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Additive Manufacturing Technologies in Restoration: An Innovative Workflow for Interventions on Cultural Heritage

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032—055

The current advancement of this research within the construction sector is the missing link for bridging the gap between the digitisation of building processes and the fabrication of architectural components. Renewed market needs and contemporary design languages require increasingly in-depth digital proficiency for the management of representation and production. The primary challenge of turning digital data into matter in the building design field must be overcome in order to demonstrate a possible transfer of benefits for new constructions, or interventions on existing buildings. The scientific community unanimously states the importance of deepening the most updated digital fabrication systems. With the aim of elaborating a methodological approach that prevents the technique from prevailing over the cultural assets a project requires, the present study proposes an innovative workflow for restoration projects on culturally relevant architecture in a state of degradation.

#additive layer manufacturing

#digital fabrication

#second digital turn

#digital architecture

#cultural heritage

Introduction

Digitisation of design processes enables architects and engineers to interface with a common language, reduce uncertainties, and ensure greater awareness in decision-making phases.

In parallel, unceasing development of construction technologies aimed at processing digital data, and subsequently reproducing their spatial characteristics (Rocker 2006; Gershenfeld 2012), opened up new and unexplored design possibilities. This challenges and fundamentally transforms well-practised design traditions (Keating et al. 2014).

Indeed, when the first digital revolution came into play (Carpo 2013), the formal elaboration of architectural projects remained confined within the digital environment, represented through two- and three-dimensional simulations. The transition to the second digital era, theorised over the last decade as the second digital turn, determined the development of automated tools. These tools are programmable to materialise the digital space with great flexibility, without limitations imposed by standardised production methods (Carpo 2017). Digital manufacturing technologies, such as robotic arms, 3D printers, smart-assembly or combined tools, to name a few, laid the foundations for the customisation of performative architecture, spanning the technological unit and the architectural organism. This ongoing cultural breakthrough, which falls into the definition of post-digital (Figliola 2017), aims to make the digital space tangible and perceivable (Gramazio and Kohler 2008). This fills the gap left by the first digital switchover, which failed to develop an aesthetic and material sense in architectural production (Picon 2014).

Consequently, the design output is no longer just a link between the conceptual phase and the built result, as in the past. We are witnessing a substantial change to the typical architectural professional process, in which design is not separated from construction, and the transition between one and the other is almost instantaneous. This change reiterates processes and optimises methods leading to pioneering conceptual and aesthetic paradigms by allowing simultaneous work within digital and virtual environments.

Advancements in CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) interplay allow evaluation of successful digital architecture production experiments (Mostafavi and Bier 2016). Such experiments entail using secondary technological structures to articulate new constructions or existing volumes. Similar sequences comprising off-site technological units in factories or research laboratories, and on-site assembly of more complex architectural systems unite this applied research.

On-site automation is widely under study as the uncertainties of construction environments are still crucial features to be faced in order to change previously known building site settings.

Given these premises, it is of particular interest to explore the advancement of scientific knowledge within the restoration field. This requires case-by-case design solutions based on unpredictable variables such as lack of information regarding the buildings' geometry, assembly materials, and possible structural instabilities (Brandi 1963).

The present contribution investigates digital technologies and the role of manufacturing tools to support decision-making phases for innovative interventions on cultural heritage. In turn, it requires knowledge of traditional construction systems and craft methods as a metaphorical boundary in which design outcomes should be tailored.

Methodology

Today, valorisation and restoration projects on existing architectural heritage refer to established techniques used by artisans. Making decisions directly on site is a common task, although not always supported by adequate tools to ensure the digital documentation, repeatability, and measurability of the performance.

European approaches developed in the 1970s aimed at industrialising the construction process shifting from the serial prefabrication of building elements to the mass production of standardised housing estates and building systems (Zaffagnini 1981). Current methodologies are instead more oriented to customisation and personalisation (Bock and Langenberg 2014). This change opens new possibilities for industrialisation in sectors that require bespoke solutions, such as restoration.

The immediate consequences could be cost reduction and more reliable results over time, especially when the production of non-standardised components is required and serial production for their realisation is not viable.

Industrialisation within the building industry mostly refers to the off-site production of materials, products, and technologies subjected to quality supervision in a controlled environment. So far, in the European framework, on-site industrialisation is not widespread. It could particularly help to optimise the rate of time and quality for the production of discretised elements, that are not realisable through mass production.

The present study analyses projects on existing buildings realised through traditional procedures and, in parallel, deepens relevant experimentations on building site automation. For each set of case study projects, it draws attention to the main technical complexities that architects and researchers encounter and still requires in-depth analysis and applicability evaluations. Therefore, the paper classifies these technical complexities based on the priority in which they should be solved.

These considerations laid the basis for the definition of a first-hand experimental activity to explore a digital workflow for restoration processes, from design to construction.

Such methodology encourages dialogue between craft and information technology (IT) integration within interventions on cultural heritage.

Case studies: large-scale digital construction

Large-scale digital technologies generate complex geometries in a short time frame compared to non-automated implementations. In this analysis, depending on the construction process, they are categorised as subtractive technologies, additive assembly systems, additive layer manufacturing, and combined processes.

For each technology, design, production, or assembly processes are to some extent digitally controlled. Below are some examples in support of this research.

Researchers have explored subtractive processes primarily using computer numerical control (CNC) machines or hot wire cutters.

In 2015, the company D-shape[1], in collaboration with the Institute of Digital Archaeology[2] realised a scaled-down prototype of the Monumental Arch of Palmyra using a CNC machine on marble blocks. The arch was severely damaged after conflictual events and, for a long time, Palmyra's site was inaccessible. During that period, the scientific community promoted a campaign to create a database of photos of the area to produce a digital model using a photogrammetry technique. The following step was to display a symbolic reconstruction to raise awareness of the arch's cultural importance and continue encouraging documentation. Robotics, in this context, allow for an immediate reaction to a cultural loss and to address resources for effective reconstruction once local socio-political instability is over.

Research projects have mainly used robotic hot wire cutting (RHWC) to investigate design processes. Significant examples are the RDM Vault at Hyper-body's robotics workshop in Rotterdam (Feringa and Søndergaard 2014), and the REVAULT project at the University of Michigan.[3] An example is the realisation of study prototypes for the continuing construction of Gaudí's Sagrada Familia Church (Sheil 2012). Researchers previously investigated digitally-assisted stoneworking for columns and masonry components through scale models to learn the geometrical intricacies for each piece. This allowed professionals to deeply engage with the understanding of the geometry relations that Gaudì himself could not in his time understand because of the computational difficulties that contemporary digital design methods can resolve with higher success.

The realisation, in 2006, of the façade of the Gantenbein cantine[4] set the beginning of a series of process iterations led by Gramazio and Kohler Research (Wangler et al. 2016). Their approach is described as "the process of joining materials to create constructions from 3D model data" (Labonnote et al. 2016). The In-Situ Robotic Fabrication project specifically provides a significant step forward in the study of building automation regarding the future deployment of robots directly on site. In order to do that, the robot must recognise its position, the geometry of building elements nearby, and material tolerances (Gramazio, Kohler, and Willmann 2014). Current research enabling interactions with human workers can expand these capabilities. For the *Endless Wall* installation, for instance, a human drew a curve on the ground, and a robot correspondingly shaped a brick wall. This real-time update is a crucial point to support a robotic breakthrough in the construction sector (Keating and Oxman 2013).

Additive layer manufacturing (ALM) is a research area that requires technical optimisation for full-scale building applications. ALM's promising potentials lie in safety, limitation of raw material waste, cost-efficiency, control of material storage, and experimentation with innovative materials. Speed and geometrical freedom are not fully resolved aspects. Although advanced building construction companies are integrating additive processes on site, these tools lack the level of development of industrial robots. The "process of joining materials to make objects from 3D model data, usually layer upon layer"[5] is achievable through two foremost tested systems, based on different methods for the generation of the machines' toolpaths: powder-bed deposition and bulk-material plotting. These terms are often approximated to 3D printing, which is instead a subset of these techniques.

Researchers applied the first process additive construction using a powdered sand mixture cured through hydration with an inorganic binder. *Radiolaria*, a prototype realised in 2007 by D-shape, is generally considered to be the first large-scale freeform additively manufactured structure.

Material plotting is the most used in academic research. It is usually clay based. Among the most effective experimentations we can find are Woven Clay (Friedman, Kim, and Mesa 2014), Pylos (Dubor, Cabay, and Chronis 2018), and InFormed Ceramics (Ko et al. 2018) projects.

This study, from the technical perspective, refers to ALM as:

1. An end effector installed on a robotic tool;
2. A means of fabricating objects from the

digital environment;
3. Through material deposition;
4. Using a print head.

Scaling up the ALM process to the architectural scale requires awareness of the interplay between equipment objects. Large extruders limit robot behaviour during fabrication, and the overall efficiency of work may decrease every time workers must fill the container with new material. This can also affect the object's drying process and deformation.

The present research is interested in the analysis of additive manufacturing procedures. It will address a laboratory experience, based on this approach, to collect data and find critical solutions for some technical complexities that occur during implementation.

Cases of restoration making

The digitalisation of building sites under restoration is an opportunity to link digital design and digital building processes. At the time of writing, digitisation has revolutionised design, thanks to dedicated architectural software. By merging digital production and assembly, digital construction can simplify the process from digital design to digital production of finished structures and buildings (Labonnote et al. 2016).

As previously mentioned, it is essential to remember that restoration processes require a case-by-case approach. Although a long construction tradition codifies possible decisions, they cannot always be evaluated in advance or processed through digital means.

The traditional construction site is structured with a sequence of events following a linear scheme (National Heritage Training Group 2005). Each occurs when the previous action is concluded (Zaffagnini 1981). *In situ* procedures can be completed with off-site integrations or with architectural discretised components installed directly on site.

To date, definition of the digital building site is underway. Construction phases do not necessarily have to follow a deterministic scheme. Innovative construction tools may include robotic arms to lay building materials, customise on-site standard components, and build volumetric additions if required.

The tools currently available on the market need enhancements to develop a complete construction cycle *in situ*. Evidence of this can be found in case studies disseminated at an international level, which hybridise on-site and off-site production (Gramazio and Kohler 2014).

Notably, additive manufacturing can be considered an attempt to replace wet construction systems, because it does not require extended drying time or formwork for casting and curing.

This study primarily focuses on damage to buildings' geometries, such as the collapse of building elements, gaps in the building envelope or decorations, and the loss of elements of the volume.

Given this limitation, this paper examines several projects of volumetric additions or fragment replacement on historical architecture (*Fig. 1*).

The same decision-making approach unifies such projects. For each building, architects consolidate the existing surfaces and design the missing parts by choosing a recognisable language, in contrast with historical patterns. A brief description of selected restoration cases follows.

The first analysed project is the Hedmark Museum in Hamar, Norway, it is Scandinavian vernacular architecture restored by Sverre Fehn in 1971. The building holds three layers of history:

1. The thirteenth-century Bishops' fortress ruins of the Ancient Diocese of Hamar;
2. The eighteenth-century barn built using the ruins of the ancient medieval palace as parts of the walls;
3. The twentieth-century intervention bringing the building to its contemporary state.

The present temporal layer lies atop the ruins. The architect emphasised openings and gaps in the building envelope, covering them with plate glass, touching the structure with metal pins on each corner, and providing an ephemeral contrast to the massiveness of the pre-existent structure.

Architects applied a similar approach to the Monastery of San Juan in Burgos, in the north of Spain. The parish built the historical volume in the eleventh century. It suffered damage due to two successive fires in the fifteenth and sixteenth centuries. At present the structure is mainly in ruins, though exterior sidewalls survive. Conservation efforts led in 2015 for the construction of a roof which floats above the ruins. This roof preserves the ruins as an independent structure, keeping the perception of the original architecture unaltered. It is shaped like a large folded plane that evokes the ecclesiastical three-nave temple that initially existed. All volumetric integrations were designed by BSA studio using different materials, colours, and textures from the pre-existent masonry.

Another notable example in the European context is the Kolumba Museum in Cologne, Germany. Designed by Peter Zumthor, it was built between 2003 and 2007. Previously, the site was occupied by the Romanesque Church of St. Columba, destroyed in World War Two and replaced by a chapel in 1950. The new structure combines existing fragments of the Gothic church and the 1950s chapel into one complete building. The museum shares its site with the ruins, wrapping a perforated grey brick facade around them. The new work adopts the original plan of the ruins to become part of the architectural continuum.

Finally, the eleventh-century Cathedral of Bagrati in Kutaisi, Georgia, is a restoration case of reintegration. It focused on the substitution of damaged elements with modern materials, inside a valuable example of eleventh-century Georgian architecture. The building has been heavily damaged throughout the centuries and was reconstructed to its present state through a gradual process starting in the 1950s, with significant conservation works conducted in 2012 by Andrea Bruno. The contemporary volume is adjacent to the historic walls, and it is recognisable by differences in geometry and colour from the ancient masonry.

As for digital constructions, research extrapolates technical complexities that a traditional restoration construction site requires. Among these:

1. Production of customised elements to be installed within geometrical constraints;
2. Structural enhancement; and
3. A formal language to resolve the interface between the pre-existing and the new intervention.

Researchers transferred these variants in a hypothetical digital restoration site, which is considered a consistent option once the advancement of technology solves some key aspects in order of priority. Among these:

1. The space required for automated systems to be installed near ruins;
2. The possibility to produce non-standardised elements in touch with irregular vertical or horizontal surfaces;
3. Development of engineered materials with load-bearing properties;
4. Systems to control the colour scheme of ALM outputs.

A simulation of a possible digital construction site for restoration projects follows.

Test-bed: the Woodward Avenue Presbyterian Church

The innovative contribution of the present research is underway at the College of Architecture and Design (CoAD) of the Lawrence Technological University (LTU) in Southfield, Michigan in collaboration with the Department of Architecture of Ferrara, Italy.

The common goal is to address the use of digital fabrication in restoration, as an opportunity to update cultural heritage conservation processes. In this field, digital tools are rarely implemented owing to a lack of studies that assess their applicability and benefit.

Researchers at CoAD are mapping historical architecture in the Detroit area under degradation, resulting from the collapse of the local economic system in the 1970s.[6] Most of these buildings are included in the Federal National Register of Historic Places.[7]

Survey activity has produced a dataset used to classify architecture of cultural relevance that is partially or entirely damaged, starting with those that are already labelled to be preserved.

Researchers use this cataloguing process to find a consistent test-bed. The test-bed chosen is an abandoned building characterised by several critical geometric conditions analysed using digital tools. Researchers decided to examine the Woodward Avenue Presbyterian Church, a neo-gothic building constructed in 1911, which has been a national landmark since 1982.[8] The last religious service in 2005 marked the beginning of its abandonment (*Fig.* 2).

A preliminary photographic analysis identified the main critical aspects. They specifically concern the structure and the external envelope. Cracks in windows have allowed rain to wet stones and wooden elements over the years. Thus, several architectural components have experienced repeated freeze-thaw cycles, exacerbated by Michigan's harsh continental climate. Moreover, gaps exist in the perimetric walls, and the layers of the internal vaulted systems are no longer cohesive.

Survey activity integrated data obtained from complementary tools. An *imaging 360-degree laser scanner* collected point clouds of overall building geometry.[9] A *structure-sensor* operating through a photogrammetric technique created meshes of decorations or structural details that are out of range for the scanner's visual cone (*Fig.* 3). In addition, a *lidar sensor* connected to a drone integrated geometric data for inaccessible areas (*Fig.* 4).[10]

The aforementioned analysis of restoration making cases helped categorise damage within the building system. In fact, this phase of the research consisted of mapping areas of the building united by certain characteristics. These include loss of portions of materials and presence of uneven vertical and horizontal surfaces. The wall gap was used as an investigation field (*Fig.* 5).

Experimentation: filling the gap through additive manufacturing

The quantitative data collected during the survey of the Woodward Avenue Church were turned into matter through the full-scale realisation of a wall's portion.[11] This wall prototype is a test-bed to simulate possible on-site operations of additive manufacturing for the production of large-scale architectural elements on complex geometrical constraints as wall gaps (*Fig.* 6).

Researchers employed specific equipment for testing the digital manufacturing process. A six-axis robot executed kinematic sequences. Installed on the robot head is an end effector, or a nozzle connected to a flexible hose, for extrusion of printing material. A pipe pushed the printing material into the end effector under compressed air power.

Researchers modelled the volume of the wall gap and linked this model to a parametric digital environment,[13] to ease iterations and possible variations of the process. Researchers then sliced the model into horizontal layers that were filled with an internal support geometry. The project team broke resulting polylines into a list of targets for the robot to reach. Researchers offset each layer multiple times to generate the required wall thickness.

Thereafter, researchers generated the robot toolpath over the model. To do so, they employed a plug-in[14] that extends the software's capabilities and allows the remote programming of the robot axis. The project team used this component to design a script, or toolpath generation algorithm, that converts target points into robot code and simultaneously detects collisions, reachability issues, and singularities (*Fig. 7*). Before uploading the code in the robot controller, researchers validated axis kinematics by visualising the robot at each of the targets and checking for targets out of reach, joints out of range, singularity issues, self-collisions, and collisions with surrounding objects (*Fig. 8*). The virtual simulation provided an early opportunity to correct possible issues that may have occurred. This was followed by a simulation of the robot kinematics in the physical world. Before interacting with the wall prototype, researchers wrote a basic script to analyse whether the robot could operate effectively within a simple geometrical constraint. The wall crack was approximated to a rectangular gap (*Fig. 9*). This allowed the project team to check the positioning and the rotations of the nozzle at every target point.

Currently, extrusion testing is under study. Clay was chosen as a base material for the experimentation because it is easily recyclable, comparatively inexpensive, and workable to achieve a high-quality finish (*Fig. 10*).

During experimental phases, certain aspects will be monitored. Researchers will evaluate the precision, replicability, and measurability of the process performance.

The responsiveness of the material, in terms of viscosity, hardening rapidity, and compressive strength limitation, is critical in relation to the different surfaces slopes deposited through the end effector (*Fig. 11*). The accuracy of the robot in the physical world, following the software simulations, determines whether the end effector is just touching, or colliding with the wall surface. Moreover, linear and rotation limits of the robot axes set up the most suitable toolpath speed for the realisation of the wall gap volume.

The achievement of the expected research results is a tangible opportunity to merge the design processes and construction, or making, procedures (Stevens and Nelson 2015). They contribute to defining the characters of the future digital craftsman, within which "the automatic feedback between the machine and the material is the next step of digital craftsmanship" (Carpo 2013).

Speculation on additive manufacturing

The output of this research includes the algorithm design, based on overcoming the concept of standardisation. This premise is commonly used for the elaboration of generative volumes. In this context, the research took advantage of these potentials to deepen new design paradigms in restoration for volumetric integration of complex shapes in building envelopes (Codarin and Medici 2018).

This project's outcome is an algorithm that guides a robot to reach target points and make clay extrusion possible. It allows for the management of ALM processes in all aspects.

The script is composed of a sequence of information:

1. Input geometry;
2. ALM geometry;
3. Robot toolpath;
4. Axis kinematics;
5. End effector installed,
6. Analysis data; and
7. Output.

Every component can be modified to explore different iterations and proofs of concepts.

On the one hand, ALM use shortens the production process of customised components and reduces on-site storage of building materials. In this research context, layers are the architectural units to measure a building process. They are basic components, a new statement to describe a future holistic concept of tectonic construction.

Restoration practices could benefit from this approach. Digitisation of the restoration site opens the door to replicability, prediction of architectural systems' performance, use of new building techniques, or elaboration of traditional craft.

Additionally, the use of on-site robotics could help operations in inaccessible areas, especially in post-emergency conditions where fast measures are required. Moreover, it could enhance the quality of results, thanks to the programmable level of detail. Robots read and turn digital algorithms into restorative actions. The elaboration of a wide database of program scripts could help address digital documentation on Cultural Heritage and encourage further studies or application testing.

In this shift of design paradigms, the architects have the role of the professional who achieves several complex tasks. They produce the idea and develop the concepts through the project. They then have the knowledge and the tools to simulate the three-dimensional result in the digital environment. Finally, they can realise the physical model using large-scale tools associated with end effectors that link digital data to the tangible world in a continuous, uninterrupted flow.

The process takes place in a digital continuum (Leach 2002), which is the operative expression of the digital infrastructure we live in (Levitt and Dubner 2014), where skills and professional competencies meet.

Digital tools expand the designer's workspace, introduce the possibility of customising production, and extend the digital designer-craftsman arm (Sennett 2008), simultaneously linking design and fabrication.

The designer must define an innovative system of man-machine relations through a conscious approach that draws on traditional craftsmanship.

Acknowledgements

The experimentation is made possible thanks to the College of Architecture and Design of Lawrence Technological University – Southfield – Michigan - USA.

Notes

1. For further information, see: https://d-shape.com/(online: 10 March, 2019).

2. For further information, see: http://digitalarchaeology.org.uk/ (online: 10 March, 2019).

3. For further information, see: https://taubmancollege.umich.edu/research/research-through-making/2011/revault (online: 10 March, 2019).

4. For further information, see: http://www.gramaziokohler.com/web/d/bauten/52.html (online: 10 March, 2019).

5. See the ASTM definition of additive manufacturing: https://www.astm.org/ (online: 10 March, 2019).

6. Significant abandonment of Detroit's built heritage began during the oil crisis, which affected the United States of America from 1973 to 1979 and significantly affected Detroit's auto industry-dependent economy.

7. For further information, see: https://catalog.archives.gov/ (online: 10 March, 2019).

8. The documentation about the Woodward Avenue Presbyterian Church is available at: https://catalog.archives.gov/id/25338557 (online: 10 March, 2019).

9. The point cloud of the Woodward Avenue Church is available at: http://webmodel.space/ (online: 10 March, 2019).

10. The present analysis addresses some deductions: 1) the most accurate geometric digital output (point cloud) is given by the laser scanner; 2) the structure-sensor is a useful complementary tool that can be used for quick surveys; 3) drones have the potential to collect data in inaccessible areas, but are not necessarily easy to use. Drone-supported scanners are not static tools, and the downdraft generated by the propellers raises dust and sediments from architectural components.

11. The experimentation is underway at the makeLab of the Lawrence Technological University. For further information, see: http://make-lab.org/ (online: 10 March, 2019).

12. The robot arm employed is a Kuka Kr6-arc, used for research and academic purposes at CoAD of Lawrence Technological University.

13. See: https://www.grasshopper3d.com/ (online: 10 March, 2019).

14. See: https://www.robotsinarchitecture.org/kuka-prc (online: 10 March, 2019).

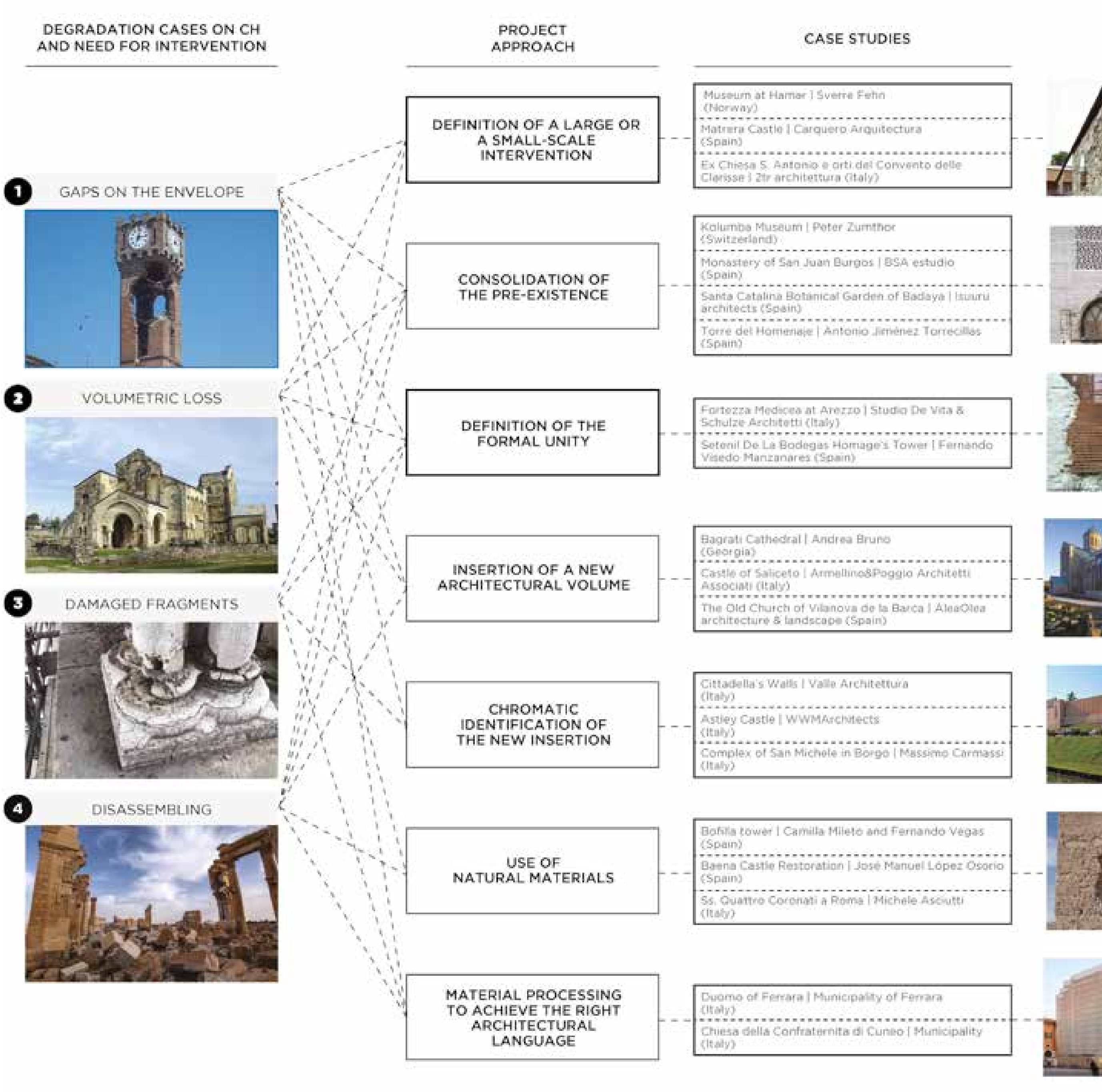


Figure 1: Cases of restoration of architectural heritage in the international framework. The selected projects are characterised by a similar design approach, using a contemporary language. Source: *author.*

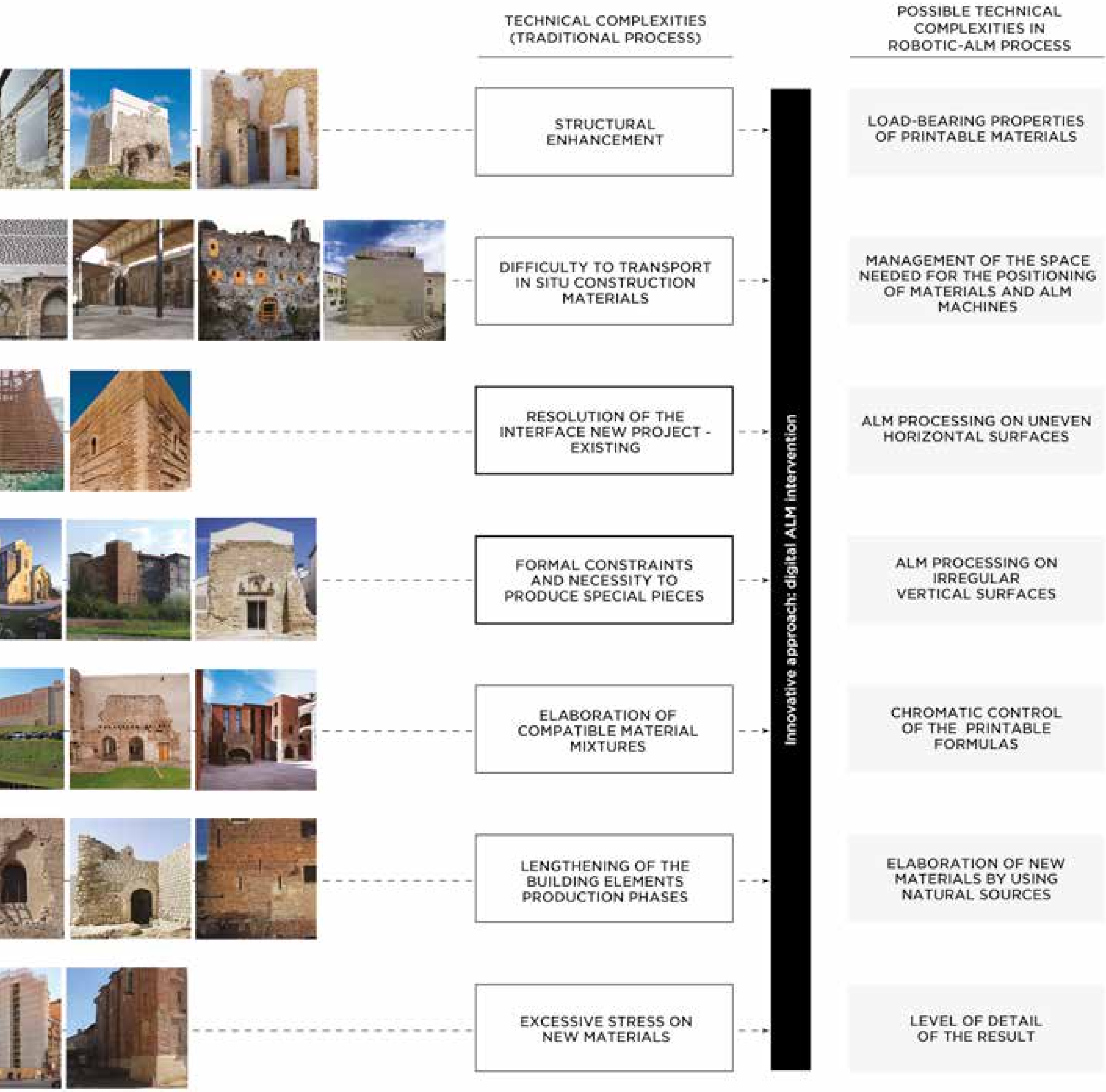

TECHNICAL COMPLEXITIES (TRADITIONAL PROCESS)
POSSIBLE TECHNICAL COMPLEXITIES IN ROBOTIC-ALM PROCESS
STRUCTURAL ENHANCEMENT
LOAD-BEARING PROPERTIES OF PRINTABLE MATERIALS
DIFFICULTY TO TRANSPORT IN SITU CONSTRUCTION MATERIALS
MANAGEMENT OF THE SPACE NEEDED FOR THE POSITIONING OF MATERIALS AND ALM MACHINES
RESOLUTION OF THE INTERFACE NEW PROJECT - EXISTING
ALM PROCESSING ON UNEVEN HORIZONTAL SURFACES
FORMAL CONSTRAINTS AND NECESSITY TO PRODUCE SPECIAL PIECES
ALM PROCESSING ON IRREGULAR VERTICAL SURFACES
ELABORATION OF COMPATIBLE MATERIAL MIXTURES
CHROMATIC CONTROL OF THE PRINTABLE FORMULAS
LENGTHENING OF THE BUILDING ELEMENTS PRODUCTION PHASES
ELABORATION OF NEW MATERIALS BY USING NATURAL SOURCES
EXCESSIVE STRESS ON NEW MATERIALS
LEVEL OF DETAIL OF THE RESULT
Innovative approach: digital ALM intervention

Figure 2 (top, opposite page): Interior of Woodward Avenue Presbyterian Church. Students and researchers at the College of Architecture and Design of Lawrence Technological University conducted a geometric survey for research purposes. Source: *author.*

Figure 3 (bottom, opposite page): Digital mapping achieved by using a Lidar sensor. It provides real-time geometric and photogrammetric information. This tool is used in quick assessment surveys. The outcome is useful in the preliminary phases of a project. Source: *author.*

Figure 4 (top): Experimental survey conducted with a drone connected to a structure sensor for collecting data in inaccessible areas. Use of this tool highlighted some critical aspects, including impact of the drone's kinematics on dust and stone debris, and flight time division into regular intervals to increase data accuracy and approximation. Source: *author.*

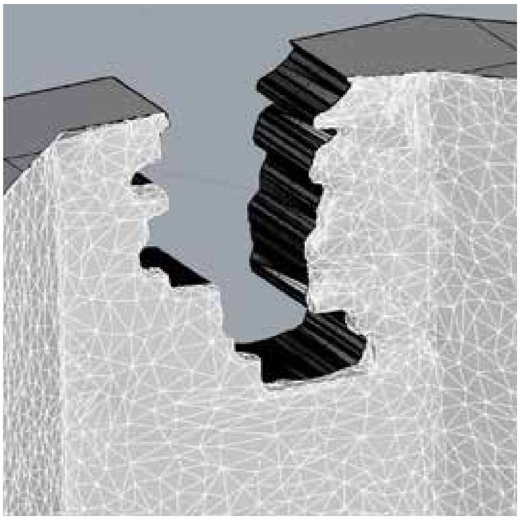
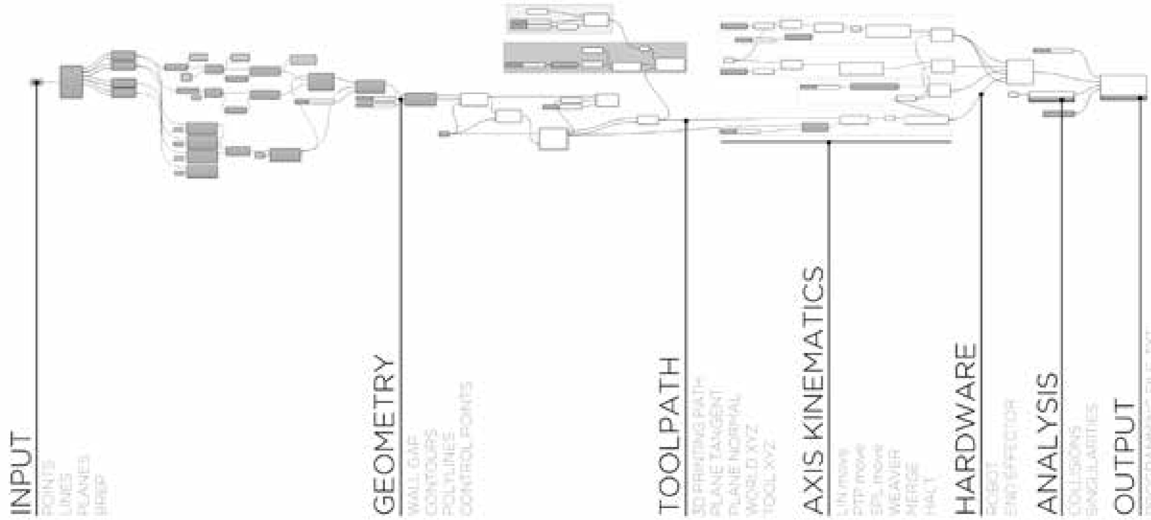


Figure 5 (opposite page; top to bottom, this page): Elaboration of the test bed. 3D modelling of the building's wall crack and overlapping of the geometry with photogrammetric information. Lidar sensor scans supported the proposed workflow for quick decision-making in urgent response scenarios. Source: *author.*

Figure 6 (top, page 48): Experimental settings for the simulation of an on-site digital robotic process. Operating in the physical world allows us to analyse all possible interactions between the robotic arm and the static geometries surrounding it. Source: *author.*

Figure 7 (top, page 49): The algorithm developed to guide the robot through the ALM process. Every cluster of inputs is strictly related to the mathematical rules underlying geometry. Therefore, geometry in space related to an action's execution time determines the robot's kinematics. Source: *author.*

Figure 8 (middle, page 49): Definition of the ALM toolpath and robot's movements within a geometric constraint in the digital environment. This procedure detects errors, such as collisions or positioning of unreachable target points, in an early stage of the design process. In the event of such mistakes, the virtual robot turns red. The script generates a graph describing which robot axis has issues and when. Source: *author.*



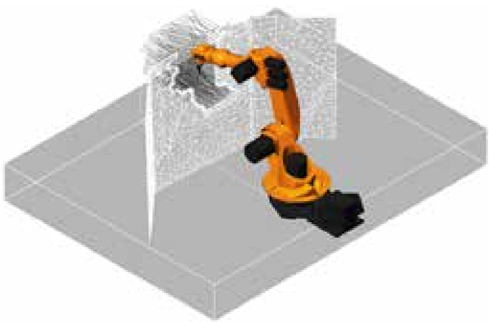


Figure 9 (below): Video frame images of the robot interacting with simple geometrical constraints generated by two vertical surfaces. This was an early stage before adding levels of complexity to the experiment. Source: *author.*

Figure 10 (opposite page): First extrusion of the toolpath. It is composed of the outlines and the internal supporting geometry. Initial testing was made on a flat surface to analyse the material's response to the robot's speed and to the nozzle's orientation relative to gravity. Source: *author.*

Figure 11: Iterative testing of the additive manufacturing process, using the end effector installed on the robot's head. Source: *author.*

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Bio

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