Title:

A Generative Design Method for Cultural Heritage Applications: Design of Supporting Structures for Artefacts.

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Introduction:

In the field of Cultural Heritage (CH), CAD and CAE have provided great improvements in the transportation, restoration and conservation of ancient artifacts. For example, [9] provides a method for design automation of the packaging for artefacts and, in [10], a survey is provided considering other methods, like the usage of lattice structures, within the latest digital techniques to support the CH field. In [1], it has been proven that is possible to apply FEM with good approximation to an ancient bronze statue and, in [3], [4] and [5], FEA has been applied to support the restoration of an ancient bronze statue to explore different positions of statue's fragments. Also, in [2], Topology Optimization has been used to design the inner frame of a statue. Regarding the pottery, a lot of work has been done in the automatic alignment of fragments [7]. However, nothing has been found in the literature about the creative design and the generative design of supporting structures for the exposition of ancient pottery. This is probably because, commonly, these structures are mostly designed by architects according to the exhibition needs and then, artisanally manufactured. Therefore, it represents a very time-consuming procedure since it requires the knowledge of pottery's geometry and the decision of the anchor points for the assembly. Moreover, this choice is not supported by a FEA and thus, it exposes the fragment to possible stress concentrations which may lead to a failure of the artefact.

Within this framework, a Generative Design Method (GDM) to aid the design process for highly customized components in Cultural Heritage is proposed. In particular, the developed GDM focuses on the conceptual design of supporting structures for fragments of pottery for both exhibition and conservation. In order to provide an effective tool for the designers and archaeologists, the GDM is simulation-driven and manufacturing-oriented since the structural performances have been validated through Finite Element Analysis (FEA) and Generative Design (GD) has allowed to consider manufacturing constraints, in addition to limitations connected to orientation and visibility issues in exposition. Moreover, the GDM relies on Reverse Engineering (RE), parametric and explicit modelling, Genetic Algorithms (GAs). Parametric modelling has been chosen for the ease of use of the CAD environments and the basic components of the support (namely 'S_i') for the GDM have been designed to not constrain the design process to known shapes. FEA has allowed early-design evaluations within CAE environments and the selection of the best configuration through GAs. GD has been used to derive several lightweight conceptual structures of the fragment's support for the desired orientation and position of the artefact according to exposition needs.

The GDM has been carried out using a simplified fragment for the development of the procedure and then, it has been applied to a geometry closer to a real shaped artefact to assess its robustness and weaknesses in relation to the increase of shape complexity. The GDM workflow is divided into two main phases: Phase 1 ('P_1'), the parametric modelling and optimization of the support's interface regions (namely 'S_i' components) between the artefact and the support itself; Phase 2 ('P_2'), the generation of a variety of supporting structures within the Generative Design environment of Autodesk Fusion 360. The goal is to provide a GDM able to speed up the traditional design workflow for the exposition and the preservation of the structural integrity of ancient artefacts with the possibility to evaluate trade-offs between concepts of supports based on both aesthetics and structural performances, also providing the least effort on the designers to use a CAD environment in the conceptual design phase. Structural performances are measured in terms of average displacement and maximum stress of the fragment; Aesthetics is measured in terms of the frontal area occupied by the support in the field of view of the observer in a reference orientation. The effort on the designer is reduced since the parametric modelling activities focus only on the parametrization of the characteristics of the basic components ('S_i') while the overall lightweight support's structure is achieved through generative design.

The following sections provide an overview of the GDM using a simple case study and point out the achieved conclusions.

GDM Phase 1 ('P_1'):

The phase 'P_1' consists of the acquisition of the CAD model of the artefact, parametric modelling and optimization through GAs and Design of Experiments (DOE) of the interface regions between the artefact and its support to be developed. Indeed, the objective of the phase 'P_1' is to provide the best position and extension of the interface regions ('S_i') between support and artefact in order to minimize the mean value of the displacement of the artefact and to constrain the maximum stress (von Mises) on the artefact below a critical value according to its criticalities. These conditions are to be achieved imposing an input orientation of the piece that is commonly given by archaeologists and exposition needs.

Preliminary Operations

The preliminary operations to be accomplished pertain to the acquisition of: (1) the CAD model of the fragment through RE techniques, (2) its weight, (3) material, (4) criticalities and maximum allowable stress, (5) orientation and position for exhibition purposes. For a simplified geometry (a squared piece of pottery, made of clay, 100x100 mm, with a thickness of 10 mm), used for the development of the procedure, the CAD model (Fig. 1(a).) and its contour curves (Fig. 1(b)-1(c).) were straightforward.

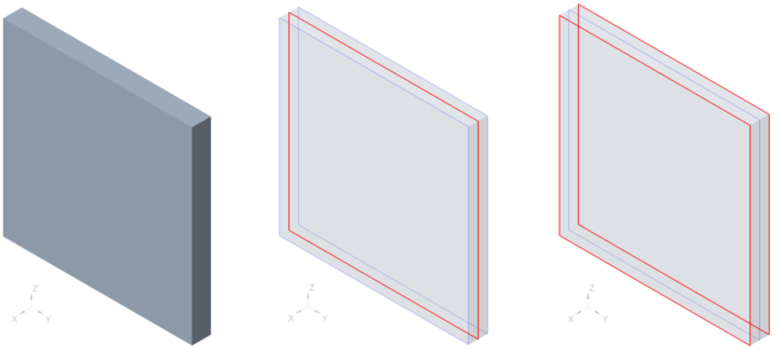

Fig. 1: (a) Simplified fragment, (b) fragment's mean contour curve (red), (c) fragment's extreme contour curves (red).

The second ones are necessary to place the 'S_i' components (made of ABS) as explained in the following section. Lastly, no criticalities were considered, and the orientation angle was set to 45° of inclination with the horizontal plane. At the end of the preliminary operations, a first hypothesis on the number of the 'S_i' components (interface regions) has been made. For this 'beta-test', it was assumed that three regions of interface were sufficient to sustain the structure and avoid accidental falls of the artefact (one along the bottom edge and the other two on each lateral one).

Parametric Modelling

The choice to use a parametric modelling approach has been inspired by the work of Krish [8] and by the applications of the NOA algorithm to different engineering problems [11]. Indeed, during the conceptual design phase, a minimum imposition on the designer's workflow will be provided using standard components, and a large variety of combinations can be analyzed through FEA seeking for the best solution. Once assumed 'N' interface region along the contour curve of the artefact, each basic component 'S_i' (Fig. 2(c).) has been modelled and for each of them a parameter of position (assigned to point PNT0 in Fig. 2(a).) and one of extension (extrusion of the ellipse in Fig. 2(b).) have been defined and associated to the CAD part. Subsequently, the basic components 'S_i' and the fragment have been assembled (Fig. 2(d).) and, through Boolean operations, hollows into each 'S_i' component, have been made to ensure the fit of the fragments into them.

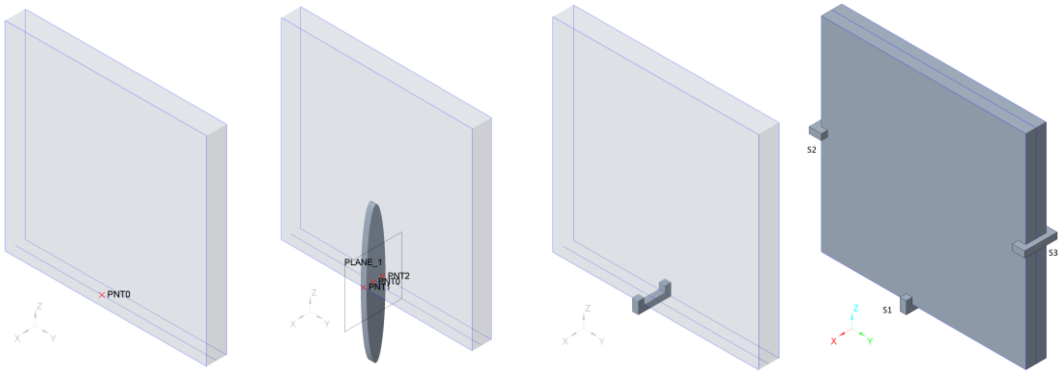

Fig. 2: (a) Parameter of position (point PT0), (b) Parameter of extension (extrusion of the ellipse in the normal direction of the PLANE_1), (c) 'S_i' component, (d) Assembly of the fragment and the 'S_i' components.

FEA Evaluations

FEA has been used to assess the structural performances of the different configurations to ensure a simulation-driven approach. Since each combination of parameters build up a different CAD model, the optimization procedure requires several FEA for the different combinations of parameters, and thus, a linear static analysis was selected despite the presence of contacts, also because it is intended to aid in the conceptual phase. In this way, it was possible to evaluate the responses in terms of maximum von Mises stress, maximum and average displacement of the fragment. Furthermore, a template script for the FEA was necessary. The template script is written in Python and is combined with the proprietary function of Altair SimLab to carry out the simulations in batch. During this step, it was fundamental to reduce as possible the number of nodes since several simulations must be performed. Once the convergence of the mesh has been achieved, the script was ready to be used in the following optimization step.

Parameters Optimization

The parameters to be optimized are positions and extensions of the 'S_i' components. For this step, the Genetic Algorithm available in Altair Hyperstudy was used. Due to hardware limitations, the parameters were discretized, and the optimization was limited to a single-objective GA for the position parameters and subsequently a full factorial DOE was performed over the extension parameters. Following this approach, the GA has found the optimized configuration of position parameters which minimize the average displacement of the artefact keeping the maximum stress below a critical value and the DOE has validated the minimum extension of each 'S_i' component in order to satisfy both aesthetics and structural performances. At the end of this step, an optimized configuration was available for the phase 'P_2' where several complete supporting structures were generated and compared through the Generative Design module embedded in Autodesk Fusion 360.

GDM Phase 2 ('P_2'):

The 'P_2' aims to achieve several complete supporting structures for the artefact according to the different combinations of obstacle geometries, materials, manufacturing methods, design objectives and constraints. Moreover, it was possible to provide some guidelines to speed up the setup for the generative design process.

Generative Design

The Generative Design phase was conducted in accordance with the framework outlined in literature, especially the one reported in [6]: the optimized configuration of the previous phase 'P_1' was imported in Fusion 360, and since the structure requires a functional region to secure the support on the exhibition table or basement with screws, three hollow cylinders (Fig. 3(a).) were designed for this aim (namely 'B' components), ensuring the contact with the basement.

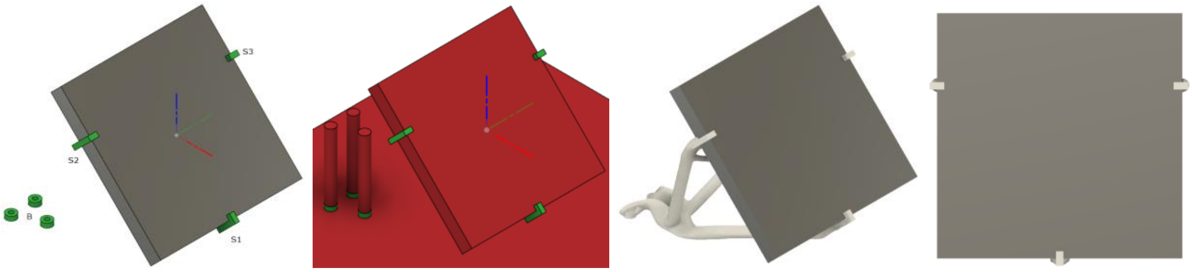

Fig. 3: (a) 'B' components, (b) preserve (green) and obstacle geometries (red), (c) concept generated, (d) front view of the assembly in the reference orientation plane.

The 'B' and 'S_i' components were set as preserved geometries that the generative design algorithm must connect avoiding the so-called obstacle geometries (Fig. 3(b).). Concerning these ones, different configurations of obstacle geometries were designed to drive the GD process towards aesthetics results in terms of non-invasiveness of the support in the field of view of the observer. Once assigned loads (equivalent load of the artefact on the 'S_i' components) and constraints, materials, manufacturing methods (unrestricted, additive), and objectives (minimize mass, maximize stiffness), the studies were generated in the Autodesk's cloud server.

For this development test, several concepts (one example is reported in Fig. 3(c)-3(d).) were obtained and the comparison among them provides a workflow to be followed in order to achieve potentially good solutions considering structural performances, aesthetics, and manufacturing constraints. Indeed, a first set of solutions should be achieved minimizing the mass and subsequently other studies maximizing the stiffness with a fine tune of the mass parameter can be performed with a given set of obstacle geometries to satisfy aesthetics. The simple case study, used for development has conducted to the possibility of extending and generalizing the entire procedure ('P_1'+'P_2') to an entire category of fragments, with different shapes, different materials, different number of ‘S_i’ components. The results of the application to a real shaped test case will be reported in the full paper.

Conclusions:

This work outlines a general procedure which aims to speed up the conceptual design phase for the design of lightweight supporting structures for ancient artefacts with a simulation-driven approach, performing an optimization with minimum imposition over the designer’s workflow. In the full paper, several case studies will be reported applying the GDM, which is divided into two phases according to the prescribed needs to find first the optimized positions and extensions of the interface regions (‘S_i’) between the artefact and the structure intended to support it. Second, the overall optimized structure can be selected within the proposed solutions set according to the given orientation and position, load, material, objectives and constraints, and considering manufacturing’s needs. Thanks to the Generative Design approach, it is possible to satisfy both performance requirements and aesthetics, designing also the concepts by taking into account the manufacturing process. Performances are measured in terms of average displacement and maximum stress on the fragment, while aesthetics is achieved by minimizing the extension of the ‘S_i’ components and by designing obstacle geometries which hide structure of the support behind the fragment in a reference orientation plane.

References:

[1] Accardo, G.; Amodio, D.; Bennici, A.; Cappa, P.; Santucci, G.; Torre, M.: Strain Fields on the Statue of Marcus Aurelius. Experimental Mechanics, 30(4), 372–376, 1990. http://doi.org/10.1007/BF02321507.

[2] Ahmad, A.; Bici, M.; Campana, F.: Guidelines for Topology Optimization as Concept Design Tool and their Application for the Mechanical Design of the Inner Frame to Support an Ancient Bronze Statue. Applied Sciences, 11(17), 2021. http://doi.org/10.3390/App11177834.

[3] Bici, M.; Brini, A.; Campana, F.; Capoferri, S.; Guarnieri, R.; Morandini, F.; Patera, A.: Design of the New Inner Frame for the Vittoria Alata di Brescia: How Engineering Design May Support Ancient Bronze Restoration. Lecture Notes in Mechanical Engineering, 951–962, 2022. http://doi.org/10.1007/978-3-030-91234-5_96.

[4] Bici, M.; Campana, F.; Colacicchi, O.; D’Ercoli, G.: Cad-CAE Methods to Support Restoration and Museum Exhibition of Bronze Statues: the ‘Principe Ellenistico’. In IOP Conference Series: Materials Science and Engineering, Vol. 364, 2018. http://doi.org/10.1088/1757-899X/364/1/012014.

[5] Bici, M.; Guachi, R.; Colacicchi, O.; D’Ercoli, G.; Campana, F.: Posture Evaluation for Fragment Re-Alignment of Ancient Bronze Statues: The Case Study of the Principe Ellenistico. Lecture Notes in Mechanical Engineering, 323–335, 2019. http://doi.org/10.1007/978-3-030-12346-8_32.

[6] Buonamici, F.; Carfagni, M.; Furferi, R.; Volpe, Y.; Governi, L.: Generative Design: An Explorative Study. Computer-Aided Design and Applications, 18(1), 144–155, 2020. http://doi.org/10.14733/cadaps.2021.144-155.

[7] Eslami, D.; Di Angelo, L.; Di Stefano, P.; Pane, C.: Review of Computer-Based Methods for Archaeological Ceramic Sherds Reconstruction. Virtual Archaeology Review, 11(23), 34–49, 2020. http://doi.org/10.4995/Var.2020.13134.

[8] Krish, S.: A Practical Generative Design Method. Computer-Aided Design, 43(1), 88–100, 2011. ISSN 0010-4485. http://doi.org/10.1016/J.Cad.2010.09.009.

[9] Sánchez-Belenguer, C.; Vendrell-Vidal, E.; Sánchez-López, M.; Díaz-Marín, C.; Aura-Castro, E.: Automatic Production of Tailored Packaging for Fragile Archaeological Artifacts. J. Comput. Cult. Herit., 8(3), 2015. ISSN 1556-4673. http://doi.org/10.1145/2716324.

[10] Scopigno, R.; Cignoni, P.; Pietroni, N.; Callieri, M.; Dellepiane, M.: Digital Fabrication Techniques for Cultural Heritage: A Survey. Computer Graphics Forum, 36(1), 6–21, 2017. http://doi.org/10.1111/Cgf.12781.

[11] Vajna, S.; Clement, S.; Jordan, A.; Bercsey, T.: The Autogenetic Design Theory: An Evolutionary View of The Design Process. Journal Of Engineering Design, 16(4), 423–440, 2005. http://doi.org/10.1080/09544820500267781.