moghimi, Z. Enhancing Virtual Site Visits via Bi-Directional Coordination between Construction Sites and Classrooms. In *Construction Research Congress*; American Society of Civil Engineers: Tempe, AZ, USA, 2020; pp. 829–837. [CrossRef]

46. Raimbaud, P.; Lou, R.; Merienne, F.; Danglade, F.; Figueroa, P.; Hernandez, J.T. BIM-based Mixed Reality Application for Supervision of Construction. In Proceedings of the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Osaka, Japan, 23–27 March 2019; pp. 1903–1907. [CrossRef]
47. Sestras, P.; Roșca, S.; Bilașco, Ș.; Naș, S.; Buru, S.M.; Kovacs, L.; Spalević, V.; Sestras, A.F. Feasibility Assessments Using Unmanned Aerial Vehicle Technology in Heritage Buildings: Rehabilitation-Restoration, Spatial Analysis and Tourism Potential Analysis. *Sensors* **2020**, *20*, 2054. [CrossRef]
48. Zhang, S.; Bogus, S.M.; Lippitt, C.D.; Sprague, J.E. Geospatial Technologies for Collecting Construction Material Information. In *Construction Research Congress*; American Society of Civil Engineers: New Orleans, LA, USA, 2018; pp. 660–669. [CrossRef]
49. Hamledari, H.; Davari, S.; Sajedi, S.O.; Zangeneh, P.; McCabe, B.; Fischer, M. UAV Mission Planning Using Swarm Intelligence and 4D BIMs in Support of Vision-Based Construction Progress Monitoring and As-Built Modeling. In *Construction Research Congress 2018*; American Society of Civil Engineers: New Orleans, LA, USA, 2018; pp. 43–53. [CrossRef]
50. Braun, A.; Tuttas, S.; Stilla, U.; Borrmann, U.S.A.A. Process- and Computer Vision-based Detection of As-Built Components on Construction Sites. In Proceedings of the International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, 28 June–1 July 2018; pp. 662–668. [CrossRef]
51. Hamledari, H.; Davari, S.; Azar, E.R.; McCabe, B.; Flager, F.; Fischer, M. UAV-Enabled Site-to-BIM Automation: Aerial Robotic- and Computer Vision-Based Development of As-Built/As-Is BIMs and Quality Control. In *Construction Research Congress 2018*; American Society of Civil Engineers: New Orleans, LA, USA, 2018; pp. 336–346. [CrossRef]
52. Barrile, V.; Fotia, A.; Candela, G.; Bernardo, E. Integration Of 3d Model From Uav Survey In Bim Environment. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W11*, 195–199. [CrossRef]
53. Brutto, M.L.; Iuculano, E.; Giudice, P.L. Integrating Topographic, Photogrammetric and Laser Scanning Techniques For A Scan-To-Bim Process. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *XLIII-B2-2021*, 883–890. [CrossRef]
54. Martínez-Carricondo, P.; Carvajal-Ramírez, F.; Yero-Paneque, L.; Agüera-Vega, F. 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). *Build. Res. Inf.* **2020**, *48*, 140–159. [CrossRef]
55. Martínez-Carricondo, P.; Carvajal-Ramírez, F.; Yero-Paneque, L.; Agüera-Vega, F. Combination of HBIM and UAV photogrammetry for modelling and documentation of forgotten heritage. Case study: Isabel II dam in Níjar (Almería, Spain). *Heritage Sci.* **2021**, *9*, 1–15. [CrossRef]
56. To, A.; Liu, M.; Hairul, M.H.B.M.; Davis, J.G.; Lee, J.S.A.; Hesse, H.; Nguyen, H.D. Drone-Based AI and 3D Reconstruction for Digital Twin Augmentation. In *International Conference on Human-Computer Interaction*; Springer: Cham, Switzerland, 2021; pp. 511–529. [CrossRef]
57. Wang, K.-C.; Gao, R.-J.; Tung, S.-H.; Chou, Y.-H. Improving Construction Demonstrations by Integrating BIM, UAV, and VR. In Proceedings of the International Symposium on Automation and Robotics in Construction, Kitakyushu, Japan, 26–30 October 2020; pp. 1–7. [CrossRef]
58. Kim, S.; Irizarry, J.; Kanfer, R. Multilevel Goal Model for Decision-Making in UAS Visual Inspections in Construction and Infrastructure Projects. *J. Manag. Eng.* **2020**, *36*, 04020036. [CrossRef]
59. Chen, Y.; Zhang, J.; Min, B. Applications of BIM And UAV To Construction Safety. In Proceedings of the 7th International Construction Conference Jointly with the Construction Research Congress (CRC 2019), Laval, QC, Canada, 12–15 June 2019.
60. Manzoor, B.; Othman, I.; Pomares, J.C.; Chong, H.-Y. A Research Framework of Mitigating Construction Accidents in High-Rise Building Projects via Integrating Building Information Modeling with Emerging Digital Technologies. *Appl. Sci.* **2021**, *11*, 8359. [CrossRef]
61. Vega, L.F.L.; Lopez-Neri, E.; Arellano-Muro, C.A.; Gonzalez-Jimenez, L.E.; Ghommam, J.; Carrasco-Navarro, R. UAV Flight Instructional Design for Industry 4.0 based on the Framework of Educational Mechatronics. In Proceedings of the IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, Singapore, 19–21 September 2020; pp. 2313–2318. [CrossRef]
62. Sakib, M.; Chaspari, T.; Ahn, C.; Behzadan, A. An Experimental Study of Wearable Technology and Immersive Virtual Reality for Drone Operator Training. In Proceedings of the 27th International Workshop on Intelligent Computing in Engineering, Online, 1–4 July 2020.
63. Nguyen, D.-C.; Nguyen, T.-Q.; Jin, R.; Jeon, C.-H.; Shim, C.-S. BIM-based mixed-reality application for bridge inspection and maintenance. *Constr. Innov.* **2021**. [CrossRef]
64. Chen, K.; Reichard, G.; Akanmu, A.; Xu, X. Geo-registering UAV-captured close-range images to GIS-based spatial model for building façade inspections. *Autom. Constr.* **2020**, *122*, 103503. [CrossRef]
65. Levine, N.M.; Spencer, B.F. Post-Earthquake Building Evaluation Using UAVs: A BIM-Based Digital Twin Framework. *Sensors* **2022**, *22*, 873. [CrossRef] [PubMed]
66. Kim, J.; Lee, S.; Seo, J.; Lee, D.-E.; Choi, H. The Integration of Earthwork Design Review and Planning Using UAV-Based Point Cloud and BIM. *Appl. Sci.* **2021**, *11*, 3435. [CrossRef]
67. Wang, D.; Wang, X.; Ren, B.; Wang, J.; Zeng, T.; Kang, D.; Wang, G. Vision-Based Productivity Analysis of Cable Crane Transportation Using Augmented Reality–Based Synthetic Image. *J. Comput. Civ. Eng.* **2022**, *36*, 04021030. [CrossRef]
68. Leite, F.; Cho, Y.; Behzadan, A.H.; Lee, S.; Choe, S.; Fang, Y.; Akhavian, R.; Hwang, S. Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry. *J. Comput. Civ. Eng.* **2016**, *30*, 04016035. [CrossRef]

69. Hamledari, H.; McCabe, B.; Davari, S.; Shahi, A. Automated Schedule and Progress Updating of IFC-Based 4D BIMs. *J. Comput. Civ. Eng.* **2017**, *31*, 04017012. [CrossRef]
70. Phung, M.D.; Quach, C.H.; Dinh, T.H.; Ha, Q. Enhanced discrete particle swarm optimization path planning for UAV vision-based surface inspection. *Autom. Constr.* **2017**, *81*, 25–33. [CrossRef]
71. Jung, S.; Song, S.; Youn, P.; Myung, H. Multi-Layer Coverage Path Planner for Autonomous Structural Inspection of High-Rise Structures. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*; IEEE: Madrid, Spain, 2018; pp. 1–9. [CrossRef]
72. Bolourian, N.; Hammad, A. LiDAR-equipped UAV path planning considering potential locations of defects for bridge inspection. *Autom. Constr.* **2020**, *117*, 103250. [CrossRef]
73. Ji, X.; Xiang, X.; Hu, T. Data-driven augmented reality display and operations for UAV ground stations. In Proceedings of the 2017 6th Data Driven Control and Learning Systems (DDCLS), Chongqing, China, 26–27 May 2017; pp. 557–560. [CrossRef]
74. Nesbit, P.R.; Hugenholtz, C.H. Enhancing UAV–SfM 3D Model Accuracy in High-Relief Landscapes by Incorporating Oblique Images. *Remote Sens.* **2019**, *11*, 239. [CrossRef]
75. Jiang, S.; Jiang, W. Efficient structure from motion for oblique UAV images based on maximal spanning tree expansion. *ISPRS J. Photogramm. Remote Sens.* **2017**, *132*, 140–161. [CrossRef]
76. Fonstad, M.A.; Dietrich, J.T.; Courville, B.C.; Jensen, J.L.; Carbonneau, P.E. Topographic structure from motion: A new development in photogrammetric measurement: Topographic Structure from Motion. *Earth Surf. Process. Landforms* **2012**, *38*, 421–430. [CrossRef]
77. Westoby, M.; Brasington, J.; Glasser, N.F.; Hambrey, M.J.; Reynolds, J.M. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* **2012**, *179*, 300–314. [CrossRef]
78. Agüera-Vega, F.; Carvajal-Ramírez, F.; Martínez-Carricondo, P. Assessment of photogrammetric mapping accuracy based on variation ground control points number using unmanned aerial vehicle. *Measurement* **2017**, *98*, 221–227. [CrossRef]
79. Rodríguez-Moreno, C.; Reinoso-Gordo, J.F.; Rivas-López, E.; Gómez-Blanco, A.; Ariza-López, F.J.; Ariza-López, I. From point cloud to BIM: An integrated workflow for documentation, research and modelling of architectural heritage. *Surv. Rev.* **2018**, *50*, 212–231. [CrossRef]
80. Dore, C.; Murphy, M. Current State of the Art Historic Building Information Modelling. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-2/W5*, 185–192. [CrossRef]
81. Adami, A.; Scala, B.; Spezzoni, A. Modelling and Accuracy In A Bim Environment For Planned Conservation: The Apartment Of Troia Of Giulio Romano. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-2/W3*, 17–23. [CrossRef]