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Digital Intervention Methodologies and Robotic Manufacturing for the Conservation and the Restoration of 20th-Century Concrete Architecture Damaged by Material Loss

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This article deals with the characterisation of robotic manufacturing systems and digital interventions adapted for the conservation and the restoration of 20th-century concrete buildings. By exploiting the potential for analysis and implementation of robotic manufacturing technologies used in the field of heritage science, two associated non-invasive, non-destructive and integrated intervention solutions are presented here, using two research approaches. Through the use of digital recording tools, digital modelling / simulation and additive manufacturing techniques, the first approach develops a direct repair process by adding material with the help of aerial robots. The second focuses on printing recyclable plastic mouldings in order to reproduce partially degraded or completely destroyed architectural details. The results of these two diverse and complementary researches, as well as their experimental approaches applied to conservation and restoration practices, aim to test the proposed robotic manufacturing-based method, regarding the criteria of transferability and methodological feasibility.

Keywords: 20th-Century Concrete-Built Heritage, Conservation and Restoration Practices, Digital Modelling, Robotic Manufacturing, Democratisation.

RESEARCH CONTEXT

In Europe, from the 1910s and the beginning of the standardisation with the first molded cement masonries, until the widespread use of reinforced concrete technologies in the mid-1960s, concrete architecture continued to evolve through the implementation of innovative, ground-breaking manufacturing techniques for the time (Avenier, C, 2017). Now, the conservation of this endangered architectural heritage is being debated at a time when the emergence of advanced intervention technologies is creating new paradigms and challenges. Indeed, in view of the numerous cases of damage identified by extensive research programs

(Redmonest, 2016), most 20th-century concrete architecture is now affected by an upsurge of degradation through corrosion (Pardo Redondo, G et al., 2021) generally caused by the exacerbation of certain environmental factors (climate change, pollution, erosion...), by the weakening of internal structures (carbonation, reinforced steel expansion, water infiltration...) and even by anomalies and defects present when the building had originally been built. Therefore, these problems call for innovative and advanced technical solutions which rise to the challenges of sustainability, economy and respect for the intrinsic value of the buildings (ICOMOS, 2002). In view of the urgent need to

conserve and restore damaged parts of these buildings, certain innovative practices seek to preserve the integrity of architectural features of concrete buildings as much as possible (LRMH, 2020). Regarding to the current intervention methods and knowledge on concrete building damage (Khemakhem, M et al., 2020), (Quénée, B et al., 2021), some approaches (like purging and cleaning) carried out for curative conservation and restoration proposes, still require the use of heavy, invasive or hardly reversible manufacturing techniques. Using such procedures is not without limitations for the preservation and the enhancement of 20st century concrete architectural features. Moreover, from the context identified, on the current capacities and the technical limitations of human conventional practices (Table 1), we question the hypothesis of the complementarity of digital manufacturing techniques for advanced conservation and restoration of concrete damages (Table 2).

Current practices	Technical limitations
A case-by-case approach	Long-term approaches to restoration
Standard concrete patch repairs	Invasive / Low reversible interventions
Small/ Minimal scale interventions	Integration of low level of complexity/ Low precision results
Reproducing original craftsman work techniques	Low-tech/ high-cost manufacturing techniques
Potential for reprocessing	Heavy work/tasks

In continuity with the context of the Second Digital Turn and the digital mass customization paradigm introduced by Mario Carpo (Carpo, M., 2017), related to the possibility for a broaden use of digital manufacturing processes, heritage science research is now embracing the adoption of light, specific and low-impact intervention methods.

AIM AND APPROACH

Significant scientific studies have already addressed this issue by developing new practices for the implementation of processes designed to safeguard and enhance the value of existing buildings. Used more and more in the field of archaeology for the conservation of ancient works of art which require cutting-edge techniques and technologies, the use of robotics is now far more widespread and employed on a larger scale, for a broader range of subjects (Acke, L et al, 2021, p. 278). In the light of the gradual expansion and democratisation of these processes in the fields of architecture and heritage, it is now possible to optimise traditional manufacturing techniques for complex projects. To this end, methodologies adapted to each kind of intervention must be put in place to ensure the execution of certain difficult manufacturing tasks. Thanks to 3D printing, digital milling using robotic arms, or even the use of drones (lyoda,T et al., 2018), relevant scientific research studies have demonstrated the efficacy (and economic efficiency) of these intervention methods on existing buildings (Chan, B et al, 2015). To bring scientific innovation into the field, the research aims to develop digital intervention methods using robotic manufacturing for maintenance, repair and reconstruction of the damaged structural parts and detailed ornaments. The goal is to define decision-making processes and intervention support for integrated, non-invasive and reversible solutions, complementary to conventional practices used for the conservation and the restoration of 20th - century concrete architectural heritage.

Table 1
Current practices for the conservation and restoration of 20th-century concrete heritage buildings.

Table 2
Hypothesis for
robotic
interventions
in the research field
for the
conservation and
the restoration of
20th-century
concrete heritage
buildings

The next section of this article aims to focus on the study of robotic and digital manufacturing systems and, more specifically, on the use of additive manufacturing technologies to complement intervention methods.

SCIENTIFIC RELEVANCE (STATE OF THE ART)

Much of the current research in heritage science focuses on the potential of the additive layer manufacturing technology (ALM) applied to existing buildings. Used in the building industry to optimise and produce non-standard shapes, it contributes to the development of methods which aim to include the transfer traditional of manufacturing techniques to the challenges of digital turn (Mastrorilli, A et al., 2017). Consequently, it extends to the architectural conservation and restoration field, by providing technical and methodological support for work on existing buildings. Other recent studies have resulted in experiments relating to the development of the potential of this technology for repairing material loss (by volume) (Codarin, S., 2020). By carrying out direct intervention scenarios on damaged architectural elements, they show how an integrated process with robotic technologies can achieve tasks with high levels of complexity. Inspired by other referenced work in the field of large-scale robotic production, such developments are part of the control system and optimisation objectives achieved by automating certain tasks. Similarly, additive manufacturing by fused deposition modelling (FDM), used to reconstruct lost architectural fragments and details (Higueras, M et al., 2021) or to replace damaged elements (Bustamente, A et al., 2017), represents one of the most accessible robotic manufacturing methods (Scopigno, R et al., 2015). It gives rise, for example, to a greater scope of techniques for the production of replica or substitute moldings (at full or reduced scale) depending on the cases observed.

Hypothesis for robotic interventions	Research improvements
Integrated approaches	Short-term restoration approaches
Non-standard concrete patching repairs	Non-invasive / highly reversible interventions
Maximum scale interventions	Integration of a very high level of complexity/ high precision results
Optimising original craftsman work techniques	High-tech /low-cost manufacturing techniques
Automation/ task control	Lightweight work/ tasks

Therefore, robotic additive manufacturing allows to anticipate the risk of errors by evaluating physical and technical constraints prior to conservation and restoration work phases. As reverse engineering methods (Segreto, T., 2017), those technologies can help to reconstitute original knowledge of and techniques used in the existing building, thanks to digital recordings and the analysis of historical data. They provide endless possibilities for adapting the various responses to the process of safeguarding and enhancing the architectural heritage (Weigert, A et al, 2019). Thus, from the diagnosis of existing structures to the use of additive manufacturing technologies, most of these scientific studies have enabled us to identify three levels of application for regularly used digital and automated tools.

METHODOLOGY

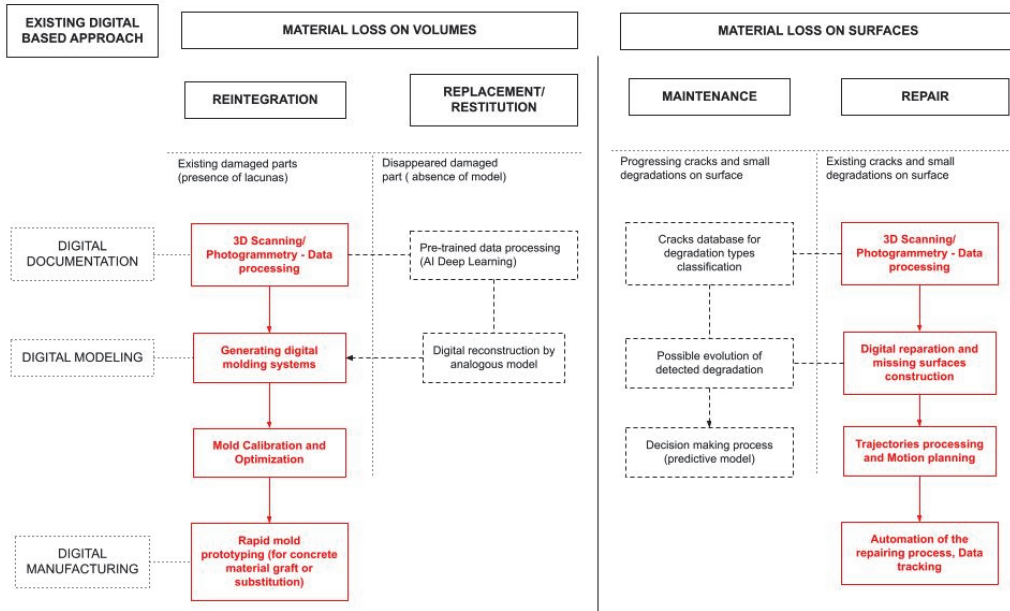


Figure 1
Existing digital based approaches used and the proposed methodology for the conservation and the restoration in architectural built heritage

Generally speaking, the approaches described demonstrate broad-ranging techniques and methods of manufacture from the maintenance to reconstruction of damaged building parts. Given the technical particularity of the intervention context, we suggest the development of a methodology for exploring these three different levels of digital and robotic applications (Figure 1). In comparison to the current approaches in progress, the research calls for the determination of two complementary intervention scenarios that combine knowledge of the concrete-built heritage history and the definition of innovative methodologies and techniques, to face current practice's limitations.

The latter will go further to demonstrate that the use of digital manufacturing technologies is also relevant for the repair and reconstruction of concrete buildings because of the reverse engineering processes they allow to perform, in

order to better understand the causes of concrete degradation and the interventional logic.

On the other hand, the methodology is also exploiting the growing capacities of robots in terms of perception, planning and manipulation, by encouraging the construction of a control protocol, directly derived from the developments in robotic engineering. Also depending on the interactional characteristics developed, it is therefore allowing the anticipation of tasks that could be carried out by handling the digital tools used.

The proposed methodology is constructed in the following 3 steps:

The first step refers to the knowledge of original concrete manufacturing processes, and on the determination of diagnosis related to the type of damage encountered. In order to respect the conditions of non-invasive intervention, this first

phase recommends the use of digital recording tools for facilitating the acquisition of data related to the architectural details and the continuous monitoring of their degradation. It considers the use of terrestrial and aerial 3D scans, and digital imaging technology (photogrammetry, spectrophotometry, etc.). Allowing specific measurements to be taken, diversifying recording methods and avoiding any contact or risk of disorder and collapse of the architectural elements, it aims to gather the material, geometric and environmental characteristics of the types of concrete concerned (reinforced concrete, moulded cement, mortar render...). This work allows to establish digital documentation databases, with the aim of initiating the construction of an appropriate intervention. It also facilitates the development of a digital archiving of the studied elements, which will help to understand the techniques used at the time and to enhance the intervention in future cases.

The second step concerns the digital modelling and simulation of damaged concrete elements as well as the computation of an interventional environment. It includes the use of parametric design and modelling tools allowing, the understanding of existing materials value of concrete elements, the generation and visualisation of manufacturing scenarios, and the definition of a programmable robotic simulation environment, for the creation of integrated digital intervention-based methods. At this stage, the digital modelling of the concrete damaged parts makes the interpretation of two distinct levels of assessment possible, depending on the presence of material loss on the surface (cracks, fissures) or material loss in volume (formation of gaps, erosion/disappearance of mass).

Concerning this distinction, digital repair tests aimed at filling or adding mass, can be carried out based on 3D models. Regarding the conditions of non-invasive intervention for architectural preservation, benchmark tests are allowed to determine the most suitable intervention scenarios for the case studied.

The third step relates to the manufacturing prototype and repair protocol for the robotic intervention suggested. Based on scenarios generated in the previous stages, it proposes the use of additive manufacturing technologies thanks to robotic applications. The focus here is on the implementation of preparatory procedures for complex interventions aimed at ascertaining the feasibility of the proposed methods for maintenance, repair, reintegration and reconstruction of damaged concrete elements (Figure 1). This stage intends to essentially develop manufacturing and restoration tests based on conclusions drawn from simulations of intervention procedures using the digital model. Therefore, this phase would ensure the use of built-in solutions for material loss issues which have a low impact on the architectural elements and the environment.

EXPERIMENTS AND RESULTS

In this section, we propose two experimental approaches to the afore-described digital intervention methodology.

Through the analysis of the degradation effects observed on the reinforced concrete structures or sculpted/moulded ornament, these can be divided into two approaches to interventions: (1.) the repair of cracks by adding cementitious materials using a drone – for conservation and preventative maintenance purposes, and (2.) the reconstruction of complex architectural details by printing reusable plastic moulds.

Robotic Remote Intervention Protocol (RRIP) for the repair of concrete cracks

In the framework of a thesis financed by the research project CIRMAP (Circular economy via customisable furniture with Recycled MAterials for public Places) (Interreg NWE, 2020), this example was first aimed to develop a remote repair in a digital environment. Given the innovative nature of the subject, the experimentation carried out allows to evaluate the capacity of the method constructed, mobilising

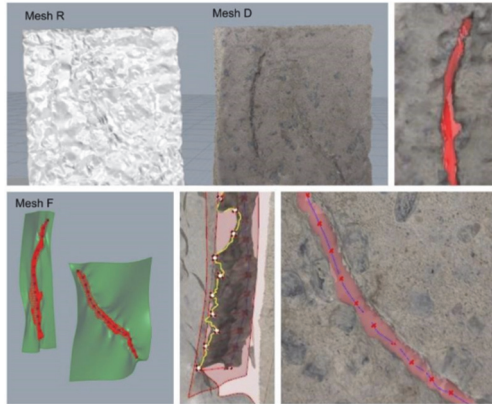


Figure 3
Degradation
modelling and
geometry cracks
analysis.

digital and robotic tools, to generate, extract and send repair information to a simulated drone. Simulated from building areas that are difficult to access without a lift or scaffolding, the damage requires the repair of two degradation cracks manifested in two vertical and oblique directions. In view of the risk involved and to avoid damaging the integrity of the structure, the operating protocol proposes three phases: digital repair, identification of trajectories followed by the configuration and intervention of the robot.

Firstly, the damaged area was scanned using photogrammetry with a drone (DJI Mavic 2). By constructing a point cloud thanks to the collected data (Reality Capture), two 3D meshes were modelised. The first indicated the "Context" (Mesh C), defining the boundaries of the study area. The second indicated the "Degradation" (Mesh D), focusing on the cracked area and providing the geometric information necessary to identify the type of crack observed (length, opening, depth). Once established, this mesh was digitally patched (Blender) in order to create a third mesh, called as "Repair" (Mesh R). The use of parametric design software (Rhinoceros 3D/Grasshopper) and Boolean modelling tools for the generation of the "R" & "D" meshes, eased the creation of a "Crack" mesh (Mesh F). The latter, which was broken down into over a hundred points, facilitated the extraction of the

cracks opening and depth surfaces, to use a patching process adapted to the configuration of the damaged parts. Therefore, the intersecting surfaces in the Mesh D generated two curves that determined the profile of the degradation (Figure 3).

In the second stage, by dividing these curves by points, it was possible to determine the precise positions required to calculate the trajectories (XYZ coordinates and directional vectors) of the surface and depth of the cracks. These values were then used as movement cues to simulate the position of the robot. On one hand, the work based on the cracks opening trajectories determined the movements of the drone towards the area of intervention, considering the location of the operator and the on-site aerial repair robot. On the other hand, the relationship between the degradations profile curves (previously generated) resulted in the determination of the trajectories for the cement mortar infill, in order to drive the drone's robotic arm according to the steering vector of each intersection point. It was then possible to visualise the drone and its injection arm's planned movements in advance, to extract the data for the next stage (Figure 4).

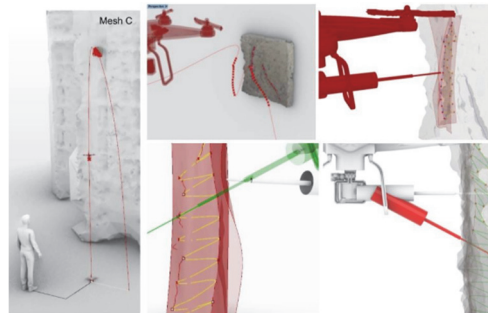


Figure 4
Two-phase
trajectories
generation
(for drone and robotic
arm access).

The third phase consisted first in building a control and exchange environment, linking the previously extracted data with existing robotic interaction systems. To do this, a communication channel, or "websocket client" (in our case via the connection

with the same network of two operating systems) was put in place. Powered by Grasshopper's "Bengesht" plugin, it allows connection to the open-source robotics operating system, or ROS (Robotic Operating System). Once in place, it was possible, using the parametric design software, to subscribe and publish on 'topics', such as those controlling the movements of a drone. Thus, we were able to retrieve the projected trajectory data and implement it in a flight simulation environment, controlled by communication nodes such as Mavros, Move_group or Mavlink. The particularity of the ROS tools allowed to integrate information on the geographical context and the physical parameters of the intervention site, in order to anticipate any possible collisions or potential errors. At this stage, two levels of the simulation trajectory had to be managed: that of the drone guided towards the degradation zone (Gazebo & QGroundControl), and the robotic arm, steered according to the geometric features of the crack (Moveit!). Once the flight simulations were tested, the automation of the repair protocol and the collection of displacement data in real time became possible (Figure 5).

Figure 5
Illustration of the preparation and automation phases of the repair process.

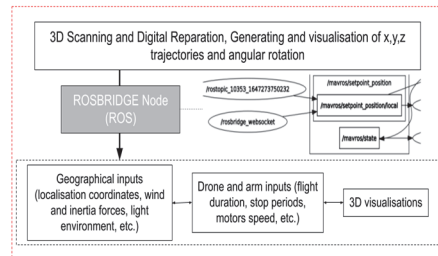
Robotic moulding systems for reconstructing complex details

The second example treated shows a practical application of the proposed research methodology, from the analysis of the material loss observed on the details of the moulded/sculpted architectural ornaments to the production of prototypes for the reconstruction of the missing parts. The research results describe below is related to a PhD experimental work in progress, focusing now on the digital mass customization of the moulding manufacturing process, for the restoration of large-scale concrete sculptures and reliefs, featuring more complex undercut geometries. In this case, we proceeded tests of robotic moulding for the restoration of damaged ornament details presents in the church of St-Michel (1928) of Roubaix in the Hauts-de- France, built with moulded cement techniques developed by the architect A.J Nasousky

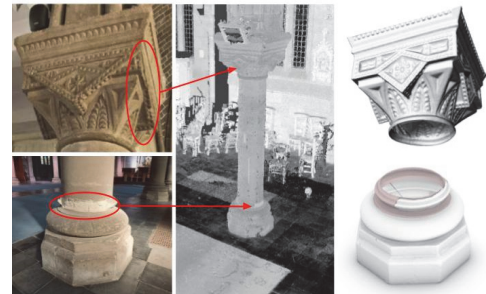
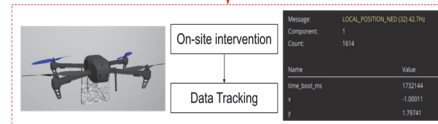
Figure 6
Illustration of the digital recording phase and results of the digital reconstruction modelling. St Michel Church in Roubaix, France

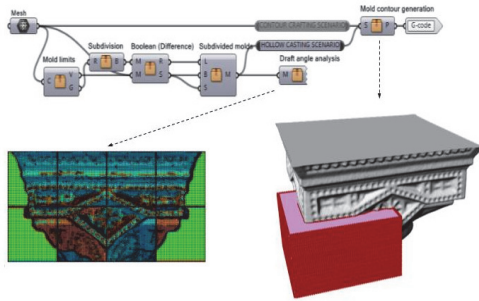
(1864-1943). These elements show remarkable architectural features and ornaments on the capitals of the central columns. Today, due to the gradual erosion of the concrete, there is visible degradation in places which changes the visual aspect of the original sculptures, and in some cases their relief (Figure 6). In order to intervene on the areas impacted by degradation and to preserve a trace of the intact parts in some places, we chose to digitally record several examples of identical details using a 3D laser scan (FARO X130) with an accuracy of +/- 2mm. Thanks to the collection and sequencing of point clouds on digital tools (Autodesk RecapPro, CloudCompare), a mesh of the existing decorative elements was created in order to explore different modes of reconstruction.

PREPARATION



AUTOMATION



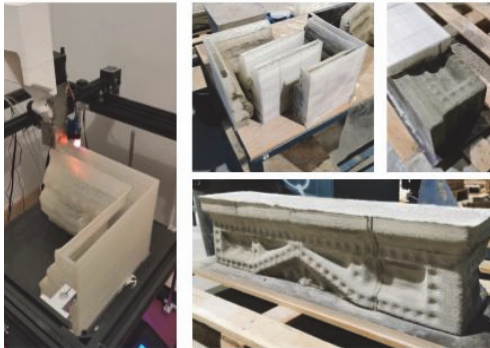


parts in the upper part (on the abacus), we were inspired by traditional hollow casting techniques—consisting in the creation of a negative formwork of a model— which had been used when the building was originally built.

Based on an analysis of the inclination of the modelled hollow mould walls, a division into "n" single mould parts was made, in order to reduce geometrical constraints and facilitate the cutting of each element in the manufacturing process (Figure 7). After determining the XYZ position parameters, the nozzle speeds (60-80mm/s) and the material bead width (2-3mm) by using the digital simulation from the g.code file, we printed four moulding modules from different degrees of detail, with plastic pellets (PLA). Once these were assembled, using a wooden frame and dry sand infill as a counterbalance, concrete mortars from previous research projects (CIRMAP and MATRICE) were used to cast the elements, with a drying time varying between 2 and 3 days (Figure 8). At the end of the manufacturing phase, the moulds, which were designed to be reusable, showed good resistance to mechanical stress in the most complex undercuts. Also, the results of the printing process provided the anticipated levels of finish according to the chosen intervention, producing basic models for hand-carving by a sculptor. Nevertheless, in some places, the roughness of the concrete used reveals the fragility of the plastic layers during the casting phase due to internal chemical reactions. The re-use of the casting is therefore possible in absolute terms, but only for a limited number of applications, if we want to carry out "like-for-like" restoration operations using additive manufacturing technologies.

Figure 7
Draft angle analysis of the digital moulding system (Rhino/Grasshopper) resulting from the hollow casting scenario.

Figure 8
Additive manufacturing of a complex mould detail. Result of the moulded cement prototype.



The comparison of these data with photographs taken of the other parts of the building allowed us to assemble several 3D models in order to restore the damaged ornament to its original state (Figure 6). Thanks to inputting the parameters on the 3D model, the nature of the concrete degradations observed distinguished two scenarios for reconstruction through robotic moulding manufacturing: with direct casting mould (positive casting) and hollow casting mould (negative casting) of the digital imprint. According to traditional impression taking methods used for mould manufacturing, the development of the direct moulding scenario was based on the modelisation of the geometry contours. This allowed us to consider the moulding of different fragments and details with simplified undercut geometries. For the reconstruction of the complex moulded cement

DISCUSSION

The results obtained demonstrate the potential of robotic manufacturing systems for the conservation and the restoration of 20th-century concrete architectural heritage. For maintenance and repair of occasional or superficial material loss, the automation of the intervention process by using a

drone-based system for detection and interventions with cement mortar printing seems to be a feasible solution, when the application area is inaccessible or high up. Thanks to the configuration of the simulation data, the scenario allows to optimise the infill of the damaged parts, according to the width, depth and direction of the cracks. Through the integrated approach of digital detection and analysis tools used for modelling different types of cracks, the initial result of the current experiment validates the hypothesis of the proposed digital intervention methodology for rapid, inexpensive and sustainable concrete repairs. Currently, application tests are underway to further develop the proposed approach. Firstly, in order to assess the limitations of the operating protocol on more complex geometric configurations (depth and openings of larger cracks, localised degradation in corners or on the underside). Then, in order to study the behaviour of the robot during the operational phase, by considering its material load capacity. Finally, in order to include the operator in the process, the question of how to mobilise the virtual reality/augmented reality tools (VR/AR) will be addressed. Similarly, the development of a robotic moulding manufacturing methodology for the reintegration and the reconstruction of details indicates interest in the optimisation of conventional restoration techniques. Thanks to the digital printing of complex geometry mould using robotics, the scenario offers a reliable manufacturing alternative, adapted for reproducing detailed ornament features. Other experiments are underway too so as to investigate possible opportunities for digital moulding applications to enhance the 'like for like' restoration techniques of sculptural complex details on fresh concrete. These two scenarios also demonstrate the benefits of these complementary approaches, based on the impact of AI technologies for detecting and interpreting damaged or missing features of concrete building elements. In view of the numerous risks linked to the intensification of concrete degradation, these developments would permit the collection of pre-formed data or similar

reconstruction models to support the digital intervention methodology for the conservation, the restoration and the preventive maintenance of 20th-century concrete architecture.

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