remote sensing

Review

InfraRed Thermography and 3D-Data Fusion for Architectural Heritage: A Scoping Review

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Abstract: Comprehensive documentation is the foundation of effective conservation, repair and maintenance (CRM) practices for architectural heritage. In order to diagnose historic buildings and inform decision making, a combination of multi-disciplinary surveys is fundamental to understanding a building's heritage and performance. Infrared thermography (IRT), a non-contact, non-invasive and non-destructive imaging technique, allows both qualitative and quantitative assessments of temperature to be undertaken. However, the inherent low spatial resolution of thermal imaging has led recent work to fuse thermographic and geometric data for the accurate 3D documentation of architectural heritage. This paper maps the scope of this emerging field to understand the application of IRT and 3D-data fusion (IRT-3DDF) for architectural heritage. A scoping review is undertaken to systematically map the current literature and determine research gaps and future trends. Results indicate that the increasing availability of thermal cameras and advances in photogrammetric software are enabling thermal models to be generated successfully for the diagnosis and holistic management of architectural heritage. In addition, it is evident that IRT-3DDF provides several opportunities for additional data integration, historic building information modelling (H-BIM) and temporal analysis of historic buildings. Future developments are needed to transform IRT-3DDF findings into actionable insights and to apply IRT-3DDF to pressing climate-related challenges, such as energy efficiency, retrofitting and thermal comfort assessments.

Keywords: infrared thermography (IRT); close-range photogrammetry; structure-from-motion (SfM); terrestrial laser scanning (TLS); data fusion; architectural heritage; scoping review

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1. Introduction

Comprehensive documentation is the foundation of effective conservation, repair and maintenance (CRM) strategies for architectural heritage. Encapsulated by variability and vernacularism, the coordinated appraisal of architectural heritage is fundamental to the determination of appropriate restoration and management practices. By utilising a holistic, multi-scale, multi-disciplinary approach to heritage documentation, conservators can make informed decisions regarding a historic building whilst maintaining its cultural value and significance [1–4]. To address the inherent complexity of building diagnostics and decision making, the collection of geomatic data at a project's inception has become a recognised pre-requisite, with complimentary geometric and radiometric surveys allowing the behaviour of a heritage asset to be better understood [5]. From this cornerstone, the incorporation of additional scientific and cultural investigations can be undertaken to aid building diagnostics and inform effective CRM practices.

Infrared thermography (IRT), a non-invasive, non-contact and non-destructive testing (NDT) technique, has become an established tool for building diagnostics, central to the assessment of an existing building's thermal leakages, energy performance and thermal comfort [6,7]. Capable of producing rapid, real-time and easily interpretable measurements of a building's thermal signature, IRT provides information on the infrared radiation emitted by objects above absolute zero, allowing for qualitative and quantitative assessments of temperature differences [8,9]. By capturing 2D images from a thermal infrared (TIR) camera, the results can be transformed from an electronic signal into a spectrum of temperature values, enabling the analysis of a building's structural integrity, material decay and heat transfer [10–12]. Notably, the application of IRT for cultural heritage has enabled the identification of historical construction techniques, materials and subsuperficial structures [13,14]; the assessment of murals, architectural heritage and archaeological sites [15–17]; and cleaning, repair or consolidation practices [18,19].

Whilst IRT has demonstrated its competency as a stand-alone NDT technique, a growing body of research is looking to exploit emerging photogrammetric computer vision and surveying engineering techniques to fuse complementary 2D- and 3D-NDT datasets of historic buildings [6,7]. Over the past two decades, the generation of 3D models from structure-from-motion photogrammetry (SfM) and terrestrial laser scanning (TLS) has become an established process for heritage documentation, fusing spectral and spatial data to generate digital representations of built assets. Data fusion, as defined by [20], is the process of combining datasets of varying source (sensor) and resolution into a unified product. Data fusion research has looked to classify 2D- and 3D-data fusion through purpose-, data- and dimension-based levels [20]; outline applications and opportunities for heritage documentation [21–23]; and demonstrate the integration of additional NDT datasets for heritage diagnostics [3,24–26]. The fusion of radiometric and geometric data for architectural heritage bolsters their individual use, enabling interpretations of complex buildings to be made with greater objectivity [27].

Conceptualised in Figure 1, infrared thermography 3D-data fusion (IRT-3DDF) research has begun to demonstrate efficacy in the AEC industry [28–31], with studies looking to overcome the inherent low spatial resolution of thermal imaging by developing methods that correct image distortions, identify common features and register images to existing reality-based surveys [11,32,33]. This has resulted in several studies demonstrating successful thermal modelling approaches applied to energy performance [30], 4D-thermal BIM [34], and thermal cloud segmentation [35]. In addition, several studies have utilised historic buildings for IRT-3DDF, albeit doing so without consideration for their cultural value or significance [10,35,36]. As historic buildings present significant challenges in terms of architectural, structural and material variability, the analysis of specific cases relating to architectural heritage is needed to evaluate IRT-3DDF effectively. Whilst 3D-data fusion has been outlined by [3,20,21,26], a systematic review of data fusion methods and applications is necessary, notably with a focus on the integration of IRT into a singular interpretable product. Similarly, existing IRT review studies have yet to comprehensively explore 3D thermal data for architectural heritage and CRM practices [7,9,18,37,38].

1.1. Aims and Objectives

This paper reviews the existing literature on IRT-3DDF for architectural heritage by undertaking a scoping review to answer the following research question. How can IRT-3DDF advance building diagnostics and inform the conservation, repair and maintenance (CRM) of architectural heritage? A scoping review is chosen for its effectiveness in synthesising knowledge to not only assess the breadth of a field of research, but to enable research gaps and future trends to be identified. A scoping review protocol (PRISMA-ScR) [39] shall be adopted with the following objectives:

1. Undertake a systematic literature search for IRT-3DDF;
2. Undertake initial bibliometric analysis for the scoping literature;
3. Chart the scoping literature to underpin an accompanying thematic analysis of research gaps and emerging trends within IRT-3DDF.

This review shall look to provide professionals and researchers with avenues of exploration for the continued development of IRT-3DDF methods; applications for CRM-related IRT-3DDF outputs; and the identification of parallel fields to monitor the continued advancement of IRT-3DDF. In addition, this paper looks to demonstrate the suitability of scoping reviews for multi-disciplinary research, with particular attention given to the adoption of an a priori protocol for evidence synthesis.

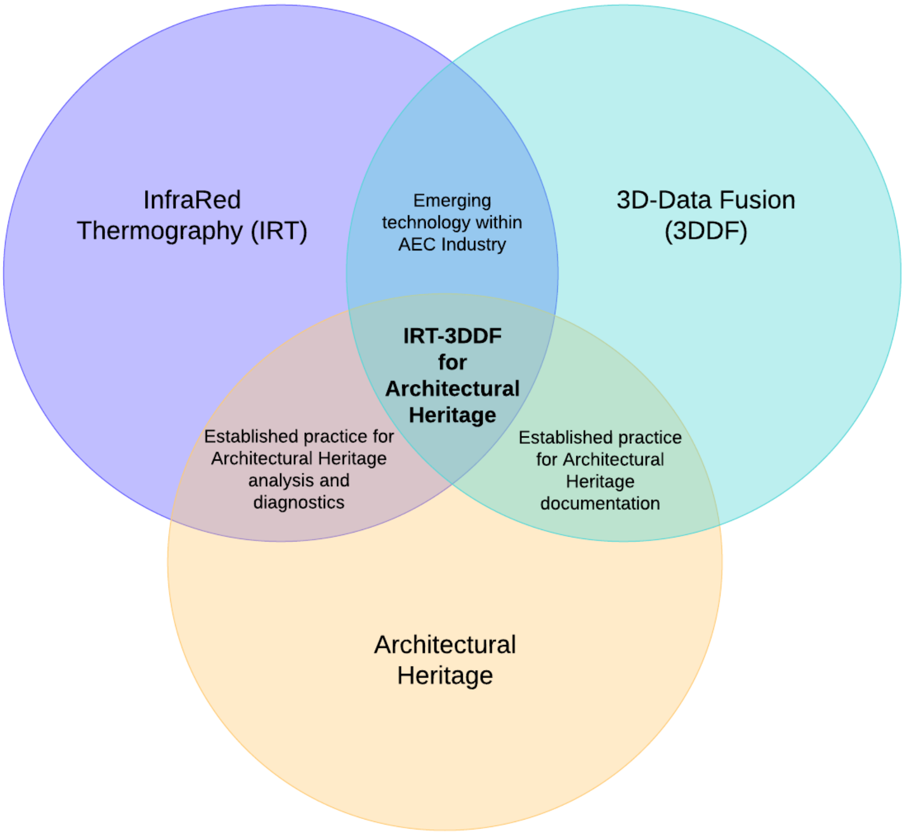

Figure 1. Mapping the inter-connectivity of infrared thermography (IRT), 3D-data fusion (3DDF) and architectural heritage research.

1.2. Paper Structure

This paper is structured as follows: Section 2 outlines the scoping review methodology and the process of the PRISMA-ScR protocol. Section 3 outlines the results of the scoping review and bibliometric analysis. Section 4 undertakes a thematic analysis of the data charting, summarising the scoping literature. Finally, Section 5 discusses the scoping review, determines its effectiveness in answering the research question and highlights future considerations for IRT-3DDF.

2. Materials and Methods

The materials and methods section has two distinct objectives: (1) to define a scoping review and outline its rationale for IRT-3DDF; and (2) to present the application of the PRISMA-ScR protocol by the reviewers.

2.1. Scoping Review: Overview

2.1.1. Context

Scoping reviews, or scoping studies, allow reviewers to map the breadth of a body of research by synthesising the knowledge of methodologies and applications within a particular field. Scoping reviews have gained traction as a ‘reconnaissance’ review style suitable for the analysis of both established and emerging fields, allowing conceptual boundaries to be discovered and delineated [40]. Scoping reviews are of particular benefit for the following cases: (1) fields have yet to be comprehensively reviewed; (2) the scope of the field is not yet understood; (3) the field of research is inherently multi-disciplinary; or

(4) as a pre-requisite for a future systematic review [41]. In the seminal work on scoping reviews, Arksey and O'Malley [42] outlined six stages that define scoping reviews. These include the following:

- **Stage 1:** Identifying research questions;
- **Stage 2:** Systematic literature search for relevant studies;
- **Stage 3:** Study selection through defined inclusion and exclusion criteria;
- **Stage 4:** Data charting;
- **Stage 5:** Collating, summarising, and reporting results;
- **Stage 6 (Optional):** Stakeholder consultation.

Further enhanced by Levac et al. [43], the process for scoping reviews has been clearly differentiated from systematic reviews with the extension of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Scoping Review (ScR) protocol. PRISMA-ScR, an a priori review protocol, provides a rigorous and replicable review method for the execution of a comprehensive scoping review, helping researchers, policymakers and professionals to gain clarity on review processes [39].

2.1.2. Rationale

Research looking to delineate scoping reviews has looked to clarify terms, definitions and methodologies to separate scoping reviews from similar review styles [41]. A scoping review's primary focus is to examine the extent, range and nature of a body of research, which in turn helps clarify the direction and trajectory of a field [42]. With this in mind, IRT-3DDF provides an emerging field yet to be comprehensively reviewed, inherently multi-disciplinary in nature and requiring investigation with a broad research question capable of determining scope [39,44]. Furthermore, the ability for scoping reviews to be iterative in their review process lends to fields where the scope is purposefully refined by reviewers over the course of the review process ([42], p. 22, [39], Appendix).

Similarly, scoping reviews and evidence mapping have required considerable delineation, with the former often referred to as a systematic mapping review [40]. Miake-Lye et al.'s [45] systematic review of evidence mapping studies found that of Arksey and O'Malley [42] to be the most frequently cited publication when defining evidence mapping, with the PRISMA-ScR protocol also being targeted specifically at evidence mapping ([39], p. 467). Khalil and Tricco noted evidence mapping studies to adhere to a PICO format to determine questions of intervention effectiveness: participant, intervention, comparer, and outcome. In contrast, scoping reviews span more broadly in a PCC format: participant, context, and concept [46]. As the research question lends itself towards the PCC framework, a scoping review was chosen as the suitable review process for IRT-3DDF.

2.2. Scoping Review: Process

2.2.1. Scoping Review Protocol and Registration

This scoping review shall follow the PRISMA-ScR protocol, which outlines 20 compulsory and 2 optional steps for undertaking a scoping review [39]. Any decisions made in accordance with the protocol shall be clearly defined and justified. As this work does not fit any research field outlined by PROSPERO, no formal registration for this scoping review was undertaken [47]. In addition, the work aims to showcase the application of scoping reviews for multi-disciplinary research and should be analysed as a feasibility study for eventual inclusion into such databases.

2.2.2. Research Question: Terms and Definitions

The research question for this scoping review is as follows: how can IRT-3DDF advance building diagnostics and inform the conservation, repair and maintenance (CRM) of architectural heritage? This question is framed to identify both the breadth of applications of IRT-3DDF for architectural heritage and the emerging trends for future work. This question adopts Khalil et al.'s PCC format ([46], p. 179), with infrared thermography (**Participant**), 3D-data fusion (**Concept**) and architectural heritage (**Context**) forming the

PCC acronym. To define the key terms, the UNESCO 1972 World Heritage Convention definition of cultural heritage shall be adopted, defining architectural heritage as "groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science" ([48], p. 2). In addition, reviewers have defined CRM as any intervention to preserve, restore, manage or adapt architectural heritage through its lifecycle. Finally, IRT-3DDF shall be defined as the registration of 2D-thermographic data with high parity, geospatially derived 3D-data to provide a unified, geometrically accurate product suitable for representing architectural heritage.

2.2.3. Literature Search: Databases and Iterative Keyword Selection

Several databases were used for the systematic collection of literature for review studies, with the most frequent being Clarivate's Web of Science (WoS), Elsevier's Scopus and Google Scholar [49]. Notably, both WoS and Scopus have demonstrated stable growth since their creation, demonstrating their suitability for energy efficiency, climate impact and architectural heritage bibliometric analysis [50,51]. A combination of databases is proven to be an effective way of capturing a greater body of related literature, with [50] finding a 11% overlap between WoS and Scopus. For this reason, both WoS and Scopus shall be used to collect relevant IRT-3DDF literature.

To determine suitable keywords for the literature search, clusters were determined in accordance with the PCC format of [46]. The determination of keyword clusters was an iterative process, encouraged by [39,42], with several searches used to determine clusters that capture the scope of IRT-3DDF. This involved a narrow collection of initial keywords determined by all reviewers, denoted by (^{1}). Subsequent iterations looked to broaden each category to capture all relevant literature still adhering to the inclusion/exclusion criteria (see Section 2.2.4). VOSViewer [52] was utilised to add/remove keywords of relevance/irrelevance in subsequent iterations (^{2,3}), with syntax operators also used to maximise the inclusion of keyword derivatives ("",*). This led to the following keywords categorised into three distinct clusters:

1. **InfraRed Thermography (Participant)**: "Infrared Thermography"^{1} OR IRT^1 OR Thermography^1 OR "Thermal Imag*"^{3} OR Thermograph*^{3}.
2. **3D-Data Fusion (Concept)**: Photogrammetr*^{1} OR "Structure From Motion"^{1} OR SfM^1 OR "Laser Scan*"^{1} OR TLS^1 OR "Data Fusion"^{1} OR 3D^1 OR Model*^{2} OR "Multi View Stereo"^{2} OR MVS^2 OR "Sensor Fusion"^{3} OR "Data Integration"^{3}.
3. **Architectural Heritage (Context)**: "Architectural Heritage"^{1} OR "Built Heritage"^{1} OR "Historic* Building*"^{1} OR Archaeolog*^{1} OR Heritage^2.

2.2.4. Inclusion and Exclusion Criteria

The collection of relevant literature through specified keywords represents the initial stage of the methodology, with defined inclusion and exclusion criteria (Inc./Exc.) used to qualify publications suitable for the review. Inc./Exc. criteria are to be clearly defined not only for study replicability, but to justify selection [39,42]. The use of Inc./Exc. criteria allowed for broad keywords (e.g., Heritage*, Archaeol*) to capture all publications and subsequently reduce them to those of relevance. The application of the Inc./Exc. criteria was performed through two steps. Firstly, only titles and abstracts were assessed, with all qualifying publications carried forward to a full review. Secondly, the complete review of the publication was undertaken in accordance with the Inc./Exc. criteria.

This two-step process was purposefully executed to give as many articles as possible the 'benefit-of-the-doubt' and execute a full review. This included no criteria, limiting research fields, as ([51], p. 81) argued the analysis of heritage building to be inherently multi-disciplinary, spanning numerous disciplines. In addition, no initial constraints were applied to the publication type (i.e., journal article, book chapter, and conference paper) or year, with the ambition of capturing all relevant open access literature that were published. In addition, to obtain as many relevant studies as possible, a 'snowballing' approach was adopted to gather cited references from the literature. For each article gathered that qualified through a full review, articles cited within each publication in reference to IRT-3DDF research, methodologies and applications were reviewed through the full review process. The following Inc./Exc. criteria were determined for the iterative literature search:

1. **Review study, conference proceedings, conference review (Exc.):** All publications must present a case study of IRT-3DDF that can be analysed for its methods, results and applications.
2. **Publication stage (Inc.):** All publications must be published.
3. **English language (Inc.):** All publications must be available in English.
4. **Open access (Inc.):** All publications must be open access (or granted access from the authors).
5. **Presence of IRT (Inc.):** The presence of IRT as defined by Section 2.2.2.
6. **Presence of Architectural Heritage (Inc.):** The presence of architectural heritage as defined by Section 2.2.2.
7. **Presence of IRT-3DDF (Inc.):** The presence of IRT-3DDF as defined by Section 2.2.2.

2.2.5. Bibliometric Analysis

To accompany the PRISMA-ScR protocol, bibliometric methods are undertaken to support the scoping review and provide objective means of assessing the collected body of research. Bibliometrics has gained significant traction due to the emergence of computer tools such as VOSViewer, Gephi and Leximancer [50,53], enabling review studies to extract bibliographic information (e.g., keywords, authors, citations, and institutions). As stated by Donthu et al., bibliometric analysis takes two forms: performance analysis (PA), which looks to quantify the contributions made within a body of research, and science mapping (SM), which looks to visualise the relationships within bibliographic data [53]. The following metrics are used to map the collected literature prior to data charting:

1. **Number of publications per year** (PA).
2. **Bibliographic visualisation** (SM).
3. **Keyword co-occurrence (abstract and keywords)** (SM).

Undertaking bibliometric analysis prior to data charting and thematic analysis presents several marked benefits. Firstly, performance analysis enables reviewers to gain an initial assessment of research strength, taking this into consideration when generalising findings and deriving conclusions. Secondly, the mapping of prominent authors and research groups allows reviewers to identify links between collected publications and track the progression of a group's work. Finally, keyword co-occurrence visualisation allows for the recognition of clusters representing the inter-connectivity of subject areas, technologies and applications. Therefore, bibliometric analysis shall be undertaken at the beginning of the results (see Section 3.2).

2.2.6. Data Charting

Arksey and O'Malley's [42] 'charting' process denotes the collating of qualitative data gathered from the literature and its transformation into specific metrics. This process of a scoping review allows information to be synthesised and summarised into key themes reflecting a specific body of research. For IRT-3DDF, themes were chosen to analyse the scope of the field and identify trends within the research. Three themes were categorised for the data charting process—contextual, methodological and practical:

1. **Contextual:**
    (a) Study Location(s)
    (b) Study Building(s)
    (c) Architectural Style(s)
    (d) Primary Research Focus

2. **Methodological:**
    (a) Fusion Method
    (b) Thermal Camera
    (c) Thermography Type
3. **Practical:**
    (a) Thermal Outputs
    (b) Thermal Findings
    (c) Future Developments

The ‘contextual’ data charting theme looks to document the scope of IRT-3DDF both geographically and architecturally, mapping where research is being undertaken and on what types of historic buildings. The ‘methodological’ theme focuses on the evolution of data fusion methods evident within the research. In addition, both thermal camera and thermography type are charted to analyse the equipment and preparation at the heart of IRT-3DDF research. Finally, the ‘practical’ data charting theme is formulated with the ambition of understanding what, where, and how research can be applied to architectural heritage. This theme looks to not only map emerging trends within the research but highlight where opportunities lie in the future of IRT-3DDF.

2.2.7. Thematic Analysis

Whilst Arksey and O’Malley’s original framework groups collating, summarising and reporting results as a singular stage of a scoping review (see Section 2.1.1 Stage 5), Levac et al. argue that the grouping of these steps diminishes the extent to which results can be examined and contextualised. They suggest that meaning must be applied to these results with reference to the research question posed in Stage 1, clarifying results through a thematic analysis that is constructed to “have practical implications for future clinical practice, research, and policy” ([43], p. 9). Therefore, this scoping review transfers the data charting themes into a thematic analysis, expanding the results through a qualitative discussion of each theme and their subcategories.

3. Results

3.1. Literature Search Results

As seen in Figure 2, the defined methodology collected 269 publications in three iterative searches of Scopus and Web of Science, with all three iterative searches undertaken in February 2023. Of these initial sources, 115 were found in both databases, representing a 43% overlap between Scopus and Web of Science. Of these 269 sources, 18 articles were excluded after being classified as a review study or conference review, as defined in Section 2.2.4. In addition, of these 251 sources, all met the necessary publication stage and English language inclusion criteria. The resulting 251 publications were carried forward to Stage 2.1. By reviewing the title and abstracts of these 251 publications, 118 met the Inc./Exc. criteria in Section 2.2.4. Disqualified sources, which failed to feature all three of the remaining inclusion criteria, are as follows: the presence of infrared thermography, the presence of architectural heritage and the presence of 3D-data fusion. Notably, of the 251 sources reviewed, half failed to meet the definition IRT-3DDF or identify IRT-3DDF within the title or abstract of the source.

Prior to Figure 2 Stage 2.2, 11 sources were excluded due to restricted access or the inability to gain access from the authors. After full reviews were undertaken on the 107 publications, 22 qualified to be included in the scoping review. Similarly, the most significant determining factor for disqualification was the lack of IRT-3DDF. In addition, the ’snowballing’ method outlined in Section 2.2.4 resulted in an additional 10 publications being added to the initial 22 publications. Upon inspection, these studies were not captured by the iterative searches for the following reasons: (1) they featured too few keywords to be included in the search results; (2) they provided keywords that were not specified in

Section 2.2.3; or (3) they were not part of the Scopus or WoS databases. The final literature search provided 32 sources for bibliometric analysis, data charting and thematic analysis.

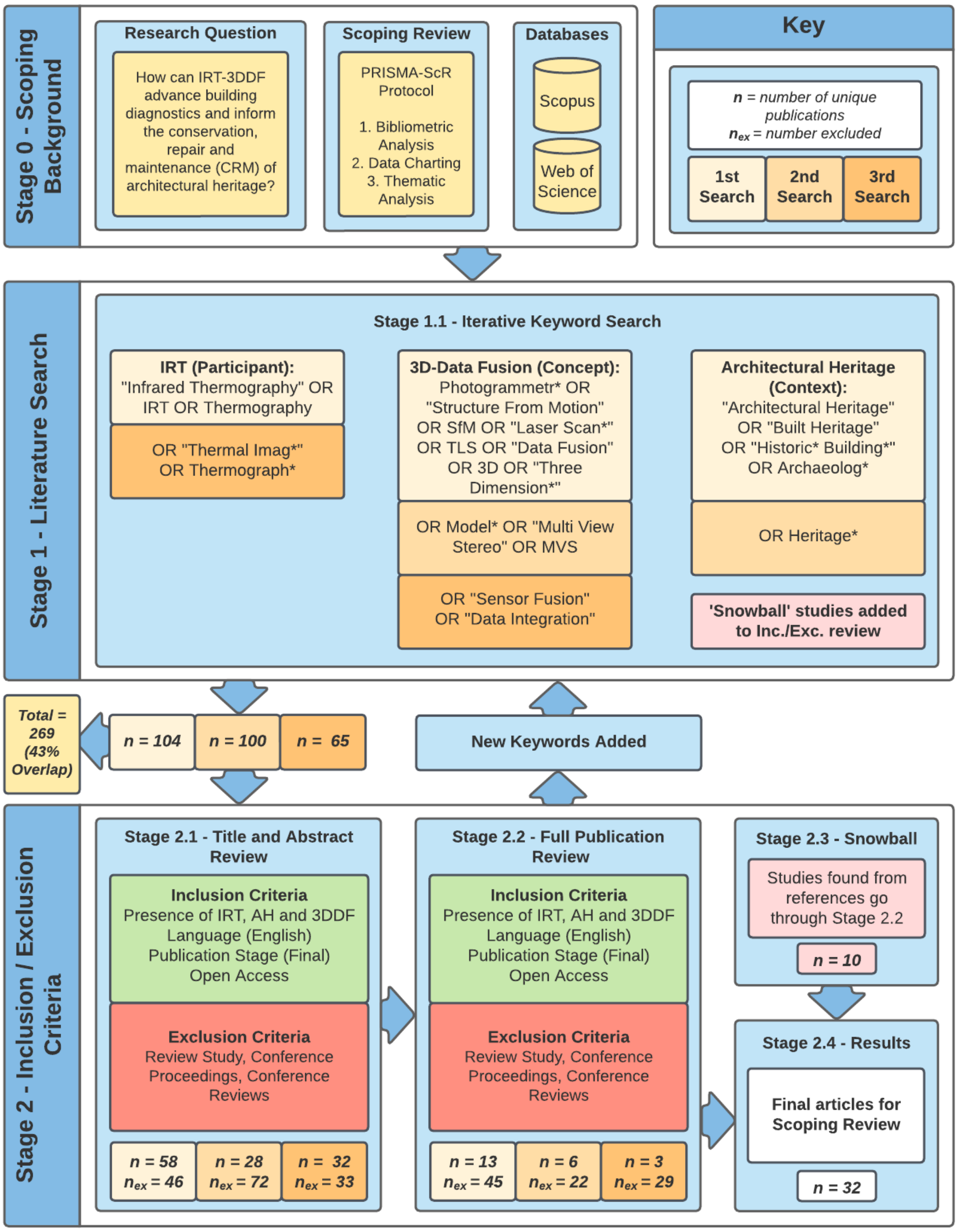

Figure 2. PRISMA-ScR scoping review workflow for IRT-3DDF literature search.

3.2. Bibliometric Analysis

As stated in Section 2.2.5, bibliometric analysis allows for the examination of the contributions and relationships present within a body of research. Bibliometric data from all collected publications were extracted to undertake the defined metrics. Of the 32 publications collected, 17 were published as journal articles and 15 were published as part of conference proceedings.

3.2.1. Publications per Year

As seen in Figure 3, the presence of IRT-3DDF for architectural heritage has begun to emerge within the last five years [26]. This growth comes after 3D-data fusion and reality capture have become synonymous with cultural heritage, originating from the development of computer vision and surveying solutions at the turn of the century [3,20,21]. It is evident that IRT-3DDF research has grown in tandem with similar fields exploiting 3D-data fusion, notably H-BIM [54], temporal analysis [22] and extended reality (XR) [55]. In addition, the timeline in Figure 3 mirrors the growth of IRT-3DDF in the AEC industry, where research has looked to apply thermal modelling to advance existing methods and broaden applications past rudimentary anomaly detection [28,29,31]. Finally, the timescale of IRT-3DDF supports similar trajectories in energy efficiency, retrofitting and non-destructive testing research for historic buildings, fields that have grown in importance for cultural heritage due to pressing climate targets [7,56].

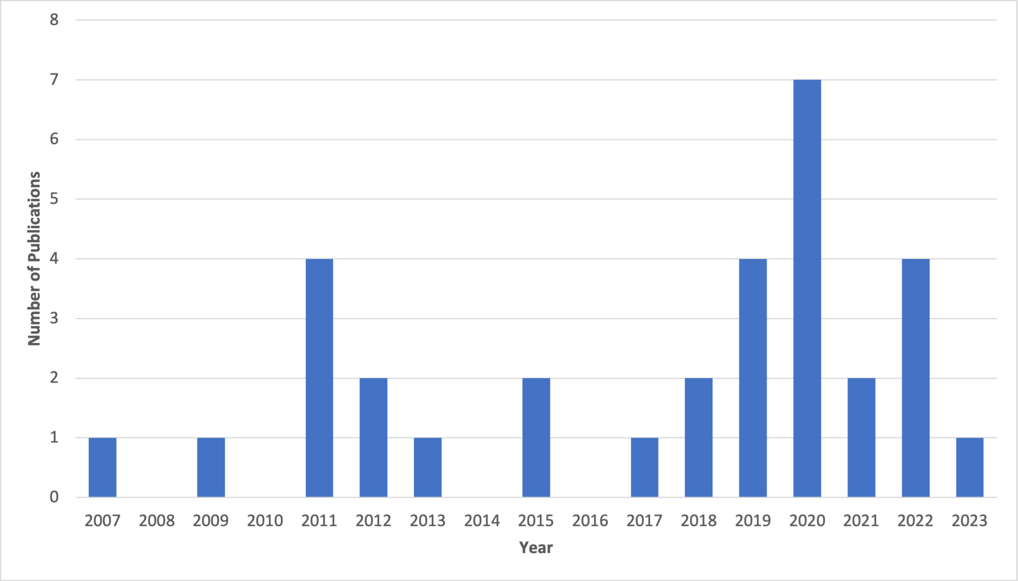

Figure 3. IRT-3DDF publications per year.

3.2.2. Bibliographic Visualisation

Several methods of bibliographic analysis exist for science mapping, allowing cited references to be analysed for relationships and weighting. To visualise the prominence of key authors and established research groups, all 780 cited authors from the scoping literature were uploaded in VOSviewer. From Figure 4, we are able to confirm that IRT-3DDF has grown out of cultural heritage 3D-data fusion research. This is supported by the prominence of cited work by several institutions focusing on geomatics and surveying engineering, including G4CH Lab—Polytechnic University of Turin (Rinaudo, Spanò) (**Green**), 3DOM—FBK Trento (Remondino, Rizzi) (**Yellow**), GeoTech—University of Vigo (Lagüela, Solla) (**Red**), DABC—Polytechnic University of Milan (Rosina, Scaioni) (**Dark Blue**), and National Technical University of Athens (Moropoulou, Avdelidis) (**Purple**). Furthermore, we are able to determine the importance of research assessing existing IRT-3DDF methods, with research groups, such as the 3D Visual Computing & Robotics Lab at the University of Castilla-La Mancha (Adán, Merchán) (**Brown**) and the Photogrammetry and Remote Sensing Unit at the University of Munich (Hoegner, Stilla) (**Grey**), demonstrating the use of IRT-3DDF for multiple applications.

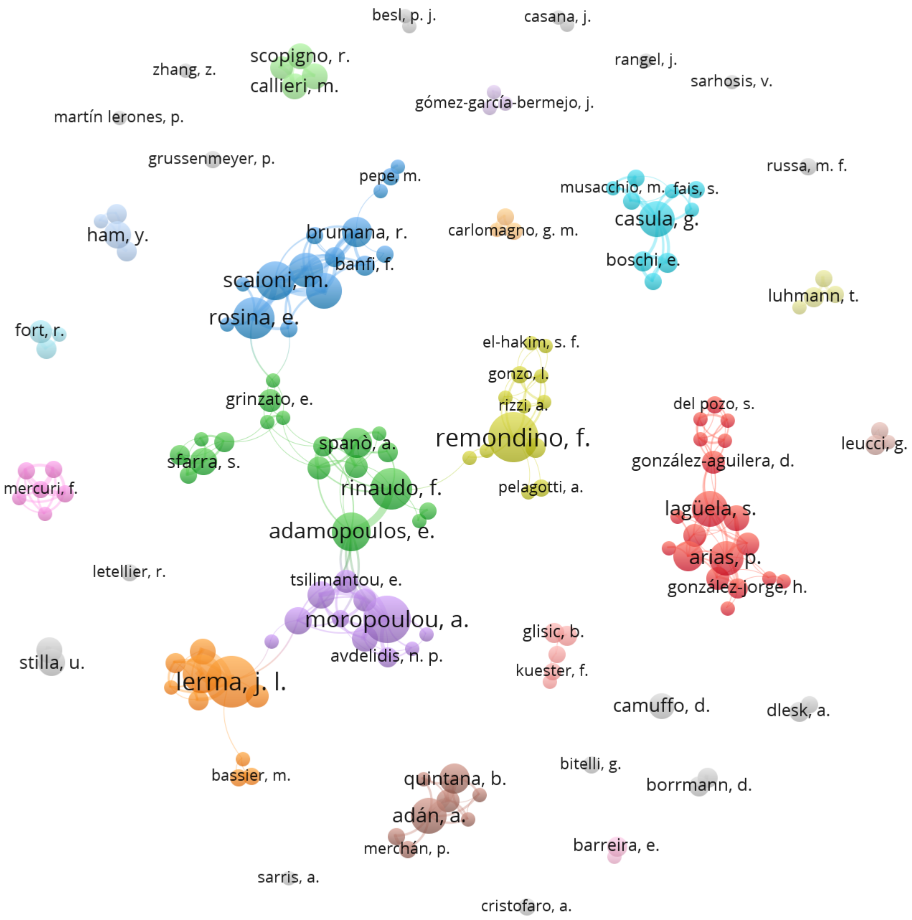

Figure 4. Bibliographic visualisation of cited references from scoping literature. VOSviewer's 'association strength' normalisation method is used to determine the weight of connections between 163 cited publications. Each of the 163 authors are featured in a minimum of 3 separate publications [57].

3.2.3. Keyword Co-Occurrence

The bibliometric analysis of keywords plays an important role in scoping reviews, allowing the visualisation of key themes and emerging trends formed within the collected literature. In Figure 5, the prominence of reality capture techniques for IRT-3DDF is evident, with "Photogrammetry" and "Laser scanning" determined as the keywords with the greatest total link strength from the 103 keywords collected. Variations of infrared thermography ("IRT", "Thermography"), captured in the keyword clusters (See Section 2.2.3), are also central to all IRT-3DDF publications. As discussed in Section 3.1, the evolution of terms representing 3DDF is apparent, with "data fusion", "sensor fusion", "integration" and "data integration" used to highlight the central theme of the scoping literature. The strength of the keywords featured in Figure 5 suggests that the iterative scoping review process outlined in Figure 2 was successful in capturing additional keywords, with "Thermal Imag*", "Thermograph*", "Sensor Fusion" and "Data Integration" added after the initial search.

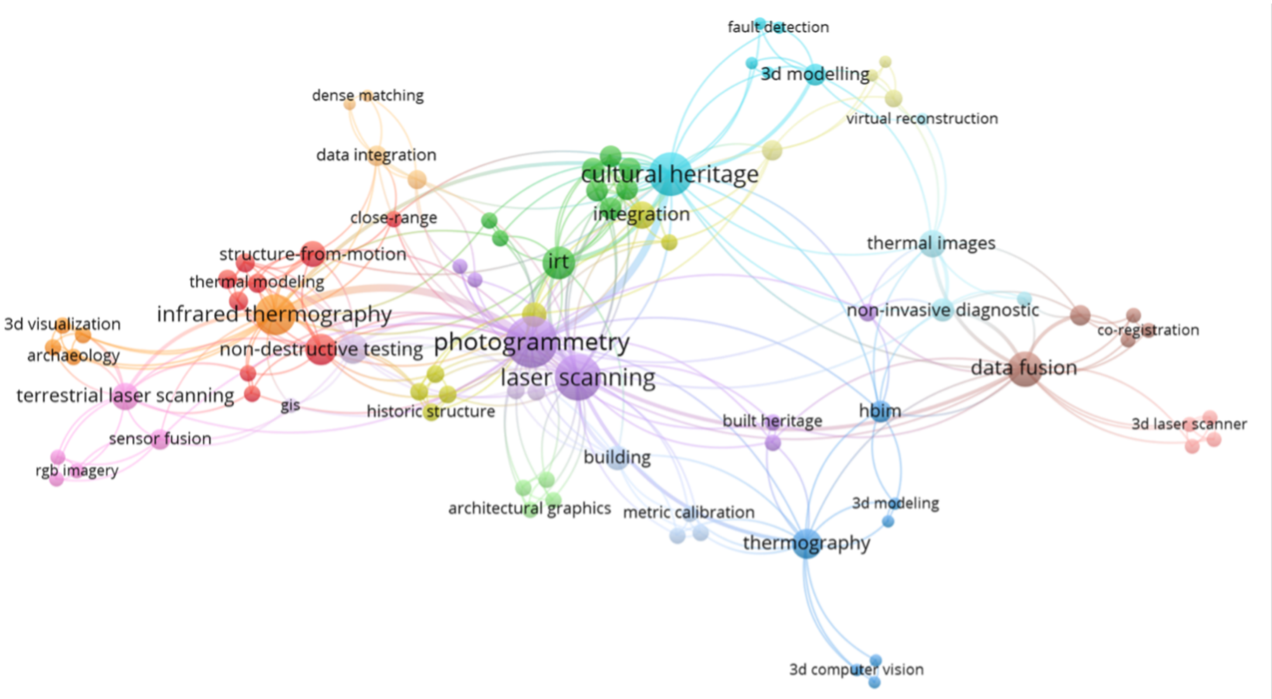

Figure 5. Keyword co-occurrence of IRT-3DDF. This figure represents 88 connected keywords present within the scoping literature, visualised with VOSviewer's 'fractionalisation' normalisation method. Relationships between keywords are determined by the proximity of bubbles and the link strength of joined keywords [57].

Interestingly, certain keywords highlight the challenges faced within IRT-3DDF research, with keywords such as "co-registration", "dense matching", and "metric calibration" suggesting the importance of photogrammetric processes for thermal modelling. However, whilst the visualisation of keyword co-occurrence identifies the strengths of featured keywords, it is important to understand which keywords are missing from the literature. Though "non-destructive testing" features prominently, keyword variations representing practical applications of IRT-3DDF, such as "retrofitting", "energy monitoring" and "building diagnostics", feature significantly less than keyword capturing methodologies. The themes identified within Figure 5 demonstrate the importance of data fusion as an established field within cultural heritage and highlights some of the emerging trends present within the IRT-3DDF scoping literature. These keys themes and emerging trends are expanded within the data charting and thematic analysis sections of the scoping review.

4. Data Charting and Thematic Analysis

The results of the data charting process, separated into three tables representing each data charting theme in Section 2.2.6, are outlined below. These tables were built as the point of reference for the accompanying thematic analysis. Subcategories within each table are analysed to identify key themes within the scoping literature and provide context for the summarised findings.

4.1. Contextual Data Charting

The contextual data charting theme, shown in Table 1, looks to provide an initial assessment of the scoping literature by analysing the locations, buildings and purposes behind IRT-3DDF. Central to the study of architectural heritage, an understanding of how cultural significance is appreciated in different regions is evaluated, with the diversity of historic buildings showcasing the breadth of IRT-3DDF.

4.1.1. Study Location(s)

The analysis of the scoping literature study locations demonstrates where research is being undertaken and the prominence of fields within countries, regions and climates. As seen in Figure 6, representing the countries of all studied buildings within the collected literature, IRT-3DDF research has been overwhelmingly undertaken in Southern Europe, with half of the publications being located in Italy. In addition, Spain (9), Poland (2), Germany (1), Greece (1) and Portugal (1) reaffirm the importance of IRT-3DDF as an active field within European cultural heritage research. This pattern was similarly highlighted by [58], who stated that most heritage-specific energy efficiency and thermal comfort research originates in Southern Europe. Furthermore, Italy, Spain, Poland, Germany and Greece all featured within the top 10 countries for photogrammetry and laser scanning NDT research from 2001 to 2021 ([7], p. 7). Furthermore, it is apparent that study locations are correlated to where researchers/research groups are based, suggesting the preference to build on previous work and compound knowledge of regional vernacularisms.

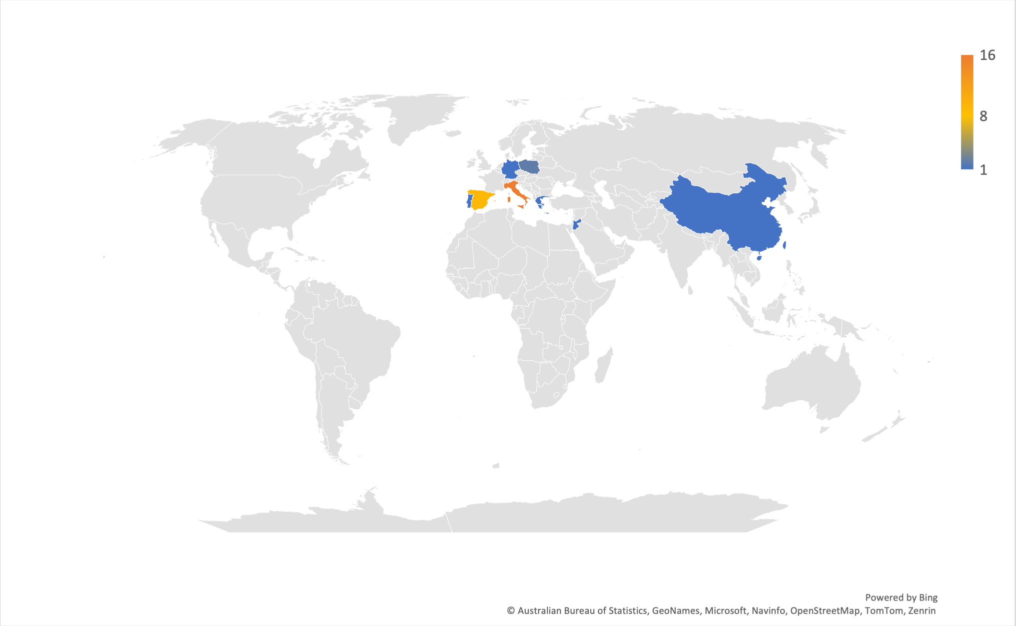

Figure 6. Geographic distribution of IRT-3DDF study locations.

4.1.2. Study Building(s)

The diversity of buildings within the scoping literature, seen in Figure 7, demonstrates the breadth of applications for IRT-3DDF, encapsulated by buildings of varying age, scale, use and significance. Martinez-Molina et al. [58] stated that 19th and 20th century buildings are most prominent within heritage-specific energy research, a pattern that is present within the scoping literature [59,60]. However, several cases of archaeological heritage feature within the scoping literature, which has been subject to greater exposure over time [61,62]. Cabrelles et al. [63] used IRT-3DDF to document the weathering of sandstone blocks at Petra's UNESCO World Heritage site, documenting years of capillary rise and salt deposition. Martinez-Molina et al. [58] also emphasised the importance of residential buildings [64], religious buildings [65] and museums [66] as subjects for cultural heritage research, a pattern similarly apparent within IRT-3DDF.

Variations in building scale are also evident within the scoping literature, with research using IRT-3DDF to assess individual building elements [67,68], façades [69,70], whole buildings [71] and even small villages [72]. Interestingly, conscious selections of building scale that have been made with the ambition of applying IRT-3DDF to showcase a methodology or application are apparent within the scoping literature. Paziewska and Rzonca [73] employed an unmanned aerial vehicle (UAV) to document a church and its stone tower, comparing an external IRT-3DDF model with internal temperature values to assess thermal leakage. The ability to comprehensively map the tall stone tower externally corroborated findings from internal IRT images that insulation was sufficient. Merchan et al.'s [71] Baritel de San Carlos' millhouse provides an appropriately small asset for the validation of a method generating complete coverage for IRT-3DDF. Furthermore, Patrucco et al.'s [72] methodology exploits case studies that support the scalability of their derived fusion method. The choice of study building(s) within the scoping literature demonstrates the awareness of research groups to apply IRT-3DDF for specific method developments or applications.

4.1.3. Architectural Style(s)

Much like the choice of study building(s), variability in architectural style has dictated the development of IRT-3DDF methods and determined key considerations for the execution of successful studies. Patrucco et al. [74] stressed that while improvements in IRT-3DDF instruments and software enable existing issues of image occlusion and homogeneity to be overcome, careful considerations must be made in relation to the materials, textures and geometries of the architectural heritage. With this in mind, their work demonstrates the need for careful survey planning to appreciate the architectural heritage being investigated, assessing thermal camera requirements; image overlap and ground sample distance; image occlusions and access restrictions; and timing to maximise solar radiation [75]. Similarly, Merchan et al.'s [71] documentation of the millhouse roof demonstrates that whilst mitigation strategies for image registration can be determined, inherent challenges, such as the lack of contrasting thermal signatures across materials, are frequently unavoidable and can lead to discrepancies in thermal modelling.

Appreciating the challenges of IRT-3DDF, several studies have ed with the intention to present research that confronts issues inherent to certain architectural styles or presenting methods with the ambition of providing suggestions rather than complete solutions. Scaioni et al.'s [64] case study looked to provide suggestions through a semi-automatic SfM method for 1960s Italian post-war concrete buildings, representative of a large proportion of poorly insulated heritage buildings in need of restoration. Similarly, Patrucco et al. [74] demonstrated that, even when careful considerations for survey planning are made for one case of architectural style, differences in effective modelling will be apparent for different architectural styles, especially when addressing industrial heritage. The varied architectural styles within the scoping literature reaffirm that a detailed understanding of a historic building and the principles of IRT are fundamental for IRT-3DDF. This is necessary if existing IRT-3DDF methodologies are to be adapted to varying architectural heritage and if similar applications are to be realised.

Table 1. Contextual data charting.

Authors	Study Location(s)	Study Building(s)	Architectural Style(s)	Primary Research Focus
Adamopoulos et al., 2020a [76]	Turin, Italy	Castello del Valentino	16th Century Suburban Mansion	Method Development
Adamopoulos et al., 2020b [70]	Turin, Italy	Castello del Valentino	16th Century Suburban Mansion	Method Development
Adamopoulos et al., 2021 [68]	Turin, Italy	Castello del Valentino	16th Century Suburban Mansion	Method Development
Adan et al., 2020 [77]	Valencia, Spain	Church of Santos Juanes	Main nave	Method Development
Alba et al., 2011 [78]	Milan, Italy	Rectorate Office and The "Trifoglio" Building, Politecnico di Milano University	Classical revival style; Italian modernism	Building Diagnostics
Artese et al., 2019 [79]	Valencia, Spain	Church of Escuelas Pias	Hemispherical dome	Building Diagnostics
Barbieri et al., 2023 [60]	Bologna, Italy	Library Tower, Faculty of Engineering, University of Bologna	20th Century Rationalist Architecture	Holistic Management
Brumana et al., 2013 [80]	Lombardy, Italy	Isola Comacina	Archaeological site	Method Development
Brumana et al., 2018 [81]	Cremona, Italy	Magio Grasselli Palace	18th Century brick cloister vaults	Holistic Management
Cabrelles et al., 2009 [63]	Petra, Jordan	Djinn Block No. 9, Petra UNESCO World Heritage Site	Archaeological tomb	Building Diagnostics
Costanzo et al., 2015 [65]	Cosenza, Italy	St. Augustine Monumental Compound	Vernacular church and monastery	Method Development
Fang et al., 2022 [82]	Nanjing, China	Beamless Hall of Linggu Temple	Series of barrel vaults and arches	Holistic Management
Griffo et al., 2019 [62]	Rome, Italy	Nymphaeum of Egeria, Caffarella Park	Caved grotto	Method Development
Laguela et al., 2011 [59]	Galicia, Spain	School of Technical Industrial Engineering, Vigo	1930s educational centre	Method Development
Lewinska and Maciuk, 2020 [83]	Kraków, Poland	AGH-UST University of Science and Technology; Barbican Fortified Outpost	Vernacular wooden and masonry architecture	Holistic Management
Maierhofer et al., 2011 [67]	Magdeburg, Germany	Cathedral of Saint Mauritius and Saint Katharina	Sandstone column	Method Development
Martín-Lerones et al., 2021 [84]	Valladolid, Spain	The Castle of Torrelobatón	Middle-Age European Castle	Holistic Management
Merchán et al., 2020 [71]	Almadenejos, Spain	Baritel de San Carlos	Archaeological mine and mill	Building Diagnostics

Table 1. *Cont.*

Authors	Study Location(s)	Study Building(s)	Architectural Style(s)	Primary Research Focus
Mileto et al., 2015 [85]	Monzón, Spain	Monzón Castle	10th Century castle and fortress	Building Diagnostics
Napolitano et al., 2019 [66]	Florence, Italy	Sala degli Elementi, Palazzo Vecchio	Internal wall	Building Diagnostics
Patrucco et al., 2020 [72]	Lazio, Italy; Turin, Italy	Santa Maria delle Grazie church; Bout du Col	Coffered wooden ceiling; Abandoned alpine village	Method Development
Patrucco et al., 2022a [75]	Valencia, Spain	Palacio de Colomina	Decorative classical architecture	Holistic Management
Patrucco et al., 2022b [74]	Cuneo, Italy; Torino, Italy	Rural Chapel; Comprehensive School; Parabolic Arch of Morano sul Po	Varied architectural heritage	Method Development
Paziewska and Rzonca, 2022 [73]	Porąbka, Poland	Parish of the Birth of the Blessed Virgin Mary	Church and stone towers	Building Diagnostics
Previtali et al., 2012 [86]	Milan, Italy	Politecnico di Milano University	Classical and modern façades	Method Development
Puente et al., 2018 [61]	Bande, Spain	"Aquis Querquennis" Roman Fort and Camp	Archaeological site	Building Diagnostics
Scaioni et al., 2012 [87]	Milan, Italy	Politecnico di Milano University	Classical and modern façades	Method Development
Scaioni et al., 2017 [64]	Milan, Italy	The Church of St. Pio X; Milanese residential building	Concrete church; 1960s protected buildings	Method Development
Solla et al., 2020 [69]	Leiria, Portugal	The Monastery of Batalha	Masonry façades	Holistic Management
Rizzi et al., 2007 [88]	Verona, Italy	Palazzo Barbieri	Neoclassical palace	Method Development
Tsilimantou et al., 2019 [89]	Rhodes Island, Greece	Acropolis of Erimokastro	Deserted castle and fortifications	Building Diagnostics
Zalama et al., 2011 [90]	Valladolid, Spain	Iglesia conventual de San Pablo	Isabelline style church façade	Method Development

Figure 7. Study buildings and architectural styles of IRT-3DDF scoping literature. The diversity of architectural heritage is represented here by (**A**) Baritel de San Carlos [71]; (**B**) The Church of St. Pio X [64]; (**C**) The Castle of Torrelobatón [84]; (**D**) University of Bologna [60]; (**E**) Castello del Valentino [68]; (**F**) Linggu Temple [82]; (**G**) Palazzo Barbieri [88]; (**H**) Milanese residential building [64]; and (**I**) Santa Maria delle Grazie [72].

4.1.4. Primary Research Focus

The research aims of a publication provide a clear indication of the studies' motivation and suggests the ambitions within the field being investigated. Here, the primary research focus was created to collate the research aims of each individual paper, categorising studies as either 'Method Development', 'Building Diagnostics' and 'Holistic Management'. Where papers were classed as 'Method Development', studies focused on advancing the generation of thermal models, a clear separation between method exploration [62,72,88] and method advancing [59,67,74] IRT-3DDF research becomes clear. Alba et al. [78] identified the current state of the art and introduced a new 'bi-camera' method to advance current practices. Similarly, Adamopoulos et al. [70] formulated their aim by embracing the existing challenges of IRT-3DDF and presenting a methodology utilising cost-effective equipment central to CRM practices. In general, 'method development' studies demonstrate research aims that have identified existing challenges within IRT-3DDF and present innovative solutions.

In contrast, both 'building diagnostics' and 'holistic management' put the emphasis on architectural heritage, determining that IRT-3DDF provides a tool for greater interpretation and documentation. Napolitano et al.'s [66] 'building diagnostics' aim places IRT-3DDF as part of a larger catalogue of non-destructive tests and numerical modelling focused on damage assessment. Cabrelles et al. [63] place IRT-3DDF in combination with other metric and non-metric surveys as the preliminary phase of research, with the aim being comprehensive documentation and informing conservation specialists. Griffo et al. [62] identify IRT-3DDF as a preliminary phase of a larger augmented reality (AR) project to visualise historical reconstructions and disseminate findings.

'Holistic management' studies demonstrate aims where IRT-3DDF contributes to ongoing management campaigns, notably through the use of H-BIM as a means of creating interoperable data management systems [69]. Fang et al.'s aim of determining a CAD workflow for conservation appreciates the evolution of their research through the future work, identifying the logical progression of their integrated surveys into a BIM for "heritage managers, experts, and visitors" ([82], p. 14). Similarly, Martín-Lerones et al.'s [84] development of a REVIT plug-in, enhancing scan-to-HBIM procedures, places IRT-3DDF as a central tool for the documentation and management of heritage assets. Brumana et al. [91] documents the history of cloister vaults to inform their H-BIM methodology, using IRT-3DDF to provide context on vault typology and construction 'stereonomy'. The identification of the scoping literature's primary research focus not only helps clarify why the research is formulated, but identifies where authors see the future for IRT-3DDF.

4.2. Methodological Data Charting

The inherent low spatial resolution of thermal images has required methods to fuse images with additional datasets that provide accurate geometries of architectural heritage. Several studies have documented the timeline of these developments within the AEC industry [11,36]; with Lin et al. classifying IRT-3DDF methods as either image-to-image (2D-2D), image-to-model (2D-3D), or model-to-model (3D-3D) [10]. However, the predominance of thermal texturing (2D-3D) methodologies within the scoping literature necessitates alternative categories for data charting. Therefore, the fusion methods outlined in Table 2 look to capture several nuances specific to architectural heritage: (1) the variations in 2D-3D thermal texturing methods; (2) the considerations made for historic buildings; and (3) the applications of the thermal outputs for CRM practices.

4.2.1. Fusion Method

As previously stated, regular developments in hardware and software have advanced the timeline of IRT-3DDF, with photogrammetric workflows central to this progression. Alba et al.'s [78] seminal study using a 'bi-camera' system represents a critical point in this landscape, coupling a DSLR and TIR camera in a fixed system. By processing the DSLR RGB images through a photogrammetric bundle adjustment, with the relative orientation of the TIR camera fixed, thermal images can be oriented and aligned to a TLS model. Here, RGB imagery is not used to provide the 3D geometry, but to determine the external orientation of TIR images, demonstrating the benefit of multiple 2D sensors in a fixed system. With the development of thermal cameras integrating RGB sensors into the same camera housing, Alba et al.'s work demonstrates the strengths of exploiting integrated (and supplementary) RGB images to determine thermal image orientation.

Exploiting developments in photogrammetric software has been central to the increasing capability and automation of image-based fusion methods, with several methods utilising an RGB-derived geometry to register TIR images. These methods scale from the manual identification of common points between RGB and TIR images [85], to semi-automatic workflows [64,68], and to fully automatic SfM photogrammetric pipelines [75]. Adamopoulos et al. [70] present a semi-automatic SfM pipeline exploiting a thermal camera's RGB sensor to register and texture a 3D model. By registering undistorted TIR and RGB images, a thermal texture is created by substituting the TIR images in the place of its corresponding RGB images, enabling the block geometry to be maintained while simply gaining a thermal texture.

Table 2. Methodological data charting.

Authors	Fusion Method	Thermal Camera	Thermography Type
Adamopoulos et al., 2020a [76]	Thermal alignment onto 2D RGB ortho-mosaic	FLIR T1030sc (1024 × 768) *	Passive
Adamopoulos et al., 2020b [70]	Thermal texturing of 3D RGB mesh	FLIR T1030sc (1024 × 768) *	Passive
Adamopoulos et al., 2021 [68]	Thermal texturing of 3D TLS mesh	FLIR T1030sc (1024 × 768) *	Passive
Adan et al., 2020 [77]	Thermal texturing of 3D TLS point cloud	FLIR A65 (640 × 512) †	Passive
Alba et al., 2011 [78]	Thermal texturing of 3D TLS mesh	AVIO (320 × 240); NEC H2640 (640 × 480) *	Passive
Artese et al., 2019 [79]	Thermal texturing of 3D TLS mesh	-	Passive
Barbieri et al., 2023 [60]	Thermal texturing of 3D parametric model	FLIR P620 (640 × 480) *	Active
Brumana et al., 2013 [80]	Thermal alignment onto 2D RGB ortho-mosaic	FLIR TAU (640 × 512) ^{X}	Passive
Brumana et al., 2018 [81]	Thermal texturing of 3D parametric model	AVIO TVS-500 (320 × 240); FLIR T640 (640 × 480) *	Active
Cabrelles et al., 2009 [63]	Thermal alignment onto 2D TLS mesh	FLIR ThermaCAM B4 (320 × 240) ^{X}	Passive
Costanzo et al., 2015 [65]	Thermal alignment onto 2D TLS reflectance mesh	AVIO (NEC) R300SR-S (640 × 480) *	Passive
Fang et al., 2022 [82]	Thermal texturing of 3D TLS point cloud	Zoller+Fröhlich T-Cam (382x288) †	Passive
Griffo et al., 2019 [62]	Thermal texturing of 3D RGB point cloud	Testo 875i (320 × 240) *	Passive
Laguela et al., 2011 [59]	Thermal texturing of 3D TLS point cloud	AVIO (NEC) TH9260 (640 × 480) *	Passive
Lewinska and Maciuk, 2020 [83]	Thermal texturing of 3D parametric model	FLIR ThermaCAM P60 (320 × 240) *	Passive
Maierhofer et al., 2011 [67]	Thermal texturing of 3D TLS mesh	Infratec VarioCAM HR (640 × 480) *	Active
Martín-Lerones et al., 2021 [84]	Thermal texturing of 3D TLS point cloud	FLUKE Ti32 (320 × 240) *	Passive
Merchán et al., 2020 [71]	Thermal texturing of TLS point cloud	FLIR AX5 (640 × 512) †	Passive
Mileto et al., 2015 [85]	Thermal alignment onto 2D TLS mesh	-	Passive
Napolitano et al., 2019 [66]	Thermal texturing of 3D TLS mesh	FLIR A615 (640 × 512) *	Passive
Patrucco et al., 2020 [72]	Thermal alignment onto 2D RGB orth-mosaic: Thermal texturing of 3D RGB mesh	FLIR SC660 (640 × 480) *	Passive
Patrucco et al., 2022a [75]	Thermal texturing of 3D TLS mesh	FLIR ThermaCAM B4 (320 × 240) ^{X}	Passive

Table 2. *Cont.*

Authors	Fusion Method	Thermal Camera	Thermography Type
Patrucco et al., 2022b [74]	Thermal texturing of 3D RGB mesh; Thermal texturing of 3D RGB point cloud	DJI Zenmuse XT2 (640 × 512) *	Passive
Paziewska and Rzonca, 2022 [73]	Thermal texturing of 3D RGB mesh	DJI Zenmuse H20T (640 × 512) *	Passive
Previtali et al., 2012 [86]	Thermal texturing of 3D TLS mesh	-	Passive
Puente et al., 2018 [61]	Thermal texturing of 3D TLS point cloud	-	Passive
Scaioni et al., 2012 [87]	Thermal texturing of 3D TLS mesh	AVIO (NEC) H2640 (640 × 480) *	Passive
Scaioni et al., 2017 [64]	Thermal texturing of 3D RGB mesh	FLIR P640 (640 × 480) *	Passive
Solla et al., 2020 [69]	Thermal texturing of 3D parametric model	FLIR T335 (320 × 240) *	Passive
Rizzi et al., 2007 [88]	Thermal texturing of 3D TLS mesh	FLIR P640 (640 × 480) *	Passive
Tsilimantou et al., 2019 [89]	Thermal texturing of 3D RGB mesh	FLIR B200 (240 × 180) *	Passive
Zalama et al., 2011 [90]	Thermal texturing of 3D TLS mesh	-	Passive

* denotes cameras that feature both an infrared sensor and RGB sensor housed in the same camera unit. † denotes thermal sensors that form part of a TTIS with TLS, RGB and TIR sensors. ^{X} denotes thermal cameras that do not feature any additional sensors, comprising solely of a thermal sensor.

In a fully automated method, Patrucco et al. [74] evaluated the effectiveness of two separate SfM workflows on varying architectural heritage, exporting the relative orientation of an RGB sensor to generate thermal point clouds. In comparison to a standard SfM pipeline using TIR images (Workflow 1), fusion methods exploiting RGB and TIR imagery (Workflow 2) demonstrated greater confidence levels, especially for structurally variable buildings. Advances in photogrammetric software are increasing the automation of IRT-3DDF for architectural heritage projects, and whilst software such as Agisoft Metashape is highlighting the capability for thermal models to be generated solely from TIR images [72,73], fusion with RGB- or TLS is fundamental to providing the necessary geometric accuracy for products and insights to be extracted.

IRT-3DDF approaches texturing 3D products from TLS data have shown similar developments that increase the automation, accuracy and coverage of architectural heritage. Early methods have looked to exploit homography, collinearity and space resection for image orientation, with the manual identification of common points being used to apply thermal textures [59,75,85,90]. Cabrelles et al. [63] exploited a systematic image resection method, exploiting direct linear transformation, collinearity and principal distance parameters, to register images onto a TLS mesh of weathered sandstone. Similarly, Costanzo et al. [65] rectified thermal ortho-mosaics to align a thermal texture onto a 2D-TLS reflectance mesh, allowing a comprehensive assessment of structural deformities to be mapped. However, significant limitations of these methodologies reside in (1) the time-consuming processing of individual images; (2) the difficulty identifying common points in images presenting uniform thermal signatures [87]; and (3) discontinuities in the texturing applied to 3D models [75].

To combat these challenges, the emergence of three-dimensional thermal imaging systems (TTISs)—scanning solutions featuring a laser scanner, RGB camera and TIR camera—looks to co-register products exploiting a scanner's position and field of view. Merchan et al.'s [71] registration of a Riegl 3D laser scanner, Nikon D90 and FLIR AX5 determined the projective transformation matrix of thermal images using identifiable markers, enabling the complete coverage of an asset. Similarly, Adan et al.'s [77] 3D-TCV (thermal computer vision) method aligned several TLS scans with accompanying thermal ortho-mosaics to demonstrate the effectiveness of IRT-3DDF for the environmental monitoring of architectural heritage. Here, exploiting IRT-3DDF allows for (1) the precise localisation of thermal discrepancies; (2) a holistic assessment of thermal comfort incorporating temporality; and (3) the coupling of quantitative sensor data with qualitative thermal data. Methods exploiting TTIS have proven how a wealth of registered data can provide comprehensive assessments of architectural heritage and demonstrates the suitability of information management systems to interpret and manage data [82].

The fusion of TIR images with 3D parametric models represents a significant evolution of IRT-3DDF, acknowledging that the creation of BIM-ready elements provides opportunities to comprehensively monitor and manage architectural heritage. Solla et al. [69] utilised Autodesk Revit plug-ins to align TIR images, GPR and pathology classification maps within an H-BIM environment. This combination exhibits the effectiveness of integrating multiple NDT datasets for building diagnostics and ongoing management. Additionally, Patrucco et al.'s [75] scan-to-BIM workflow highlights the combining of mapping historical drawings, legacy CAD plans and TIR ortho-mosaics to aid diagnostics, finding hidden elements, historical modifications and thermal anomalies on building facades. The importance of IRT-3DDF methods exploiting BIM software resides in the capability of creating repositories, where both spatial and non-spatial datasets can be analysed for various diagnostic cases.

However, considerations must be made when using BIM methods for IRT-3DDF, appreciating model accuracy, user expertise and BIM standards for architectural heritage. Martin-Lerones et al.'s [84] custom 'LOKI' plug-in, enabling 2D/3D thermal outputs to be mapped onto parametric models, demonstrates the need for considerable BIM expertise to firstly generate a parametric model, use the 'LOKI' plug-in, and develop it for various historic buildings. Furthermore, both scan-to-HBIM workflows from [60,83] demonstrate how determinations of an appropriate level of detail (LoD) for parametric models must be made, compromising the geometry available for thermal texturing. Brumana et al.'s [91] non-uniform rational B-spline (NURBS) method, creating BIM elements from survey data with grades of generation (GoG 9 and GoG 10) [92], suggests that a greater initial level of development (LOD) is needed for H-BIM (LOD500/LOD600) when compared to traditional sequential BIM (LOD100-200-400), as heritage requires greater management from a project's inception. Whilst approaches for BIM have been determined on a case-by-case basis, specific standards for H-BIM are a necessary component for the future development of architectural heritage. Importantly, by including texturing protocols within these standards, appropriate LOD for thermal modelling and its applications can be realised. In summary, the choice of IRT-3DDF needs to assess (1) the scale of the project, (2) the required detail of the base geometry, (3) the equipment available, and (4) the applications of derived products for the effective implementation of architectural heritage.

4.2.2. Thermal Cameras

As previously highlighted, the development of thermal cameras has been central to the advancement of IRT-3DDF, with a lack of spatial resolution and field-of-view (FoV) being two significant barriers to successful data fusion [64,83]. This progress has seen thermal cameras become more affordable, portable and applicable for a range of climate- and heritage sciences [38,93]. For detailed thermographic surveys of buildings, the UK Thermography Association (UKTA) recommends a thermal camera with a pixel count of at east 640 × 480 [94]. The charting of thermal cameras in Table 2 enables us to (1) determine the resolution of cameras used over the timeline of the scoping literature; (2) identify which features have been critical to IRT-3DDF; and (3) highlight thermal camera processes central to effective modelling.

Whilst Figure 8 suggests at the recent introduction of higher resolution cameras for IRT-3DDF, represented by Adamopoulos et al.'s [68,70,76] FLIR T1030sc (1024 × 768), the adoption of ∼640 × 512 thermal cameras seems to be established within the research. Adamopoulos et al. [70] embrace this by validating their SfM photogrammetric pipeline, developed with a FLIR T1030c, with a FLIR SC660 (640 × 480) thermal camera, resulting in similar projection errors to their higher resolution camera (2–3 cm as opposed to 1 cm). This supports the belief that trade-offs between cost and resolution can be made for IRT-3DDF, with considerations for model accuracy and applications determined for a project's purpose [73]. Furthermore, recent studies utilising even lower resolution thermal images (∼320 × 240) demonstrate effective modelling when (1) a sufficient number of images are taken [75]; (2) an appropriate level of detail is determined [83]; and (3) accompanying data bolster interpretation [69,82].

Although the resolution of the thermal camera is a considerable factor for IRT-3DDF, the process toward camera calibration represents a critical opportunity to improve data fusion methods. IRT-3DDF camera calibration has prioritised the development of low-cost, portable targets visible for all sensors within a thermal camera; however, Usamentiaga et al. [95] stressed the need for greater transparency in methods of self-made calibration targets. Adamopoulos et al. created a "custom-made" target from aluminium foil and cardboard but failed to mention how this is constructed or to what degree of accuracy ([70], p. 6). Lagüela et al.'s planar target looked to identify the radiation from tungsten filaments on an 8 × 8 bulb matrix but similarly only hinted at the construction and geometry [59]. The geometric accuracy of thermal images represents a critical step in the processing of IRT-3DDF, and clarity in methods is vital for the development of pre-processing methods.

Additionally, the choice of image formats, image pre-processing and thermal camera settings can enable more information to be extracted for IRT-3DDF. Previtali et al. [86] demonstrated the importance of 16- and 32-bit TIFF formats for thermal images, able to capture the temperature range and thermal sensitivity of ∼640 × 480 cameras. Software such as FLIR Tools+ and FLIR ResearchIR have shown benefits of encoding thermal information at the pixel level, using the 32-bit TIFF format to embed temperature values prior to SfM [72]. Patrucco et al. [75] pre-processed thermal images of several facades to regulate false colour palettes across specified temperature ranges, enabling better interpretation of each individual façade and its conditions. Finally, advances in thermal cameras have not merely come in the form of greater resolution, but in the ability to set parameters, such as material emissivity, temperature ranges, NUC image correction, periodic image/video capture, and atmospheric humidity/temperature. These advances offer important opportunities for IRT-3DDF, enabling greater analysis of qualitative and quantitative thermography.

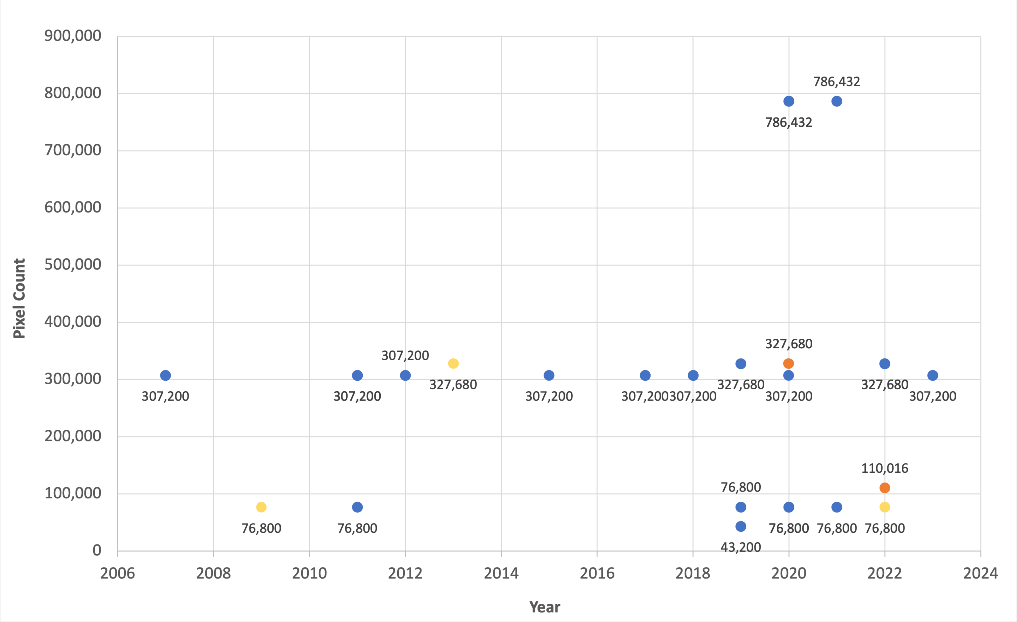

Figure 8. IRT-3DDF pixel count over time. Here, orange data points represent thermal sensors part of a TTIS, with yellow data points representing individual thermal sensors (see Table 2).

4.2.3. Thermography Type

Thermography type, the use of passive or active thermography, provides an additional variable for the analysis of architectural heritage, enabling IRT-3DDF to observe changes in historic buildings and gain additional insights for CRM practices. Passive thermography can be defined as the measurement of radiation without any artificial heat stimulation, capturing the natural thermal behaviour of a structure. In contrast, active thermography involves the artificial heating (or cooling) of an object to stimulate materials and monitor contrasts in their thermal signatures [19]. As seen in Table 2, the established use of passive thermography for NDT is apparent in IRT-3DDF [8], with survey planning maximising the thermal signature generated during image acquisition. The IRT-3DDF work acquired images in the absence of solar radiation [59,62,83]; during direct solar radiation [64]; and optimising solar radiation for specific materials, structures and investigations [63,65,75]. This consideration enables passive thermography to maximise the thermal signatures generated by architectural heritage and provides thermal images with identifiable gradients when processed photogrammetrically.

IRT-3DDF, exploiting active thermography, has looked to excite materials, generate responses, and reveal anomalies within historic buildings. In an attempt to understand the coverage of water treatment on historical brickwork, Barbieri et al. [60] captured images of bricks subject to targeted wetting over 75 minutes, allowing RGB composites to determine where treatment was deteriorated. Maierhofer et al. [67] heated a stone column with two 500W halogen lamps, capturing images throughout the duration of the active process. By normalising and fusing thermal images with a TLS mesh, correlations between temperature and material delamination could be visualised. Brumana et al. [91] pre-heated an entire room within the Magio Grasselli Palace to help identify the structural geometry of brick vault intrados, with active thermography helping bring out a discernible thermal signature. Importantly, approaches incorporating active thermography must consider how heating/cooling may affect the fabric of a historic building and whether such interventions appreciate a building's cultural significance. The exploitation of thermography type to determine material responses represents a significant opportunity for IRT-3DDF [96], with 3D-data fusion providing context on proximity and volume that can further enhance findings for architectural heritage.

4.3. Practical Data Charting

The benefits provided by IRT-3DDF, allowing for the visualisation and interpretation of thermal images in three dimensions, allowed the generation of thermal models that can have practical implications for CRM practices. The charting of thermal outputs, thermal findings and future developments helped to determine (1) how IRT-3DDF data are being utilised; (2) where the strengths and weaknesses of IRT-3DDF lie; and (3) what IRT-3DDF can enable for architectural heritage.

4.3.1. Thermal Outputs

Charting the thermal outputs, or thermal products, generated from IRT-3DDF looks to answer two important questions: (1) how have studies exploited the localisation of thermal data for their specific applications; and (2) what are the marked benefits deriving conclusions from 3D products as opposed to the conventional 2D interpretation? Scoping studies that have looked to utilise the dimensionality of IRT-3DDF have done so by focusing on the benefits that space and proximity can provide. Napolitano et al.'s [66] use of thermally textured TLS data within a numerical finite element model was able to quantify structural deformities and locate crack origins. Both [68,69] used IRT-3DDF to visualise registered RGB, IRT and GPR data in three dimensions (see Figure 9). This enabled the interpretation of GPR, typically visualised in graphical form, to compliment IRT, validate conclusions and facilitate multi-disciplinary interpretation. The importance of generating 3D products from IRT-3DDF looked to maximise the benefit that IRT provides in identifying hidden anomalies often located beneath the surface of architectural heritage. The interpretation of material degradation, moisture detection and historical restoration in 3D is critical to understand the forces acting on a building and the sources of both visible and invisible discrepancies.

However, as suggested by Cho et al. [31], the practice of IRT still overwhelmingly exploits 2D thermal images for interpretation, with IRT-3DDF supporting the effectiveness of 2D rectified products of architectural heritage. Costanzo et al.'s [65] registration of thermal images and a TLS reflectance mesh allowed the generation of 2D products capable of identifying cracks, deformations and material degradation across a whole building facade. Similarly, Mileto et al.'s 2D ortho-mosaics allowed comparisons between visible, thermal, material classification- and pathology classification maps to visualise the thermal behaviour of "porosity, critical moisture content, specific heat capacity and thermal conductivity" ([85], p. 409). Interestingly, while 2D products were favoured, the localisation of 3D phenomena, such as material density, was still accomplished through the colour palette of the thermal image, with denser materials appearing darker. The creation of a 2D thermal outputs by Scaioni et al. [87] represents a conscious choice for IRT-3DDF, undertaking image analysis on a whole building façade to determine the location, scale and degree of tile detachments. It is evident that planar IRT-3DDF outputs are often chosen to support existing data that require 2D interpretation or allow for the localisation of thermal anomalies for further analysis [75].

The determination between generating 2D- or 3D-thermal outputs is an important consideration for the scoping literature, highlighting where critical insights can be gained for IRT-3DDF. The complexity of phenomena acting upon architectural heritage, characterised by investigations of moisture detection, material degradation and heat transfer, require the appreciation of space and the importance of forces such as gravity. Fang et al. [82]

utilised 3D wall deformation, horizontal displacement (Y-axis), and ground subsidence (Z-axis) data in combination with IRT to understand the structural dynamics of masonry architectural heritage, stating that the fusion of 2D- and 3D-data allows for the comprehensive assessment of multi-faceted dynamics. Lewinska and Maciuk [83] demonstrated the importance of 3D geometry for the temporal analysis of historic buildings that have been subject to previous restoration, identifying differences in thermal signatures when the sun's position changes. Opportunities to advance the use of IRT-3DDF for architectural heritage must acknowledge the benefits of 3D data to provide context to identifiable thermal anomalies, and more use cases are needed to demonstrate the benefits that can be gained when studies lead with this ambition.

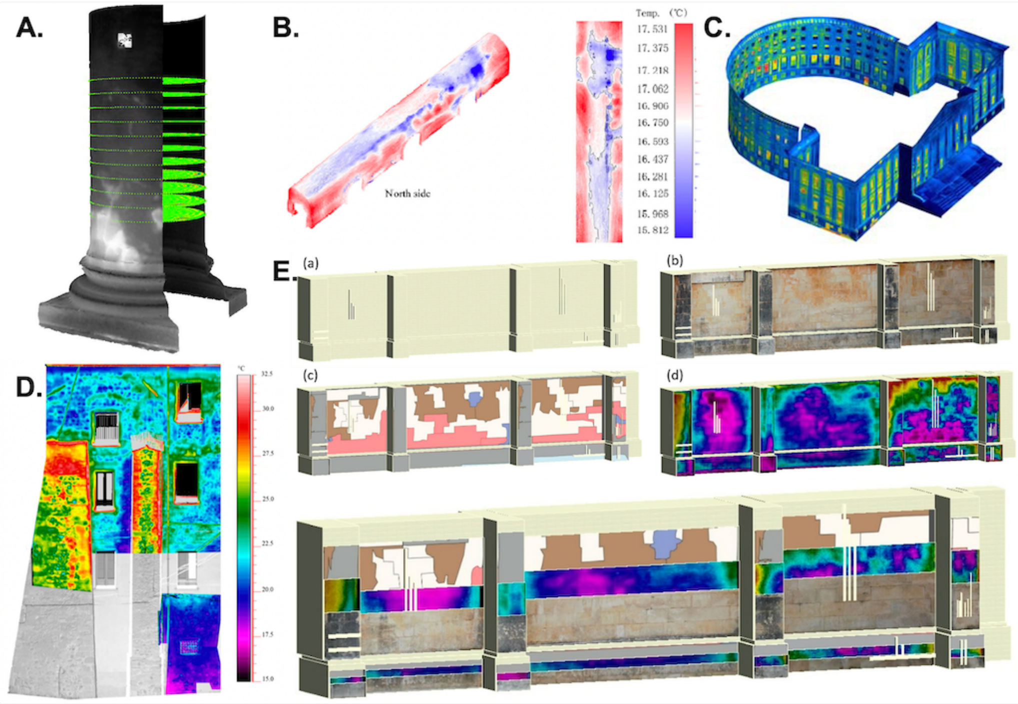

Figure 9. IRT-3DDF thermal outputs generated for (**A**) Castello del Valentino [68]; (**B**) Linggu Temple [82]; (**C**) Palazzo Barbieri [88]; (**D**) St. Augustine Monumental Compound [65]; and (**E**) The Monastery of Batalha [69].

4.3.2. Thermal Findings

The possibilities for CRM practices informed by 3D data as opposed to 2D data is an important determination for IRT-3DDF. The charting of thermal findings is performed not simply to identify where the scoping literature has mirrored findings that could be gained from 2D thermography, but to identify the opportunities that are present for data fusion. Therefore, a discussion is necessary to contextualise these findings within the scope of IRT-3DDF. Furthermore, with temperature data central to energy efficiency, retrofitting and thermal comfort assessments, it is vital to analyse studies that have applied IRT-3DDF to inform the emerging challenges of architectural heritage. As seen in Table 3, several studies are acking thermal findings, with their research centred around method development [59,71,88], model accuracy comparisons [70,74] and visualisation [62].

Table 3. Practical data charting.

Authors	Thermal Outputs	Thermal Findings	Future Developments
Adamopoulos et al., 2020a [76]	2D thermal ortho-mosaics	Material decay; Previous restoration; Structural integrity	Data integration
Adamopoulos et al., 2020b [70]	2D thermal ortho-mosaics; 3D thermal mesh model	-	Method development
Adamopoulos et al., 2021 [68]	2D thermal ortho-mosaics; 3D thermal mesh model	Material decay; Moisture detection	Data integration
Adan et al., 2020 [77]	2D thermal ortho-mosaics; 3D thermal mesh model	Thermal comfort assessment	Method development; Data integration (seasonal)
Alba et al., 2011 [78]	3D thermal mesh model	Material decay; Structural integrity	Method development; Research application
Artese et al., 2019 [79]	3D thermal mesh model	Crack detection	On-going conservation
Barbieri et al., 2023 [60]	3D thermal H-BIM model	Treatment failure	Data management (H-BIM)
Brumana et al., 2013 [80]	2D thermal ortho-mosaics	Archaeological investigation; Hidden structures	Data integration
Brumana et al., 2018 [81]	3D thermal H-BIM model	Construction age; Structural integrity	Data management (H-BIM); Structural simulation (FEM)
Cabrelles et al., 2009 [63]	2D thermal ortho-mosaics; 3D thermal mesh model	Material decay	Inform conservation practices
Costanzo et al., 2015 [65]	2D thermal ortho-mosaics	Crack detection; Material decay; Previous restoration; Structural integrity;	Data integration
Fang et al., 2022 [82]	3D thermal point cloud	Moisture detection; Structural integrity	Data management (BIM); Data integration (GPR)
Griffo et al., 2019 [62]	3D thermal point cloud	-	Augmented reality
Laguela et al., 2011 [59]	2D thermal ortho-mosaic; 3D thermal point cloud	-	Method development
Lewinska and Maciuk, 2020 [83]	3D thermal parametric model	Previous restoration	Data management (H-BIM)
Maierhofer et al., 2011 [67]	3D thermal mesh model	Material decay	On-going conservation
Martín-Lerones et al., 2021 [84]	3D thermal point cloud; 3D thermal parametric model	Crack detection	Data management (H-BIM)
Merchán et al., 2020 [71]	3D thermal point cloud	-	H-BIM creation; Segmentation
Mileto et al., 2015 [85]	2D thermal ortho-mosaic	Construction age; Material decay; Material density	On-going conservation
Napolitano et al., 2019 [66]	2D thermal ortho-mosaic; 3D thermal FEM model	Crack Detection; Material Decay; Structural integrity	Simulation; Numerical modelling
Patrucco et al., 2020 [72]	2D thermal ortho-mosaic; 3D thermal mesh model	Hidden structures	Archaeological investigation
Patrucco et al., 2022a [75]	2D thermal ortho-mosaics; 3D thermal mesh model	Hidden structures; Previous restoration	Data management (H-BIM)

Table 3. *Cont.*

Authors	Thermal Outputs	Thermal Findings	Future Developments
Patrucco et al., 2022b [74]	3D thermal point cloud; 3D thermal mesh model	-	Method development
Paziewska and Rzonca, 2022 [73]	3D thermal mesh model	Heat leakage	Energy modelling; Method development
Previtali et al., 2012 [86]	2D thermal ortho-mosaics	Material decay	Method development
Puente et al., 2018 [61]	2D thermal ortho-mosaics; 3D thermal point cloud	Material decay; Previous restoration	Visualisation
Scaioni et al., 2012 [87]	2D thermal ortho-mosaics	Material decay	Method development
Scaioni et al., 2017 [64]	3D thermal mesh model	-	Method development
Solla et al., 2020 [69]	3D thermal H-BIM model	Material Decay; Moisture detection	Data management (H-BIM)
Rizzi et al., 2007 [88]	3D thermal mesh model	-	Method development
Tsilimantou et al., 2019 [89]	3D thermal mesh model	Material decay; Structural integrity	On-going conservation
Zalama et al., 2011 [90]	3D thermal mesh model	Material decay; Moisture detection	Method development

Where studies have focused on the use of IRT-3DDF for building diagnostics, the breadth of thermal findings is apparent: identifying cracks, determining material loss, detecting moisture and discovering previous restorations. Refs. [61,85,89] demonstrated the use of IRT-3DDF for material classification and comparison, with the latter using this knowledge to determine re-construction stages. Patrucco et al. [75] showcased how multidisciplinary interpretations of architectural heritage are necessary to extract value from IRT-3DDF, using combinations of 2D- and 3D products to identify hidden architectural elements and determine volumes of previous modifications. Napolitano et al.'s [66] IRT-3DDF showcases an example of IRT being combined with numerical modelling to determine conservation insights. The fusion of TLS data and TIR images representing an internal wall of the Palazzo Vecchio enabled the identification of cracks penetrating the fresco, only visible due to the inclusion of IRT. These thermal findings generated from the scoping literature highlight the benefits to be gained from IRT-3DDF, with the appreciation of dimensionality critical in determining the origins of thermal discrepancies.

The desire for thermal findings to inform CRM practices was accentuated when the scoping literature's primary research focus, methodology and applications were aligned for a singular purpose. Maierhofer et al.'s [67] novel IRT-3DDF method appreciates the benefit to be gained from active thermography and TLS data, choosing a case study of deteriorated sandstone columns with visible spalling. Here, active thermography provided the means of differentiating material detachment in periodic thermograms whilst TLS data enabled the quantification of loss (up to 5mm thick layers). Costanzo et al. [65], analysing the effects of several earthquakes on the St. Augustine Monumental Compound, utilised IRT-3DDF to generate rectified images capable of determining structural irregularities and their origins. Previtali et al.'s [86] use of geographical information systems (GIS) software for cases of Italian heritage undergoing restoration allowed (1) the greater control of temperature values through 16-bit images; (2) the setting of material emissivity values obtained through lab experiments; and (3) the determination of suitable spatial and attribute queries for image analysis. The identified areas of tile detachment are in need of further investigation. When studies exploit IRT-3DDF with a deeper understanding of the architectural heritage at hand, workflows are developed that maximise the benefits of individual data sources and extract the value from their fusion when informing conservation practices [91].

4.3.3. Future Developments

The determination of future developments is a central task in the execution of a scoping review, enabling emerging trends and research gaps to be comprehensively mapped. The charting of future developments looked to capture themes identified within each study and collate those represented across all IRT-3DDF research. In addition, the contextualisation of these themes within broader research fields can identify possible research gaps in need of exploration. Firstly, research with a primary research focus on method development highlights the opportunities for effective workflows to evolve and become commonplace. Noting the sufficient resolution of TIR images for qualitative analysis, Adamopoulos et al. [70] suggested the ease of integrating imagery from a thermal camera's RGB sensor into existing photogrammetric projects, with their method allowing IRT to be fused and providing additional interpretations with relative ease. Furthermore, Patrucco et al. [72] demonstrated the need for future methodologies to appreciate both the scale and coverage of IRT-3DDF workflows, highlighting how data acquisition, equipment needs, survey planning and data processing must be amended for different buildings and styles. With an accurate base geometry derived from TLS or SfM data, future methods should demonstrate an ability to integrate/update thermal data within existing architectural heritage projects.

The benefits of IRT-3DDF for locating hidden anomalies and thermal discrepancies also points towards the integration of complimentary datasets that can provide additional information for 3D interpretation. Several studies have highlighted the strengths of fusing GPR [61], NIR [68] and classification maps [85] with IRT-3DDF models, demonstrating that additional data can help to inform decision making. Adamopoulos et al. [68] utilised reflectance, near infrared (NIR), image composite and GPR data for IRT-3DDF for the 3D visualisation of a stone column, showcasing the suitability of low-cost modified cameras to provide multi-band imagery. Interestingly, Webb et al. [97] suggested that access to specialised imaging devices is a current barrier for many heritage professionals and advocated for the use of modified cameras to overcome this. Furthermore, whilst the scoping literature showcases a preference for image-to-model (2D-3D) fusion methods, opportunities are emerging for additional fusion methods to be investigated [10]. Both [72,73] demonstrate the ability to generate 3D thermal outputs solely from TIR images using photogrammetric software, offering opportunities for future methods to explore co-registration between 3D-TIR and RGB point clouds [10,98,99].

The importance of data management is regularly identified within the practical data charting, stressing the need for platforms that can manage volumes of data efficiently, extract knowledge, and facilitate interoparable asset management. Both [69,75] exemplify the need for H-BIM capable of registering all spatial and non-spatial datasets for effective documentation. However, as highlighted by [84,91], the need for scan-to-HBIM solutions to generate these parametric models is a fundamental challenge to address [54,100]. Though thermal BIM is still in its infancy [29], the establishment of this initial modelling stage will provide significant opportunities for energy efficiency, retrofitting and thermal comfort assessments [25,34]. Additionally, heritage point cloud segmentation research presents a parallel discipline that can aid the delineation of not only H-BIM elements [101,102], but means of informing conservation practices [103,104]. As with IRT-3DDF, the benefit of combining geometric and radiometric features is similarly apparent, with both forms used to generate features for classifying architectural elements and pathologies. Whilst the semantic segmentation of thermal anomalies [105,106] and structural elements [11,35,107] has been demonstrated, research needs to establish methods that extract and manipulate thermal features from IRT-3DDF. Extending machine- and deep learning classification methods for IRT-3DDF can materialise in the identification of invisible discrepancies; the isolation of material degradation; assessments of structural integrity; and comparisons between new and old restoration.

The assessment of historic building's energy efficiency, retrofitting and thermal comfort are pressing issues for cultural heritage [56]; however, few studies have looked to use IRT-3DDF to inform these challenges. Adan et al. [77], coupling qualitative IRT and quantitative sensor data, provided a framework to visualise and contextualise the thermal signatures within architectural heritage. The desire to extend this study over a whole year and analyse seasonal temperature data demonstrates the capability of IRT-3DDF to provide a meaningful benefit for ongoing management. Similarly, Lewinska and Maciuk's [83] 24-h inventory of thermal textures for a parametric model provides inspiration for energy efficiency assessments that can evaluate building use, seasonal changes and retrofitting campaigns. The importance of temporality in the thermal assessments of a building, as suggested by [29,108], is a significant gap for energy modelling and IRT-3DDF. By exploiting IRT-3DDF as a means of not only visualising qualitative temperature distributions, but extracting quantitative temperature values from temporal assessments of historic buildings, challenges such as energy efficiency, retrofitting and thermal comfort can be examined with greater competency [28].

5. Discussion

5.1. IRT-3DDF Scoping Review: Reflections and Efficacy

As outlined in Section 2.1.2, the adoption of a scoping review looked to determine the breadth of IRT-3DDF for architectural heritage and to assess how these methods can inform CRM practices. This included mapping the emerging trends and research gaps presented by the scoping literature, with the ambition of identifying future areas of investigation. To meet this objective, an iterative literature search was undertaken with keyword clusters capturing each facet of the research question, resulting in 32 publications being collected for data charting. Notably, the biggest disqualifying factor of the literature search was the presence of IRT-3DDF. The evolution, diversity and absence of terms denoting 3D-data fusion, addressed in Section 3.2.3, suggests the need for a universal term to aid the development of IRT-3DDF for future identification. Whilst [77] presented the term '3D-TCV' (3D thermal computer vision), this review suggests that infrared thermography 3D-data fusion (IRT-3DDF) should be adopted to appropriately capture all work fusing thermal images to enhance its stand-alone value.

Furthermore, the undertaking of a scoping review enables researchers to suggest possible recommendations for future work, often explored through a more rigorous systematic review. Firstly, it is evident that the origins of IRT-3DDF as a field within the AEC industry present opportunities to explore the themes identified within the future development data charting. The expansion of the 'architectural heritage (context)' keyword cluster (see Section 2.2.3), formulated specifically for historic buildings, that encapsulates 'existing buildings' represents a logical progression for a systematic review. Secondly, as outlined by Arksey and O'Malley, assessments of study quality remain an optional component of the scoping review, with emphasis placed on determining the breadth and maximising the initial literature capture. Expanding this work through systematic review protocols, incorporating the suggestions above, would capture a greater number of studies and enable the study quality to be implemented more effectively through defined Inc./Exc. criteria quality metrics [41,42].

As identified in the research question, the ambition of this work is to inform CRM practices by identifying emerging trends within IRT-3DDF, helping researchers, policy-makers and professionals to determine strategic interventions for architectural heritage. Notably missing from the scoping literature are demonstrations of how IRT-3DDF thermal findings can lead to actionable insights, especially if such methods are to address the climate challenges and management needs of historic buildings. Recent work by Historic Environment Scotland and the Scottish National Trust, documenting water damage at The Hill House in Helensburgh, Dunbartonshire, demonstrates the emergence of IRT-3DDF as a viable and practical tool for heritage professionals [109]. To this end, Arksey and O'Malley's [42] stakeholder consultation (see Section 2.1.1 Stage 6) offers a framework to communicate the results of a scoping review and share findings for broader applications. Following guidance from Levac et al. [43], stakeholder consultation for this scoping review of IRT-3DDF shall look to transform the findings from Stage 5 to (1) identify suitable stakeholders for consultation; (2) transfer knowledge from the IRT-3DDF scoping review; and (3) determine a process for ongoing consultation for future work. With the ambition of evolving the scoping review, the reviewers have identified suitable stakeholders and hope to implement this review stage by communicating findings, validating conclusions and developing a plan-of-action for ongoing consultation within future work.

Finally, the execution of this scoping review, a novel approach for a multi-disciplinary research field, presents an opportunity to inform future guidelines and best practices for evidence synthesis. A supplementary objective of this work is to identify the strengths and shortcomings of scoping reviews as a means of assessing research for surveying engineering, computer vision and cultural heritage. Our ambition is for this work to act as an example that can be critiqued and provide discussion for (1) the suitability of scoping reviews for all fields; (2) the creation of subject-specific review protocols; (3) the differentiation between systematic, scoping reviews, evidence mapping; and (4) the use of scoping reviews for scientific communication.

5.2. Infrared Thermography: Principles and Practices for IRT-3DDF

The effectiveness of IRT for architectural heritage is established largely due to the experience of conservators, researchers and professionals. However, this scoping review highlights a critical point for discussion: IRT-3DDF can only be as effective as the user generating the information. IRT-3DDF presents multi-disciplinarity, where a knowledge of thermodynamics, which underpins both the qualitative and quantitative uses of IRT, is critical for surveys of architectural heritage [110]. Adan et al. [77] accentuated this by integrating variables for quantitative thermography, notably, emissivity, reflectivity, atmospheric attenuation and additional radiation sources, to calculate accurate temperature values [8]. Similarly, Previtali et al. [86] undertook laboratory experiments to determine the emissivity of both angular and linear tiles, a central factor for the execution of their GIS image analysis workflow. Both [65,66] made compromises on material emissivity in accordance with their aims, methods and the use of IRT, with the former deciding not to determine specific emissivity values per material but to apply an average across a whole façade. Though the scoping literature points towards technological advancements as a likely evolution of IRT-3DDF, the ability to extract more information from IRT represents a key challenge for future work. By understanding the principles behind thermodynamics and IRT, greater insights can be gleaned for both qualitative and quantitative analyses.

Additionally, the integration of thermodynamics within surveying engineering also requires attention, with amendments to experimental design needed to appreciate IRT, fusion methods and the architectural heritage. Patrucco et al. [72] stressed that existing IRT surveys are not easily amendable for data fusion, and whilst several studies have exploited standards for image acquisition (ASTM C1153-10 [66]; ISO 6781:1983 and ISO 14583:2017 [83]; CIPA '3 × 3' Rules [74]), these fail to appreciate the requirements of IRT-3DDF. The inherent low spatial resolution and narrow FoV of TIR images necessitate that greater attention be paid to image overlap (>80%); number of images; direction of image (i.e., planar, oblique, and convergence); and distance from the target. In addition, IRT-3DDF surveys must document where decisions have been made regarding survey conditions; thermal GCP targets; thermal camera radiometric and geometric calibration; temperature control measurements; and thermography type. Sfarra et al.'s [96] hybrid IRT approach (HIRT), combining passive-, pulsed phase- and principal component thermography to quantify defect depths, demonstrates where insights can be gained when such methodological details are carefully constructed for specific investigations. Therefore, establishing guidance on best practice is a necessary task for increasing transparency and clarity in decisions for the successful execution of IRT-3DDF for architectural heritage.

6. Conclusions

The presented scoping review looked to determine the breadth and future of infrared thermography 3D-data fusion (IRT-3DDF), an emerging technology capable of informing CRM practices. The need for innovative methods to address the pressing issues facing architectural heritage warranted the investigation of IRT-3DDF, with the scoping review protocol allowing emerging trends and research gaps to be identified. After executing an iterative literature search with specific keyword clusters and criteria, a collection of publications was investigated through bibliometric analysis, data charting and thematic analysis. Due to the inherent low spatial resolution of thermal images, the ability of data fusion methods to provide 3D geometries representative of a historic building allows the benefits of multiple datasets to be realised. IRT is a critical tool in the assessment of subsurface anomalies, and its interpretation alongside complimentary NDT datasets allows for comprehensive interpretations of architectural heritage to be undertaken. IRT-3DDF enables the benefits of 2D thermography and 3D geometry to be compounded, leading to the localisation and contextualisation of thermal discrepancies. This scoping review highlights the diversity of case studies, methods and application practices of current IRT-3DDF research and identifies future opportunities that can be gained to inform CRM practices. This is materialised largely in the qualitative diagnosis of structural, material and historical changes to architectural heritage, with IRT providing the means to visualise temperature distributions and detect anomalies.

It is evident that the development of H-BIM, the introduction of temporal analyses and the integration of additional NDT datasets represent logical evolutions of this body of research. In addition, further work is needed to determine broader applications of IRT-3DDF research, with assessments of energy efficiency, retrofitting and thermal comfort strategies central to future conservation strategies. Furthermore, a discussion of the fundamentals related to IRT-3DDF stresses the importance of survey planning, the understanding of thermodynamics and the competency of modelling as critical factors in the success of future IRT-3DDF applications. Finally, this scoping review should provide inspiration for future work undertaking reviews of emerging fields, demonstrating the generalisability of scoping review processes and the need for future a priori protocols to reflect multi-disciplinary research.

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