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RePrint

Digital Workflow for Aesthetic Retrofitting of Deteriorated Architectural Elements with New Biomaterial Finishes

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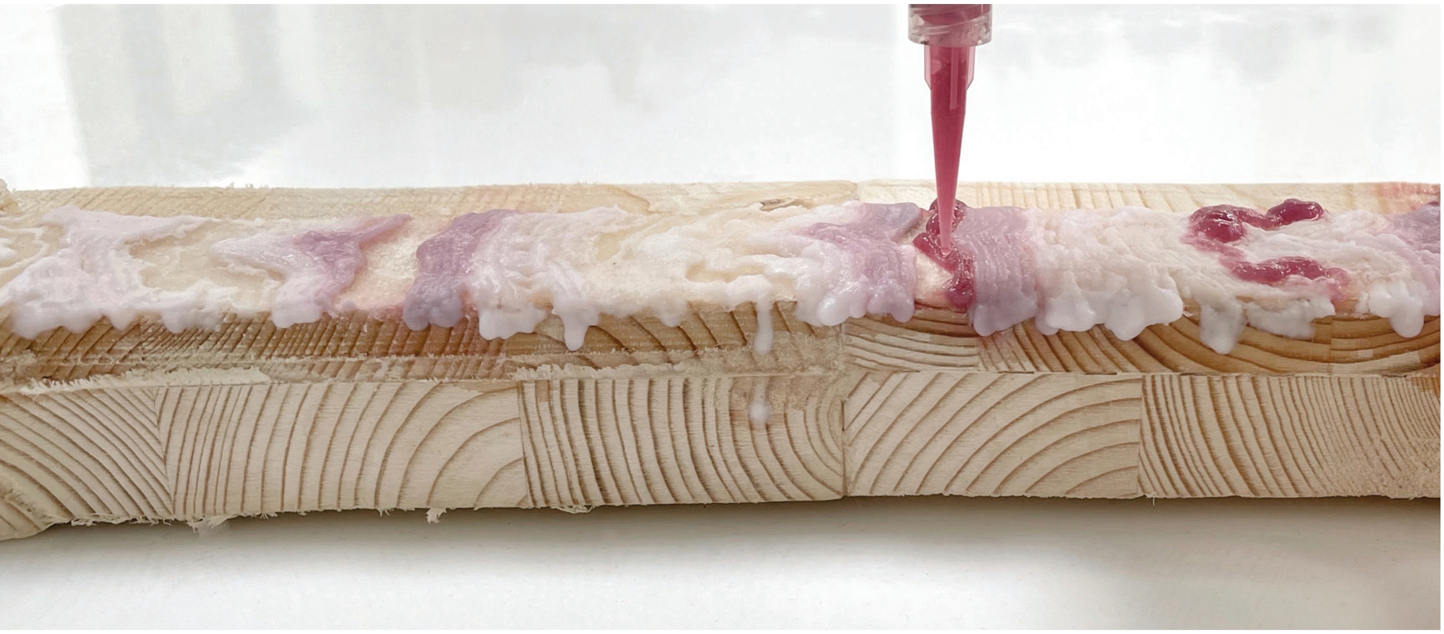

ABSTRACT

Digital fabrication offers new opportunities for revitalizing aged buildings in the time of craft expertise decline and higher demands regarding the sustainability of employed materials. Precise reproduction of architectural elements with digital 3D reconstruction methods such as photogrammetry, and their repair using agile robotic 3D printing involving new environmentally friendly materials can save time and resources, leading to more circular design and manufacturing.

This study presents digital workflows for architectural restoration, based on the concept of aesthetic retrofitting of deteriorated wooden architectural elements through the application of surface finishes from a novel biomaterial – microfibrillated cellulose hydrogel, upcycled from forestry waste. The workflows were established through experimental digital design and reproduction of wooden architectural details in an existing historical building, and executed within an integrated digital framework combining photogrammetry, 2D graphics processing, computational design and robotic 3D printing.

Overall, the investigation has sought to demonstrate the potential of microfibrillated cellulose as a material suitable for applications in renovation and conservation. Further, the intention was to elucidate the role of digital tools as new media of restoration that enable to uplift cultural assets in an alternative way - by allowing to embed aesthetic features conveying the contemporaneity of remedial interventions. Aiming to contribute to current work in experimental preservation, the study offers a novel approach in which deteriorated architectural elements are endowed with a new materiality that follows the new logic of circularity in contemporary design and construction.

INTRODUCTION

In the time of depleted resources and the construction sector generating large quantities of environmentally harmful waste, new solutions involving renewable, biobased materials are advocated to allow for a shift toward more circular and resource-efficient architectural design. Among such proposals, those that harness the potentials of existing architectural elements through repair, redesign and reuse are prominent. A good example is 'The Re-Use Atlas' issued by the Royal Institute of British Architects, presenting a large and diverse collection of experimental projects following these approaches (Baker-Brown 2017). Theoretical discourse on the subject is also visible in a growing number of critical texts on reuse and appropriation (Brilliant and Kinney 2016, Reeser Lawrence and Miljački 2018).

Related to these contexts, this study synergizes knowledge from digital restoration, novel sustainable material developments, computational design and robotic fabrication to investigate how deteriorated architectural elements could be preserved and creatively re-imagined by retrofitting them with new, 3D-printed surface finishes from an architecturally unexplored yet resource-efficient biomaterial – microfibrillated cellulose (MFC) hydrogel derived from forestry waste (Figure 1). The work forms the first stage of a larger investigation exploring hybrid interfacing of aged wood with a new material that also originates from the forest yet has a profoundly different materiality.

Our initial trials of applying pure MFC hydrogel onto various wooden surfaces indicated limitations in the types of textures it is able to adhere to without other additives (Figure 2). We also observed significant changes in the material's appearance upon drying, such as alterations of form and color. Consequently, the first stage of the study was limited to retrofitting wooden architectural elements outside the confines of a stringent conservation practice, permitting more liberal interventions. In further studies, however, we aim to establish material compositions adapted to specific types of degraded wood, to facilitate application in traditional conservation as well.

The focus of the presented work has arisen from the ambition to critically reflect on the possibility of a hybrid, extended restoration practice that would concern all aged elements, regardless of historic or cultural status. Most buildings contain degraded components, and such elements will always require careful assessment of aesthetic, architectonic, cultural and historic values. We argue that this evaluation would benefit from a dual perspective - of a historic preservationist on the one hand, and an architect designing new interventions on the other. Therewith, the customary foci of both preservation and architectural design could be broadened by placing particular emphasis on the intention of the interventions, allowing for hybrid agendas that preserve and recreate while also enriching material artifacts.

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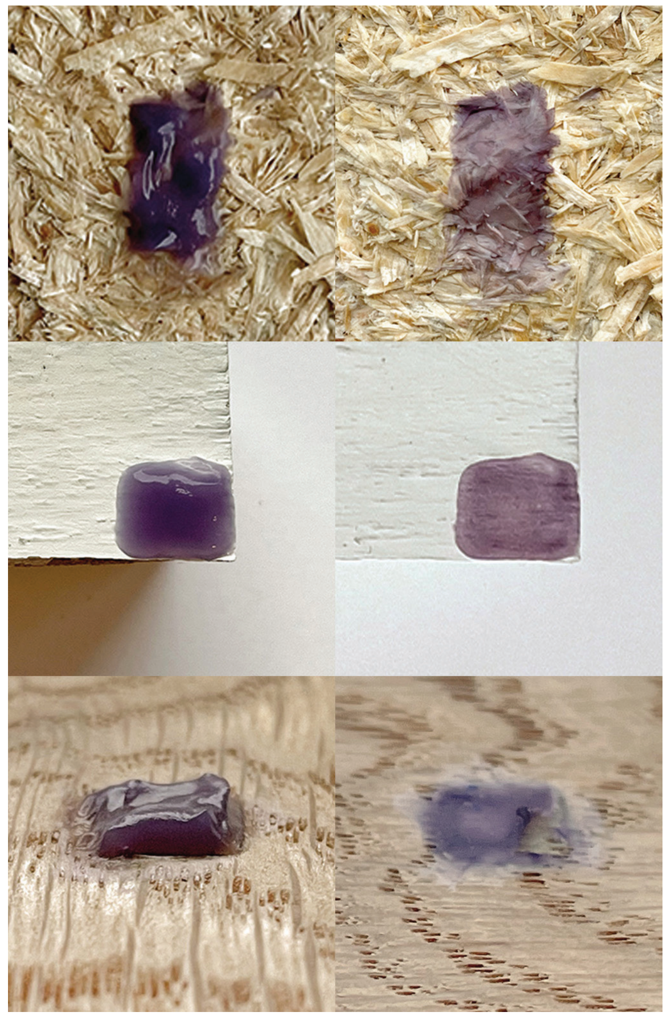

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1 Unpigmented microfibrillated cellulose hydrogel, loaded into a syringe.

2 Excerpt from initial trials of coating various underlays with MFC hydrogel, in wet (left column) and dry (right column) state. From top to bottom: on chipboard, acrylic-painted wood and oiled oak.

If architectural values of an element considered for repair or restoration are insufficient, then an extended, hybrid conservation practice could serve to negotiate a new materiality that highlights the contemporaneity of the intervention while protecting any noteworthy historical or cultural layers. This could offer a prolonged life span to numerous aged architectonic elements that would otherwise be regarded as construction waste. Instead of unsustainable strategies of landfill disposal, combustion, replacement with new products, or repair using synthetic paints, resins and other chemicals, this study argues for retaining degraded elements within buildings by retrofitting them with contemporary, biobased material layers and additions, in line with emerging concepts of circularity and rational resource use in construction.

STATE OF THE ART

Digital restoration is a field that deals with historical reconstruction and preservation using latest digital technologies. It is represented by practices such Factum Arte in Spain and the Institute of Digital Archaeology in the UK, as well as by numerous academic studies by research institutions across the globe. The primary focus of mainstream digital restoration is faithful reconstruction and creation of accurate replicas. Hence, the current methods, tools and materials comprise an established, standardized repertoire, which is essential for maintaining the required high quality and accuracy of the restorative work.

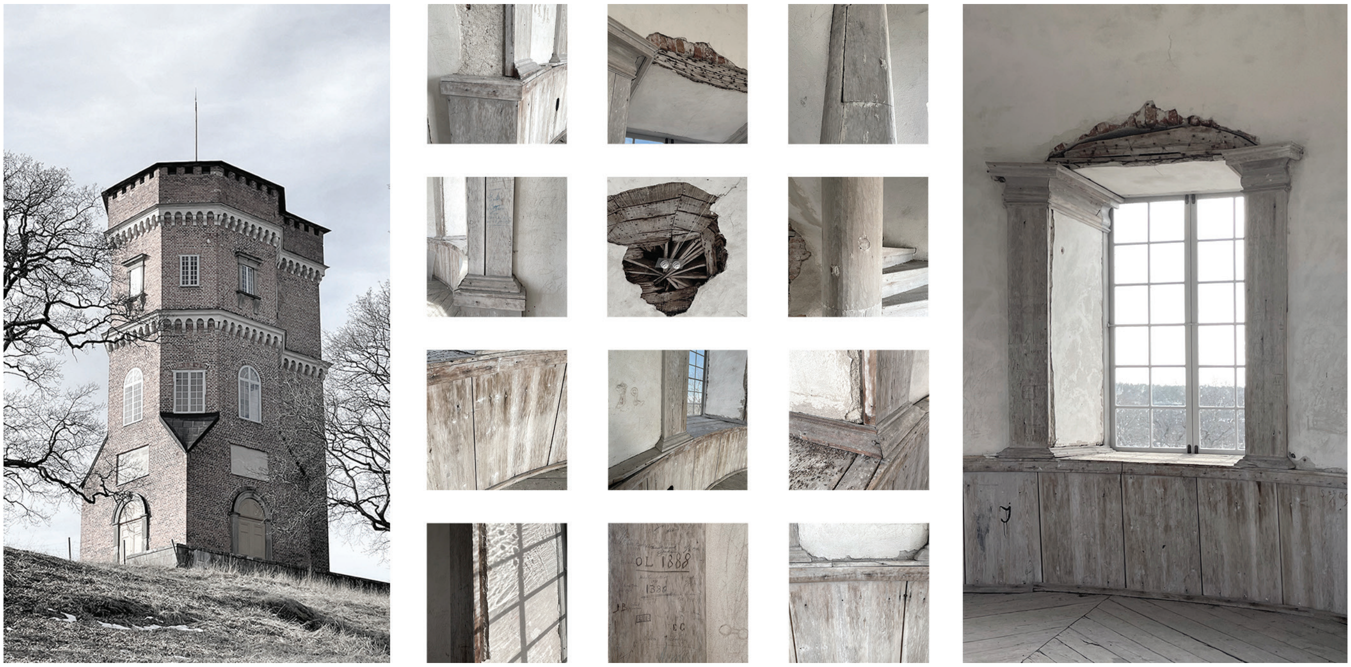
An analysis of recent literature indicates that the methodology of digital restoration relies on a common routine. It encompasses four linearly progressing steps of element reproduction, prototyping, post-processing and fitting on-site, each supported with off-the-shelf digital tools employed according to state-of-the-art protocols of use (Bonora et al 2021). The first step involves high-precision 3D reproduction of an artifact using established methods, such as laser scanning or photogrammetry (Aicardi et al 2018). The second step embraces digital processing, fitting and sculpting of the reconstructed 3D model of the artifact in a 3D modelling environment, to achieve high resemblance in relation to the physical piece. The third step encompasses standardized toolpath generation through 3D model slicing in dedicated software, followed by planar, layer-by-layer CNC milling or 3D printing of an object's physical replica (Xu, Ding and Love 2017). Usually, it is desirable to manufacture a copy with no machine traces, which necessitates a fourth step of post-processing, involving manual procedures of smoothing, sanding and coating (Higueras, Calero and Collado-Montero 2021).

The materials employed in mainstream digital restoration, for artifacts recreated using digital manufacturing techniques such as 3D printing, often feature mixes of synthetic polymers with natural ingredients, e.g., ceramics, wood fibers and stone powder, whereas the materials applied manually as the final finish layer range from traditional ones, based on natural ingredients, such as ceramic putty, to synthetic ones, e.g. acrylic paint, latex and resins (Acke et al 2021). Hence, plant-based hydrogels have not yet been established as materials for architectural restoration. Instead, prior studies demonstrated their use for 3D printing of new, standalone architectural elements (Duro-Royo, Mogas-Soldevila and Oxman 2015, Malik et al 2020).

Interestingly, alongside the mainstream work, there also exists an experimental and critical trajectory in digital restoration that aims to challenge the creation of precise historical replicas by questioning their authenticity and materiality. For instance, Factum Arte's three reproductions of a historic sculpture 'Venus Victrix', showcased at the Venice Architecture Biennale in 2016, were intentionally presented in three different materials – glass, wax and resin, and fabricated using different techniques – traditional casting into molds, modern 3D printing, and a combination of the two. In this way, the project has shown that certain features, such as fabrication tool traces and specific properties of the chosen reproduction material, should be regarded as constitutional traits of the replica, profoundly impacting its visual expression and historic interpretation. A similar intention was expressed when reconstructing the Notre Dame Cathedral in Paris after the fire in 2019. Because genuine Parisian stone and traditional crafting knowledge are no longer available, a proposal was put forth to recreate the cathedral's stone sculptures using 3D printing with a new material comprising powdered limestone and ashes collected from the fire. It was argued that, through this, the bygone materiality of the building could be closely reproduced while more truthfully displaying its new character (Geboers and Baldassari 2019).

These alternative approaches, although indicating an interesting turn of restoration and preservation toward more liberal stances, rely nonetheless on the already mentioned state-of-the art methods, tools and materials. The aim is still to achieve a certain degree of precision and similarity to the original. While these objectives of preservation are, and will be, valid in many contexts, the question of authenticity and materiality of the replica remains open. Hence, further architectural knowledge is needed to more comprehensively reveal if and how the negotiations between the known and emergent, existing and new materials, as well as the digital media employed to process them, could lead to an acceptable yet wider range of departures and deviations from the original state of the restored artifact.

With this in mind, our study aimed to elucidate this knowledge and inspire further developments in research and practice of digital restoration. Instead of aiming for faithful restoration of an original surface state, we have sought to show the potentials



3 Eighteenth-century tower 'Götiska tornet' in Stockholm, Sweden (left), with an inventory of deteriorated wooden elements (middle) and an incomplete wooden window casing selected for the experimental restorative intervention (right).

of endowing it with a new appearance. This was achieved by employing a novel biobased material, microfibrillated cellulose hydrogel, having sustainable properties radically different from those of the traditional and often environmentally non-neutral materials used in preservation.

In terms of digital workflows and tools, a novel element contributed by our study is the introduction of non-standard, bottom-up machine 3D printing toolpath design explorations, enabled by the introduction of parametric tools and custom robotic 3D printer programming into the restoration toolkit, to replace the stage of machine toolpath generation using off-the-shelf software relying on automated digital 3D model slicing. This results in a new workflow that deviates the typical linear, four-stage path mentioned earlier. Namely, it features two loops of exploration, encompassing toolpath design iteration and mockup production, to enable more extensive design investigations of the new materiality to be introduced in the restored artifact.

DESIGN RESEARCH INVESTIGATION

Intervention Site and Materials

The site chosen for design experimentation in this study is a historical, eighteenth-century tower 'Götiska tornet' in Stockholm, Sweden, having unfinished, deteriorated wooden interior cladding. A part of such cladding, comprising a window casing with profiled pilasters and panels, raw and uncoated, was selected for our experimental restorative intervention (Figure 3).

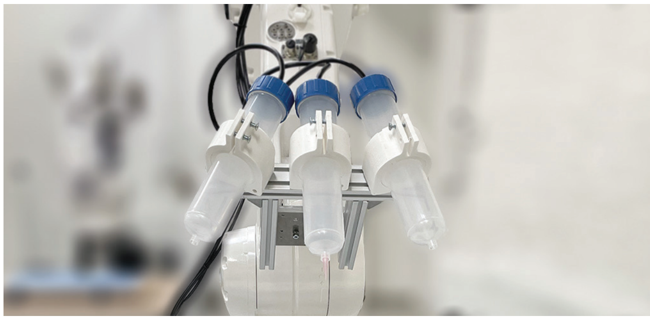
The restorative intervention was done with microfibrillated cellulose hydrogel Exilva F 01-L - a circular, sustainable material comprising 2% cellulose fibrils and 98% water. Originally translucent, in our study it was additionally pigmented using water-soluble food colorants. This specific type of a hydrogel is suitable for pressure-actuated 3D printing because it is thixotropic. Accordingly, when pressure is applied, the viscosity of the material decreases, encouraging flow and therewith enabling extrusion. Once the pressure is removed, the material returns to its original viscous state, which allows for it to maintain the desired shape after deposition.

Custom Robotic Extrusion System

The 3D printing of new coatings from MFC hydrogel was done using a pressure-actuated extrusion system, custom developed specifically for the project. The system was commissioned on an industrial robot KUKA Agilus KR10-1100-SIXX.

The end-effector of the robot comprised of 200 ml dispensing syringes, equipped with plastic plungers and mounted into custom-designed, 3D printed clamps, providing ease of material reload (Figure 4). Based on initial 3D printing experiments, the syringe nozzle diameter was 0.6 mm, and the material deposition speed was 0.015 m/s at a constant pressure of 0.25 bar. The global air pressure in the system was provided from an air compressor. Local pressure control in each dispensing syringe was enabled by pressure regulators operated via manual gauges as well as 3/2-way solenoid valves activated through digital I/O communication with the robot controller (Figure 5).

The robot work cell included an industrial robot fastened to an aluminum frame table, onto which a 70 x 120 cm printing bed



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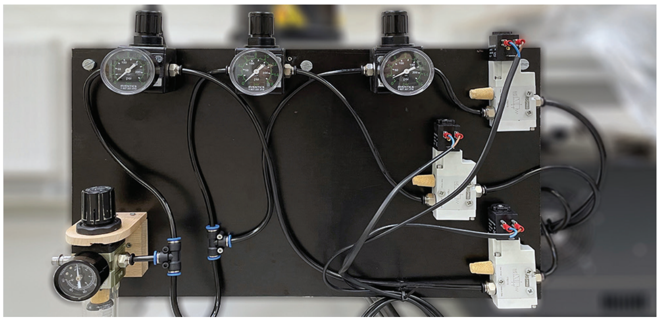

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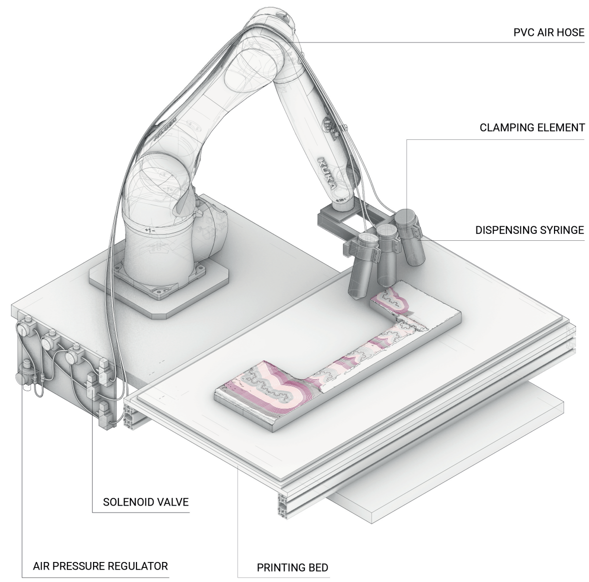

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was mounted (Figure 6). The bed was constructed from a 2 cm thick MDF board, fastened to the main table using two 4 x 8 cm aluminum profiles. The bed levelling was enabled through a system of six screws and washers placed at the mounting supports between the aluminum profiles and the MDF board.

RePrint: A Digital Workflow for Aesthetic Retrofitting of Deteriorated Architectural Elements

The workflow established in the design experiments was based on a progression from digital reproduction of an existing detail, through iterative mockup prototyping enabling extensive exploration of toolpath designs and their aesthetic implications, up to a restorative intervention through robotic 3D printing of a new surface finish from microfibrillated cellulose hydrogel (Figure 7).

The first step of the workflow involved the digital reproduction of the chosen building element through photogrammetry. To enable this, the element needed to be captured in photographs, taken according to the standard protocols for capturing data for photogrammetry, using a digital camera, in our case an Apple iPhone 12 camera. The photographs were then loaded into the photogrammetry software, i.e., a mobile application Polycam (Polycam Inc. 2022) that generated a texture-mapped, open 3D mesh model of the element in .obj file format.

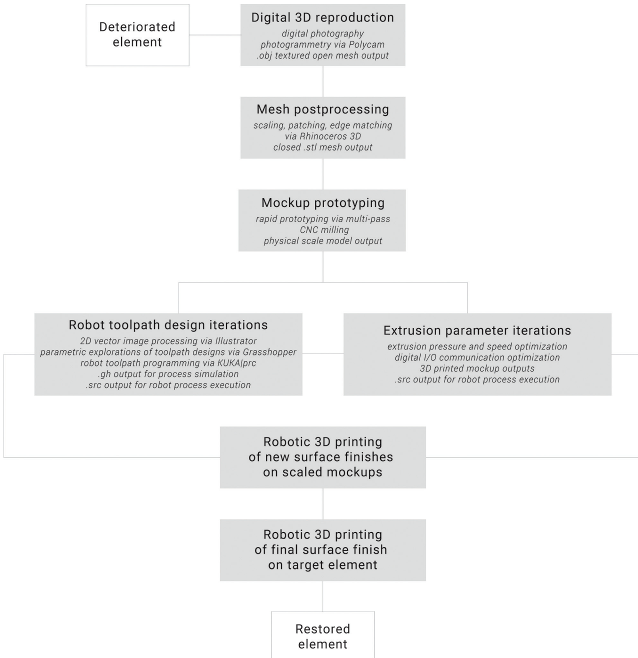
The second step of the process embraced postprocessing of the mesh to match the original dimensions of the element, patch mesh holes, and create a closed mesh exportable to an .stl format required for the next stage of the process. In our study, the mesh processing operations were done in a 3D modeling software Rhinoceros 3D (McNeel & Associates 2018).

The third step involved two interlinked, looped phases of design explorations, digital and physical, in which various options for the restorative intervention were investigated. To enable this, a scaled physical mock-up model of the digitally reproduced window casing, created as two halves, was first fabricated via CNC milling in birch wood, carried out on a SainSmart Genmitsu 3018-PROVer machine. The process then proceeded with parametric explorations of robot toolpath designs defining how the new surface finishes would be 3D printed. In our case, the toolpath designs were based on raster and vector graphics processing, done in Illustrator (Adobe Inc. 2022) and allowing to create curves that could be further explored and fine-tuned parametrically using Grasshopper (Rutten 2021). Once the toolpath designs were complete, the KUKA|prc add-on was employed for visual simulation of the robotic process, as well as to generate a robot program in the native .src file format, permitting to 3D print on the mockup models.

In the final exploration stage, the designed surface finish patterns were 3D printed onto the CNC-milled scaled physical mockups to better understand their new materiality. The mockup explorations formed a knowledge base for the last stage of the process, in which one toolpath design would be chosen for fabrication in full scale on the actual element.

Robot Toolpath Design Strategies

The robot toolpath designs relied on a simplified method of projecting 2D toolpath curves onto a 3D surface of the digitally captured object, to create material deposition paths that follow the outline of the existing element in Z-axis direction while securing a constant distance of the extrusion nozzle from the



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4 Custom-developed robot end-effector, enabling pressure-actuated extrusion of microfibrillated cellulose hydrogel.

5 Pressure regulation and control system connected with an industrial robot controller via digital I/O communication.

6 Arrangement of the work cell for robotic 3D printing with the hydrogel.

7 Digital workflow underpinning the RePrint approach (left) and outputs of the main process stages preceding the production of microfibrillated cellulose coatings on physical mockups: digital 3D mesh reproduced via photogrammetry (top right) and a scaled physical mockup digitally manufactured via CNC milling (bottom right).

surface being printed on (Figure 8). Hence, the machine setup presented herein assumes no extruder rotation and, consequently, a geometric limitation of the robot toolpath to surfaces that are close to planar. In further research, a 3D printing method for convex and concave elements will be established by introducing rotation of the robot's end-effector, to be able to follow more steeply shaped geometries of the retrofitted pieces. This further investigation will also allow to establish the maximum angle range limits of the extruder tilt in relation to local surface curvatures as these parameters will profoundly affect material adhesion for variously shaped elements.

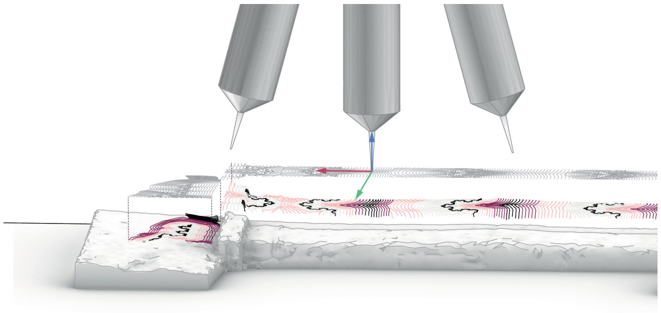
To demonstrate various directions for restoration from the conceptual standpoint, two aesthetic retrofitting strategies and accompanying toolpath designs were developed. The first strategy related to the encountered appearance and surface qualities of the retrofitted architectural elements, taking into account the noticeable weathering features. Accordingly, the toolpath was designed to highlight surface discolorations left by excessive exposure to rainwater. The imperfections were acknowledged in a new surface layer that followed the discoloration outlines. This was achieved via color hue tracing of a raster image of the retrofitted element in Illustrator to create vector paths following the boundaries of the discolorations (Figure 9). Thereafter, the vector paths were imported into Rhinoceros 3D and parametrically processed with Grasshopper.

The material hues in this strategy were inspired by those found in the Baroque interior of the Royal Palace in Stockholm, Sweden, specifically, in Queen Hedvig Eleonora's Bedchamber, featuring blue and navy tones. The color scheme was designed as congruous with the original staining pattern of the weathered wood while introducing hues from the precedent historic interior. Accordingly, the intervention featured dark blue tones corresponding with the colder and darker colors in the existing weathered wood and light blue as well as white hues relating to the warmer and brighter weathering tones. The design intention was to introduce a material layer that celebrates and preserves the past maculation traces while introducing a new materiality.

The second toolpath design strategy offered a new pattern and color distribution logic to the existing surface. The robot toolpath was generated by creating and editing a fractal Koch curve. The fractal curve was chosen to conceptually and geometrically link to the historical period in which the tower was built – the Baroque. From the standpoint of geometry, the organic aesthetic of the fractal curve was meant to relate to Baroque's characteristic curved, furcating rocaille motifs (Figure 10).

Conceptually, the proposed patterning was inspired by the theories of modern philosopher Gilles Deleuze, which in an architectonic way interpret the theories of Baroque mathematician and philosopher Gottfried Wilhelm Leibniz. In the seminal work 'The Fold: Leibniz and the Baroque', Deleuze pictorially describes different manners of folds – the folds of the soul and the pleats of matter – that make up different kinds of textures (Deleuze 1993). Relating to these notions, the proposed fractal-based patterning and coloration logic of the surface aimed to convey the tower's historical origins.

The color scheme of this intervention introduced a palette of reds, again inspired by colors found in the precedent Royal



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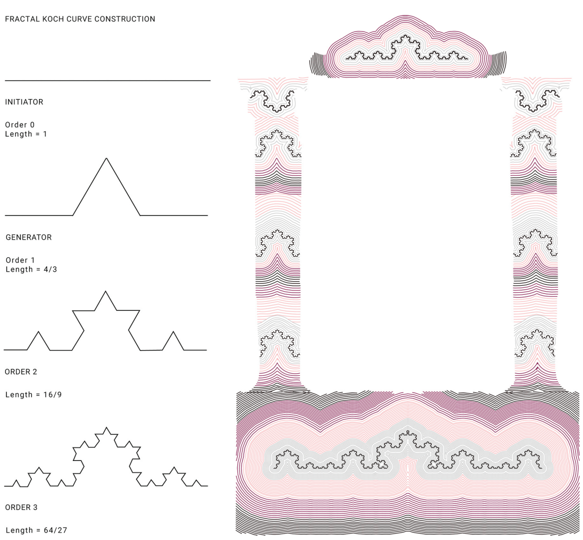

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7 Generation of a non-flat toolpath, shown as colored 3D curves, derived through planar projection of 2D curves, shown in grey, onto a 3D mesh surface to be printed on.

8 Toolpath design following the weathering pattern of the existing wooden element through vectorized color hue tracing of a raster image.

9 Toolpath design inspired by Baroque rocaille motifs, derived by parametric variation of fractal Koch curves and their processing in a vector graphics software.

Palace interior, specifically, the white-burgundy tones in the Main Staircase. To relate to the furls and folds of matter described by Deleuze, the colors were designed in gradient transitions from translucent white, through light red and red, up to burgundy. Burgundy was used to accentuate the most complex fractal curves of the pattern and highlight the edges of the lowermost part of the window casing. The other color gradients provided a smooth color transition while accentuating the furls and folds of the new surface.

RESULTS AND DISCUSSION

Material Effects and Aesthetic Expressions

Two properties of microfibrillated cellulose hydrogel have profoundly affected the 3D printing process and the final appearance of the new material layers. The first property is the hydrogel's non-homogenous character, caused by a locally uneven distribution of the cellulose fibrils in the polymer network. This has caused variations in the width and height of the deposed material strands. The generous differentiation of the strands introduced intricate features of textural variation and an irregular aesthetic expression (Figure 11). Such material-specific, unique effects would not have emerged if the deposition had proceeded in perfectly uniform, continuous layers.

The second influential property of the hydrogel was its high water content. Microfibrillated cellulose hydrogel left in ambient conditions shrinks due to water evaporation. Hence, approximately one hour and for the next 36 hours post printing, the hydrogel layer underwent geometric transitions upon water loss. The transitions were also influenced by the gradual absorption of water from the newly printed layer of the hydrogel by the wooden surface of the mockup.

The speed and effects of absorption and drying over time were not uniform. The thinner layers dried more quickly, which has led to local surface ruptures due to material strains caused by strong bonding with the wooden underlay. The water in the thicker layers of the material was absorbed to a lesser extent and these zones dried slowly. As those zones started to shrink at the end of the drying period, geometric shape transformations and local erasure of the initial toolpath traces occurred, creating new patterns that in some areas entirely deviated from the original toolpath (Figure 12).

The material coloring has also undergone changes over time during bonding and drying. The non-pigmented parts of the hydrogel that originally had a translucent white tint became fully transparent after drying. The material with small quantities of pigment became translucent, maintaining the intensity and tone of its color. The hue of the material with the largest content and darkest tone of the pigment was amplified, exhibiting much darker tones than directly after 3D printing.

11 Left: Initial aesthetic outcomes of architectural element retrofitting with microfibrillated cellulose hydrogel (fully wet prototypes, 30 minutes after 3D printing). Right: Final aesthetic outcomes of architectural element retrofitting with microfibrillated cellulose hydrogels (fully dried prototypes, 36 hours after 3D printing).

The encountered material effects could be further embraced in different ways. On the one hand, they could be regarded as design opportunities, following Manuel DeLanda's new materialism philosophy, which argues that the material world has an inherent agenda independent from our intentions and that we should allow this agenda to affect the materiality of our constructs instead of attempting to fully control it (DeLanda 2015). An opposite path would be to generate a more predictable design outcome. This could be achieved through closer collaboration with material scientists, who could fine tune the material composition to achieve specific material effects.

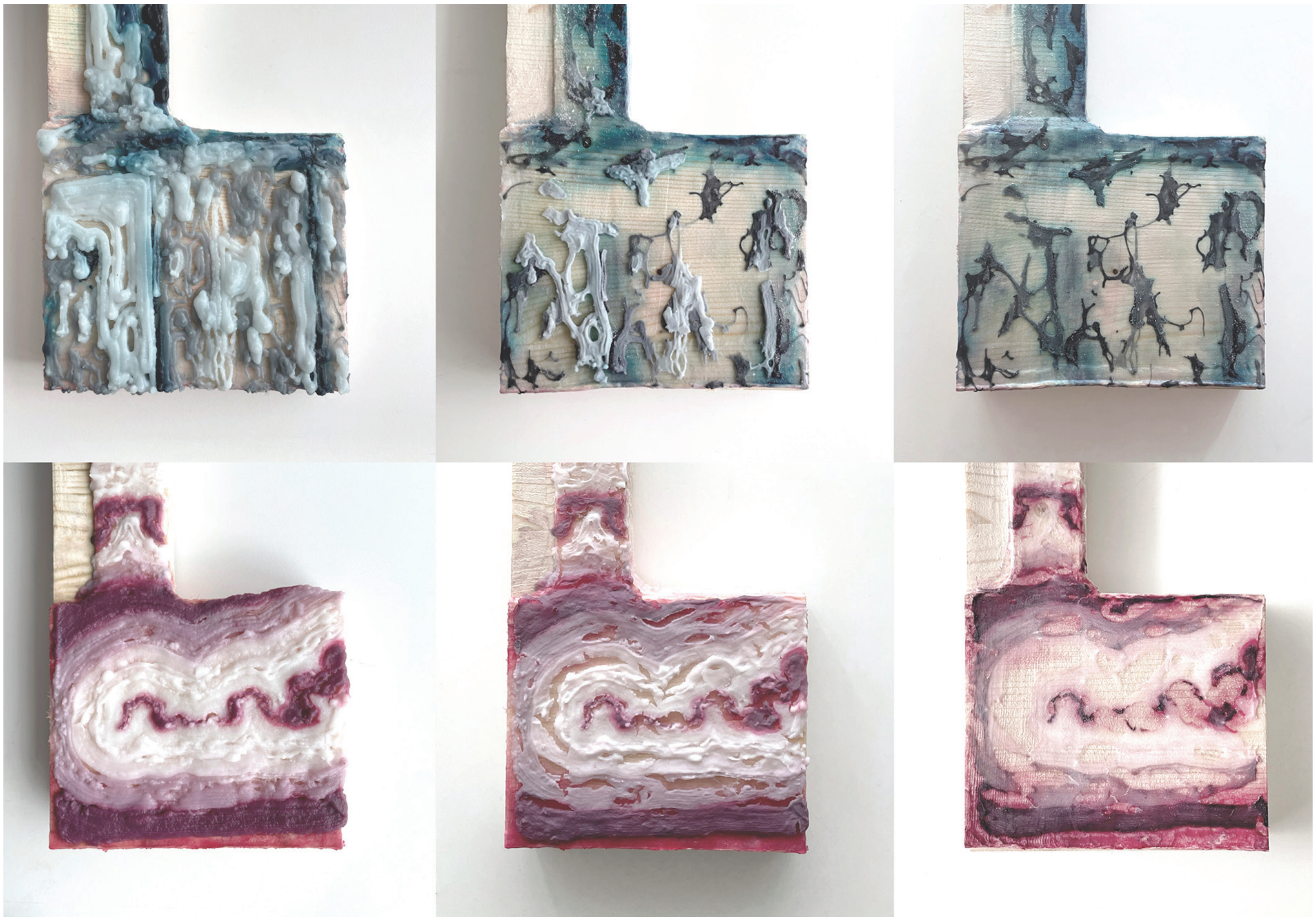
Contribution Summary and Future Research

The study has sought to contribute to the existing body of work in digital restoration, by expanding the scope of its typical digital workflow with a looped design exploration phase, enabling aesthetic versioning, evaluation and acquisition of a deeper understanding of new material interventions before they are applied onto actual architectural elements. In our scaled conceptual mockups, we have also shown how customized parametric toolpath design of new material layers allows to carefully combine them with existing ones, yielding new material hybrids and aesthetic haecceities. These hybrids and haecceities prompt to reemphasize the importance and value of careful interfacing of historical layers, contemporary materials and new manufacturing processes.

The work also contributes to architectural restoration discourse by proposing a new approach and a material solution driven by incentives of sustainability and circularity. Through this, it aligns with emergent voices in experimental restoration discussed in the 'State of the Art' section of this article, relating to authenticity and sustainability. The lack of skilled artisans, the impossibility to access the original material, and the unsustainability of the material acquisition process can often motivate the need for an alternative approach harnessing novel biomaterials and building components that would conventionally be treated as waste. This permits to retrofit a wider range of damaged or aged elements with a contemporary touch left by today's digital fabrication techniques.

Simultaneously, the proposed approach of introducing new materials to an existing historical context has limitations regarding the range of cultural artifacts it can be applied to. Careful considerations should still be in place to determine if and what fragments of architectural objects can be handled in this way, what to preserve, which historic layers to reveal and recreate and which interventions to conceal. In some cases, the character introduced by a new material and digital manufacturing technique might misalign with the existing context, outweighing the sustainability benefits and certain authenticity aspects. In such cases, a more traditional preservation approach could still have priority.

The future research includes continued in-depth explorations of biobased material interventions, to probe a wider range of architectural effects and material combinations. Another interesting aspect to explore from the computational perspective would be to include machine vision techniques in our workflow, to guide the fabrication process with real-time data inputs regarding the



12 Aesthetic and geometric transitions of the new material layers from microfibrillated cellulose hydrogel seen in detail over time for the two different toolpath variants (from left to right: 3, 18 and 36 hours post 3D printing).

geometry and texture of the treated objects. This could lead to novel, highly integrated workflows that further boost both the creative and the pragmatic aspects of digital restoration.

CONCLUSION

The work has demonstrated an alternative architectural restoration approach based on aesthetic retrofitting of existing deteriorated elements through digital design and robotic additive manufacturing with a new sustainable biomaterial. By exemplifying, through prototypes and customized digital workflows, how a novel material can be 3D-printed on degraded wood as a conceptually motivated aesthetic coating, the study aimed to cultivate familiarity with and stimulate further discussion and research on alternative digital preservation and restoration methods, highlighting potentials and issues raised by introducing new material hybrids to a historic architectural context.

Today, all design interventions, including those in historic settings, are expected to be respectful toward the natural environment. In that sense, digital restoration engaging with novel sustainable biomaterials offers a move toward more circular treatment of the built environment where respectful mending and care of existing artifacts and spaces is done using latest innovations in material science and new digital technologies. This offers opportunities for zero-waste manufacturing and an extended scope of restoration of existing architectural elements, underpinned by notions of circularity and resource efficiency.

If a structure or artifact cannot be restored with original materials and crafting skills, then it is legit to consider whether it would be more truthful to engage contemporary materials and digital tools. Exposing the nature of artifacts conceived with those tools allows to add a contemporary layer to the history of an object. This aligns with Beatriz Colomina's and Mark Wigley's reflection that design not only conveys the physical results of our ideas, but also the intangible techno-cultural structures and work processes invented throughout human history (Colomina and Wigley 2016). Therefore, it can be argued that utilizing digital tools for restoration while paying close attention to environmental and cultural aspects adds a valuable layer of history to an object, telling the story of our present attempts to redefine the current design systems into more sustainable and resourceful ones.

ACKNOWLEDGEMENTS

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REFERENCES

Acke, Lien, Kristel De Vis, Stijn Verwulgen and Jouke Verlinden. 2022. "Survey and literature study to provide insights on the application of 3D technologies in objects conservation and restoration." *Journal of Cultural Heritage* 49 (2021): 272–288.

Adobe Inc. Adobe Illustrator. V. 26.1. Adobe Inc. PC. 2022.

Aicardi, Irene, Filiberto Chiabrando, Andrea Lingua and Francesca Noardo. 2018. "Recent trends in cultural heritage 3D survey: The photogrammetric computer vision approach." *Journal of Cultural Heritage* 32 (2018): 257–266.

Baker-Brown, Duncan. 2017. *The Re-Use Atlas: A Designer's Guide Towards a Circular Economy.* London: RIBA Publishing.

Bonora, Valentina, Grazia Tucci, Adele Meucci and Bernardo Pagnini. 2021. "Photogrammetry and 3D Printing for Marble Statues Replicas: Critical Issues and Assessment." *Sustainability* 13 (2): 680.

Brilliant, Richard and Dale Kinney. 2016. *Reuse Value: Spolia and Appropriation in Art and Architecture from Constantine to Sherrie Levine.* Oxon: Routledge.

Colomina, Beatriz and Mark Wigley. 2016. *Are We Human? Notes on an Archaeology of Design.* Zürich: Lars Müller Publishers.

DeLanda, Manuel. 2015. "The new materiality." *Architectural Design* 85 (5): 16–21.

Deleuze, Gilles. 1993. *The Fold: Leibniz and the Baroque.* Minneapolis: University of Minnesota Press.

Duro-Royo, Jorge, Laia Mogas-Soldevila and Neri Oxman. 2015. "Flow-based fabrication: An integrated computational workflow for design and digital additive manufacturing of multifunctional heterogeneously structured objects." *Computer-Aided Design* 69 (2015): 143–154

Geboers, Eric and Matteo Baldassari. 2019. "Rebuilding Notre Dame: A Phoenix Rising from the Ashes." Accessed April 14, 2022. https://medium.com/@eric_geboers/rebuiling-notre-dame-a-phoenix-rising-from-the-ashes-f087bf89f5ed.

Higueras, Maria, Ana Isabel Calero and Francisco Jose Collado-Montero. 2021. "Digital 3D Modeling Using Photogrammetry and 3D Printing Applied to the Restoration of a Hispano-Roman Architectural Ornament." *Digital Applications in Archaeology and Cultural Heritage* 20: e00179.

Malik, Shneel, Julie Hagopian, Sanika Mohite, Cao Lintong, Laura Stoffels, Sofoklis Giannakopoulos, Richard Beckett, Christopher Leung, Javier Ruiz, Marcos Cruz and Brenda Parker. 2020. "Robotic extrusion of algae-laden hydrogels for large-scale applications." *Global Challenges* 4(1): 1900064.

McNeel & Associates. Rhinoceros 3D. V. 6.0. Robert McNeel & Associates. PC. 2018.

Polycam Inc. Polycam. V. 2.2. Polycam Inc. Apple iPhone 12. 2022.

Reeser Lawrence, Amanda and Ana Miljački. 2018. *Terms of Appropriation: Modern Architecture and Global Exchange.* Oxon: Routledge.

Rutten, David. Grasshopper. V. 1.0.0007. Robert McNeel & Associates. PC. 2021.

Xu, Jie, Lieyun Ding and Peter E.D. Love. 2017. " Digital reproduction of historical building ornamental components: From 3D scanning to 3D printing." *Automation in Construction* 76 (2017): 85–96.

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