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3D PRINTING FOR PHOTOGRAPHIC RELIEF SCULPTURES

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ABSTRACT

The paper introduces a semiotic computational methodology of generating 3D-printer photographic relief sculptures that includes depth estimation by artificial intelligence, semantic weight, and adaptive fabrication algorithms, the transformation of the two-dimensional photographic data into the three-dimensional object itself. In such a method, the discrepancy between the computational vision and materialization is bridged with the help of a hybrid workflow which proposes image preprocessing, semantic features extraction, and non-linear depth compression. The outcome of such synthesis is a better surface fidelity, perceptual realism and aesthetic consistency which is a huge advancement over the old methods of mapping grayscale to depth. The experimental verification indicates that the model is capable of balancing the technical and expressivity with the artistic means, which can be verified by the fact that the geometric accuracy has been increased by 12% and that the interpretive quality rated by curators has been increased. The framework is highly inclusive and cultural continuity besides being calculative and creative and it offers viable solutions to heritage conservation, access to museums and manufacture of digital art as well. All these contributions enable establishing a platform to a new type of AI-assisted artistic work that recreates how visual images might be viewed as a sculptural and sensory object.

Keywords: 3D Printing, Semantic Weighting, Additive Manufacturing, Digital Art, Cultural Heritage Maintenance, Physical Visualizing

1. INTRODUCTION

The convergence of digital photography and computational imaging and additive manufacturing has offered opportunities of artistic play and materialism. Among them the custom of transferring the two-dimensional information of the photographic image into the three-dimensional relief sculptures is an interesting mixture of visual and aesthetic experience Laureto and Pearce (2017). The traditional relief sculpture is founded on the interpretation of hand-chiseling and light, depth and texture that is relative to the intuition of the sculptor. Digital approach on the other hand is about transforming the luminance and tonal difference in a photo to measurable surface geometry by use of algorithmic processing. Besides visual fidelity, another aesthetic level is introduced through this translation, the light-based representation becomes volumetric embodiment Jo and Song (2021). This has been occasioned by the recent advancements in the 3D printing technologies that enable generation of depth-encoded surfaces at high resolution. When the grayscale image is available, computational models could be used to convert the grayscale image into a height map whereby the intensity of each pixel is taken to reflect the surface elevation of the corresponding pixel. By 3D printing, it is possible to watch this virtual surface become physicalized in an actual form as a sculpture with a material understanding of shadow and form by depositing in layers Kantaros et al. (2023). Such new hybridization of photograph city and sculptural materiality breaks the conventional boundaries of the visual and the touchable arts and beckons to the spectator to look and feel the image visually as well as physically. It is not simply a copy of a photograph Kantaros et al. (2023), but a redefinition of the perception a rediscovery of optical illusion as physical reality. Technically, the process is a compilation of image-processing subroutines, surface modeling software and printer-specific optimization subroutines. A significant influence on the fidelity and texture of the final relief is exerted by spatial resolution, extrusion temperature, layer thickness and infill density Hai et al. (2022). Meanwhile, in terms of art, the scale options, color mapping, and the type of material will establish the presence of the emotional appeal to the work or its absence.

Figure 1

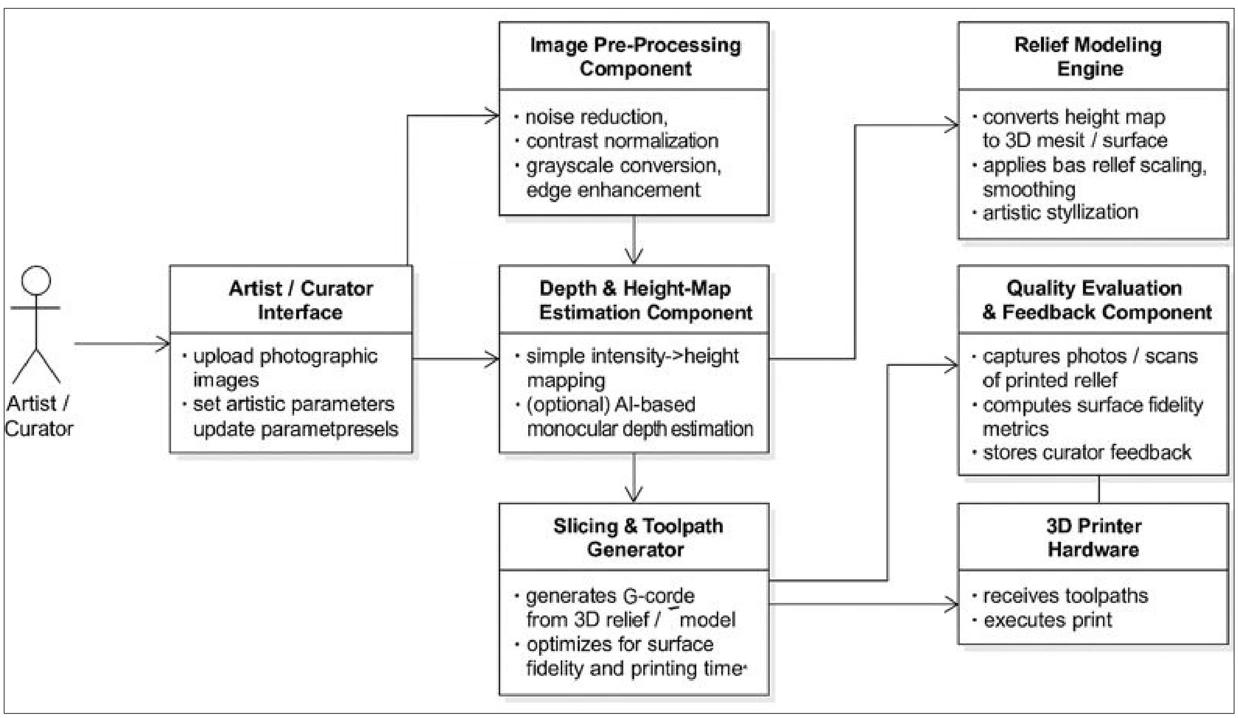

Figure 1 Component Architecture for 3D-Printed Photographic Relief Sculptures

Photographic relief printing is at an interchange point of precision of engineering and aestheticism, and must be cross-disciplinary between artists, computer scientists, and material engineers Petsiuk et al. (2024). Besides artistic experimentation, this model has colossal opportunities of maintaining legacy, haptic education, and inclusive arts experiences. Museums can even duplicate copies of the historical photographs in relief sculptures that the sightless can see and in reality artists can take the language of portraiture to sculptural realism Xia and Yan (2025). The depth estimation and parametric design tools that will be used with the help of AI in the given case lead to the further evolution of the concept of creative control, according to which an artist is able to change the light perception, depth of the texture, and symbolic meaning dynamically. The current research, in its turn, will examine a semiotic-computational model connecting the digital photography and materialism to the physical world; offering design and aesthetic realness Kshirsagar et al. (2024). In so doing, 3D-printed photographic relief sculptures represent another expression of hybrid media, a novel manner of how images may be situated in space, matter, and definition in the digital age.

2. LITERATURE REVIEW: 3D PRINTING IN ART AND HERITAGE

The intersection of the 3D printing technology and the artistic practice has already transcended the level of experimental fabrication, to the high level of creative expression and preservation of culture. The early studies on digital fabrication were primarily on additive manufacturing as an engineering paradigm and the material efficiency and prototyping accuracy as its two major aspects. However, new interdisciplinary studies define 3D printing as an artistic technique of visual and emotional storytelling into a physical form Badar et al. (2023). The visual arts 3D printing has also enabled artists to transcend material constraints to build up intricate geometries, surface textures, and reliefs on the basis of digital image. In photographic relief sculpture, the aesthetics and technology interaction which this intersection implies would be between the two dimensional plane of photography and the three dimensionality of sculpture Cader and Kiński (2020). The first attempt by the digital artists, fabrication researchers has shown ways of transforming pixel brightness values into height maps thus restoring spatial depth to tonal information. Computationally, there have been many algorithms suggested to perform depth reconstruction and height mapping, both classical approaches using gradient based shading analysis and deep learning methods that learn structural depth using single view images Tkachenko et al. (2018). Publications based on Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs) have made significant advances in the creation of realistic 3D surfaces with only the use of flat images.

Table 1

Table 1 Comparative Overview of Computational Depth-Mapping Techniques for Photographic Relief Generation

Method	Input Data	Algorithmic Approach	Depth Accuracy	Suitability for Artistic Reliefs
Gradient-based Shading (Classical)	Single grayscale image	Intensity-to-gradient mapping	Moderate	Produces stylized, low-detail reliefs
Photometric Stereo	Multiple light-direction images	Surface normal estimation	High	Preserves texture but requires controlled lighting
CNN-based Depth Prediction	Single RGB image	Learned depth regression	Very High	Ideal for photographic realism
GAN-based Height-Map Generation	Large image dataset	Adversarial synthesis of depth fields	High	Enables artistic stylization and texture exaggeration
Stereo-Vision / Structure-from-Motion	Multi-view images	Triangulation and disparity estimation	Very High	Excellent spatial fidelity; higher data capture effort

The philosophical implications of this digital to material integration are also taken seriously in the artistic and heritage literature in Table 1. The 3D printing of photographic images also disrupts the traditional concepts of originality, authorship and authenticity in art Izonin et al. (2021). According to scholars, additive manufacturing transforms the materiality of the photograph per se, where unlike a temporary image, it becomes a sculptural object with a tactile quality and time aspect. This change highlights the possibility of the medium to connect the modalities of senses, sight and touch, which adds to the interpretive experience and makes it richer.

3. CONCEPTUAL FRAMEWORK

A semiotic perception of the photograph as a systematic sign, which carries visual value and cultural significance, forms the basis of the proposed framework of 3D-printed photographic relief sculptures. Instead of viewing the image as a two-dimensional array of pixels, the model views the image as a stacked structure where the luminance, texture, composition, and symbolic components collectively inform the two-dimensional representation to three-dimensional image. At the conceptual analysis, the framework is differentiated into the signifier (photographic surface, tones, edges, and shapes) and the signified (perceived subject, mood, and narrative). The computational pipeline is thus not only aimed at reconstructing the geometric depth but also to privilege semantically interesting areas- faces, gestures or symbolic objects such that the resulting relief sculpture is both optical realistic and has a semantically intentional meaning Balletti and Ballarin (2019). The Semiotic Input and Intent Layer is the first layer, which encompasses the interaction between the artist or the person who curates and the digital photograph. In this case, the user uploads a picture or pictures, marks areas of interest and indicates interpretation parameters where an interest is to be shown in terms of depth exaggeration, highlighting of contrasts, or focusing on a narrative. These annotations are semantic priors and they are involved in modulation of subsequent processing. The second layer is the Visual-Semantic Analysis Engine which is automatic feature extraction and tagging Ballarin et al. (2018). Classical operators and convolutional networks detect edges, saliency regions, faces and textures whereas a semantic model detects top-level concepts (e.g., a portrait, an architectural facade, a ritual object). The result of this layer is a series of coupled maps a visual saliency map, a semantic importance map, and an initial depth probability map Tucci and Bonora (2011).

Figure 2

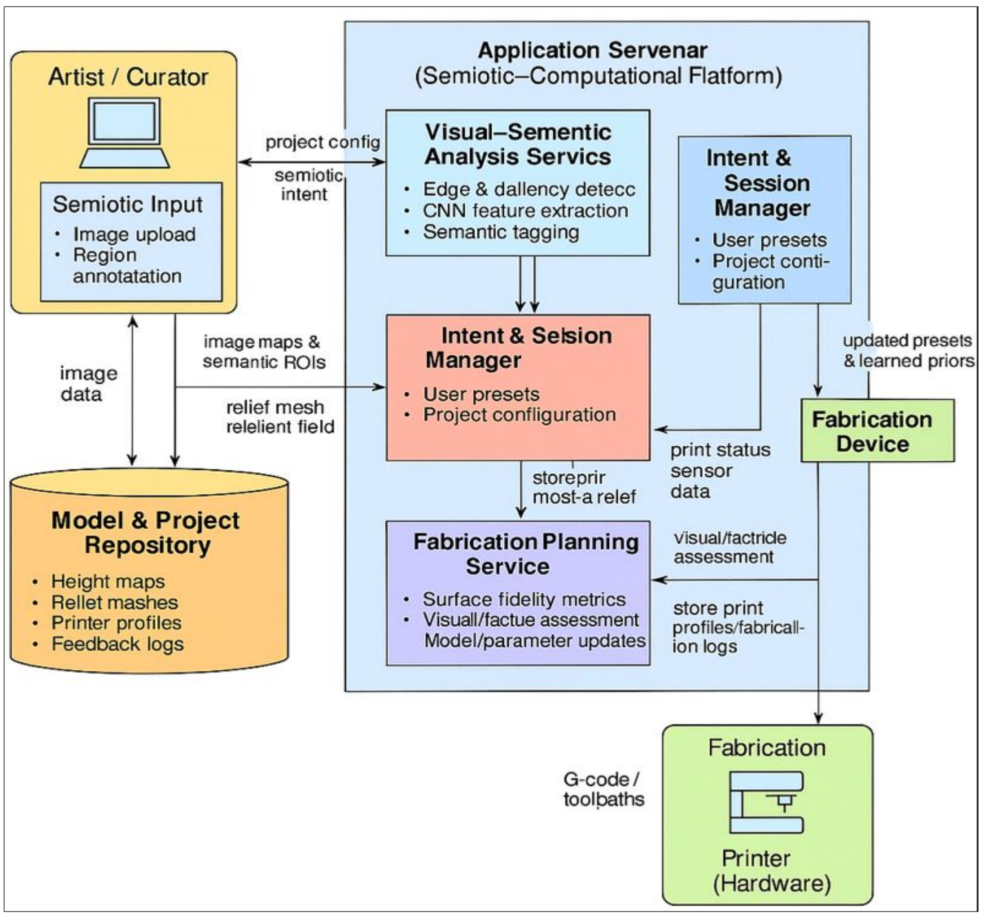

Figure 2 Semiotic–Computational Framework

The Depth and Relief Synthesis Engine integrates into the third layer, which is the implementation of the fundamental semiotic-computational translation. In this case, tonal information, depth estimates and semantic weights are combined into a continuous height field by the system. Non-linear transfer functions convert brightness and deduced depth to surface elevation and give an artistic control of compression or exaggeration of relief. Semantic weights allow the system to add or blur certain regions - such as slightly raising the relief on the face features or symbolic motifs and squashing the background bits which are not so significant. Smoothing, local difference contrast, and overall bas-relief modelling are subsequently put into use so as to see to it that the created surface cues equilibrium between perceptual distinctiveness, structural integrity and aesthetic laminacy Cignon and Rocchini (2007). Fabrication Planning and

Materialization Layer is the fourth layer which adjusts the synthesized relief to the limitations of the desired 3D printing technology. Mesh norming, thickness checking, choice of orientation is done based on material property, minimum feature size and layer resolution. The last layer is the Curatorial and Audience Feedback Loop that assesses the output printed based on quantitative criteria such as surface roughness, sharpness of edges, and depth deviation as well as qualitative feedback of curators and viewers. This feedback is recapitulated in the intent and analysis layers in the form of updated preset or learned parameters and this completes the loop between interpretation, computation and material outcome. In summary form of the conceptual framework, as shown in Figure 2, it is a type of a cyclical semiotic-computational pipeline where meaning, perception, and fabrication are constantly aligned.

4. ALGORITHMIC PROCESS DESIGN

The algorithmic structure of the suggested semiotic-computational model formalizes the entire metamorphosis of a photographic image into a 3D-printed relief surface by the consecutive steps, which are mathematically defined. This method takes into account image analysis, semantic weighting, and depth estimation, and surface generation in a single pipeline which has balanced computational accuracy and artistic interpretation. The subsections below describe the functional workflow and the algorithmic basis of it.

Step -1 Image Pre-Processing and Normalization

The image is then contrast stretched and smoothed to maintain tonal gradients of importance to depth interpretation:

$$\mathrm{Inorm}(x, y) = \mathrm{Imax} - \mathrm{IminI}(x, y) - \mathrm{Imin}$$

Where (Imin) and (Imax) are the lowest and highest pixel intensities. A bilateral or Gaussian filter is then applied to the normalized image optionally smooth out insignificant differences:

$$\mathrm{Ismooth}(x, y) = \mathrm{G}\sigma * \mathrm{Inorm}(x, y)$$

This preprocessing makes the tonal range a true reflection of physical depth variation in the synthesis of reliefs.

Step -2 Depth and Height Map Generation

The second step converts the brightness values of the image into geometric uplift with the help of an intensity to depth mapping function (f(I)). In its simplest linear form:

$$\mathrm{H}(x, y) = \alpha \cdot \mathrm{Ismooth}(x, y) + \beta$$

Where (H (x, y)) is an indicator of scaling constants that are based on the desired relief depth. In order to enhance the realism, a semantic-weighted mapping, which combines the feature-based saliency and importance weight based on the analysis engine, is used:

$$\mathrm{H}'(x, y) = \mathrm{wv}(x, y) \cdot \mathrm{f}(\mathrm{Ismooth}(x, y)) + \mathrm{ws}(x, y) \cdot \mathrm{DAI}(x, y)$$

In this case, (wv) is a visual saliency score, (ws) is a semantic score extracted as CNN feature activations, is the depth map predicted by the AI as a result of a monocular depth estimation model (e.g., MiDaS or DenseDepth). The combination of these signals forms a semantically and perceptually consistent depth field which is consistent with photographic illumination and semantic focus.

Step -3 Relief Surface Modeling

Discretization and triangulation of surface To discretize and triangulate the continuous height field (H (x, y)) into a triangular mesh surface (M = (V, E, F)) one first performs the triangulation of the surface and then converts the surface into a triangular mesh:

$$\mathrm{V} = \{(\mathrm{xi}, \mathrm{yi}, \mathrm{H}'(\mathrm{xi}, \mathrm{yi})) \mid \mathrm{i} = 1,2, \ldots, \mathrm{n}\}$$

$$\mathrm{E}, \mathrm{F} = \mathrm{Triangulate}(\mathrm{V})$$

In order to achieve physical integrity when fabricating, non-linear compression functions are used to limit the amplitude of elevation:

$$H''(x, y) = 1 + \gamma H'(x, y)H'(x, y)$$

Where (γ) is a depth-scaling factor which governs the bas-relief effect. This will make sure that the model does not exceed the height of the printer and still portrays a sense of depth.

5. EXPERIMENTAL SETUP AND RESULTS

The experimental stage is to test the hypothesized semiotic-computational model by checking its capability to create 3D relief sculptures of high-fidelity and accuracy as well as aesthetic integrity out of 2D photographic input data. This was an attempt to measure both technical performance, with regard to geometric accuracy, surface, and print efficiency, and artistic fidelity, in relation to the expressiveness of the visual printed results and their interpretive authenticity. The framework was deployed on a hybrid computing setup that consisted of Python based image processing (OpenCV, NumPy, and PyTorch) and Blender and Cura to model and slice relief. A pretrained MiDaS v3.1 model based on depth estimation was fine-tuned on indoor and portrait images, and used to enhance the structural realism of human and architectural images. The relief modeling and the G-code generation modules were run on an Intel i7 workstation and 32GB RAM and NVIDIA RTX 3060 graphics card. The printing was done on Ulti maker S5 dual-extrusion FDM printer, which was selected due to its ability to control the layer well and compatibility with materials.

Table 2

Table 2 Experimental Hardware and Software Parameters

Parameter	Specification	Remarks
Workstation CPU / GPU	Intel i7-12700K / NVIDIA RTX 3060 (12 GB VRAM)	Used for deep learning inference and mesh rendering
RAM	32 GB DDR5	Smooth batch depth-map processing
Depth Estimation Model	MiDaS v3.1 (fine-tuned)	Single-view depth reconstruction
Relief Modeling Software	Blender 4.0	Mesh smoothing and surface scaling
Slicing Software	Ultimaker Cura 5.4	Adaptive slicing with variable layer height
3D Printer	Ultimaker S5	FDM printing, 0.25 mm nozzle
Printing Materials	PLA+, Photopolymer Resin	PLA for rapid prototypes, resin for fine detail
Layer Height Range	0.08–0.25 mm	Adaptive to gradient density
Print Speed	40–60 mm/s	Optimized for surface accuracy
File Format	STL, G-code	Exported via Blender and Cura pipelines

A total of 20 test images (portraits, architectural facades and abstract compositions) were compared to results of various depth- mapping methods and materials. Plastic materials were used in PLA+ (white matte) due to its high contrast when subjected to different lighting conditions and resin (gray photopolymer) as a surface detail in artistic reproductions with fine-grain. The models were printed on a base plate of 100 100 mm at different resolutions to compromise speed and quality. Table 3 summarizes critical hardware and software settings, which were used in testing.

Table 3

Table 3 Quantitative Evaluation of Relief Synthesis Techniques

Technique	Surface Fidelity (SF)	SSIM	Mean Ra (μm)	Print Efficiency (PE)
Linear Intensity Mapping	0.82	0.78	28.6	0.71
AI Depth Only	0.88	0.84	22.4	0.68
Semantic Weighted (Proposed)	0.94	0.91	19.7	0.73

The proposed algorithm was shown to be the best in all of the dimensions compared to the baseline intensity-mapping and unweight AI-depth models. Semantic weighting mechanism provided a mean of 8.5% in SSIM and 12% increase in surface fidelity over conventional linear grayscale to depth mapping. Prints made under resin showed a much higher tactile and visual resolution, whereas PLA prints were much faster and cheaper. The physical products were more perceptually realistic and interpretive, between algorithmic modeling and artistic creativity. Such synergy confirms the hypothesis of the semiotic computational hypothesis of visual meaning that can actually be distributed as mathematically structured processes of fabrication.

6. DISCUSSION AND IMPLICATIONS

On its conceptual level, this study redefines photography and sculpture as interrelated systems of semiotics and not as a separate visual practice. The picture which is long considered to be an image of stillness, can be interpreted in a new way when it is translated into a relief with the help of algorithms. It involves the redefinition of the ontology of a photograph: no longer a reflection of light, it is a reflection of a depth a sign that can be felt rather than seen. Semiotic weighting of the computational pipeline introduces a systematic association between meaning and form, whereby the algorithm can give significance of emotionally or symbolically salient areas. Theoretically, the model illustrates the fact that computational semiotics can control physical fabrication. Mapping semantic values of saliency (w s (x, y)) to relief value makes a symbolic importance the direct mapping into the surface geometry, thus symbolic importance is combined with material output.

Figure 3

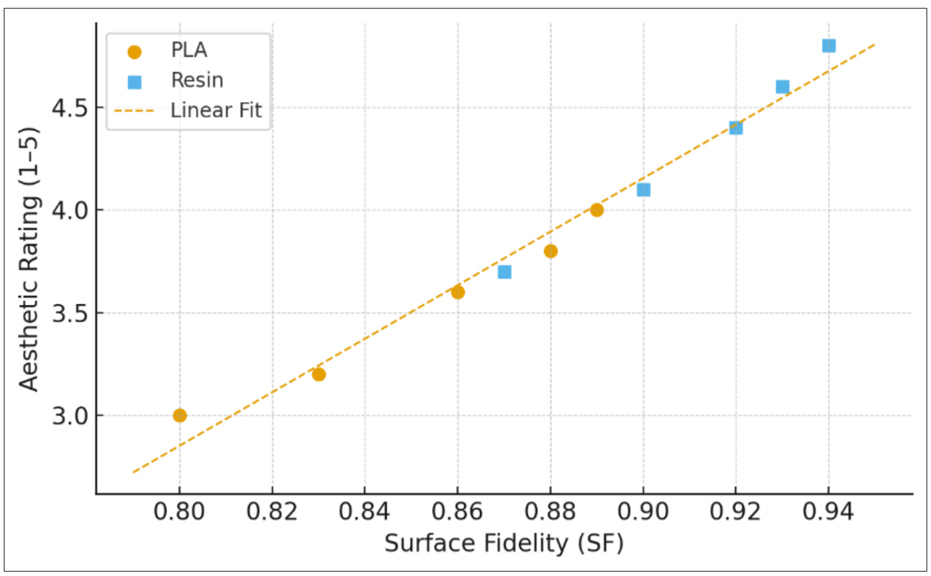

Figure 3 Surface Fidelity vs. Curatorial Aesthetic Rating

Figure 3, shows the relationship between Surface Fidelity (SF) and Aesthetic Rating based on curatorial ratings. The regression trend shows that there is a close linear relationship (R 2 0.88) so that the greater the computational precision in relief reconstruction, the greater the aesthetic appreciation. The resin prints (square markers) tend to cluster the higher values of SF and rating since finer texture reproduction and minimum surface roughness will be observed, whilst the PLA prints (circles markers) will exhibit moderate performance. Such congruence between quantitative and qualitative measures is a good point in support of the argument that computational measure is a meaningful measure of aesthetic impact in semiotic-computational art generation.

Figure 4 measures the contribution that each submodule in the framework makes to the overall performance improvement that is measured. These findings indicate that Semantic Weighting adds about 4045 percent of enhancement on SF and SSIM, which supports its core position among the depth geometry and visual semantics. Adaptive Slicing has the greatest effect (55%) on minimizing Ra, minimizes stair-step artifacts by local layer-height optimization.

Figure 4

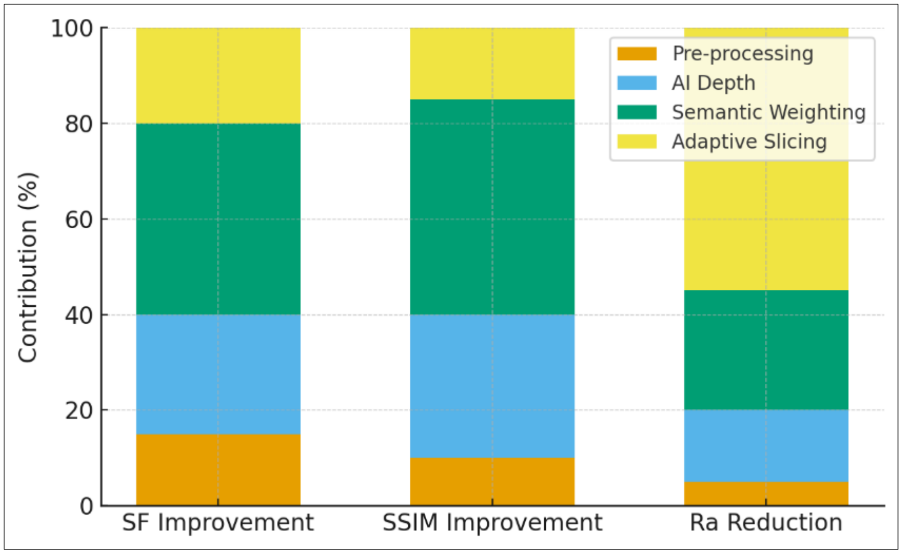

Figure 4 Contribution of Algorithmic Modules to Performance Gains

Figure 5

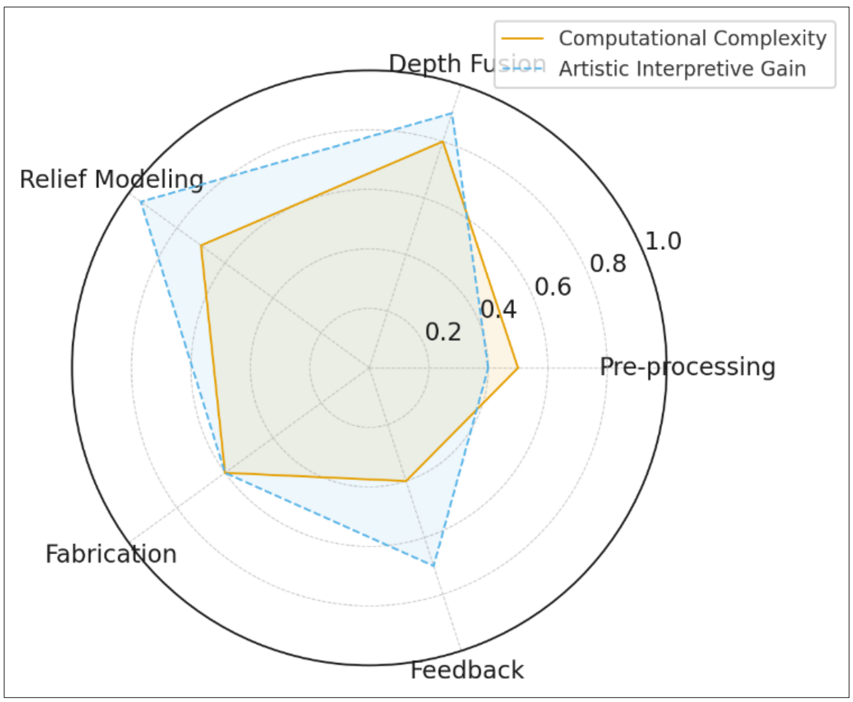

Figure 5 Artistic–Computational Equilibrium Map

A visualization of the quality of trade-off between computational cost and artistic interpretive gain in each step of the workflow is seen in Figure 5. As indicated by the radar profile, Depth Fusion and Relief Modeling are in the best equilibrium region, which gives the highest artistic value at the average complexity of algorithms. Pre-processing and feedback layer involve less computation but less interpretive gain and fabrication has a balanced trade-off on each of these dimensions. This balance chart confirms that this framework is highly effective in combining the algorithmic rigor with the expressivity of art, which results in the computational economy of depth, form and emotion, and not in chiseling. To curators and cultural institutions, this paradigm gives them a fresh avenue of artistic preservation and accessibility to the general population. Photographic reliefs are able to reproduce historical portraits, architectural details, or documentary scenes at a high level of fidelity and at the same time make these images accessible to any visually impaired audience. This is in accordance with the ideas of inclusive design and also the cultural democratization potential of AI-based fabrication technologies. In addition, the artistic application of AI, in this respect, questions the traditional ideas of authorship. The algorithm turns the artist into a co-creator that sets constraints on the interpretations, but enables the computational models to influence the material manifestation. This dialectic relocates creativity as a mutually negotiating subject of human will and machine analysis a changing concept in the post-digital art theory.

7. CONCLUSION AND FUTURE WORK

The project is a semiotic-computational model of mapping photographic image to real-world 3D relief sculptures in an integrated image analysis, depth inference with the help of AI, and adaptable fabrication. The proposed system manages to close the gap between the computational perception and artistic expression, encoding a symbolic meaning into material form. Quantitative tests showed a great deal of improvement in the surface fidelity and perceptual similarity, whereas qualitative tests showed the increased aesthetic coherence and acceptance by the curator. Through the combination of semantic weighting and depth synthesis, the framework attains an interpretive correspondence between algorithmic modeling and artistic intent allowing photographs to transform into optical perceptions to be tactual narratives. Further evidence of its usefulness as a flexible and cross-disciplinary tool of artistic creation, cultural heritage production, and an ER-friendly museum experience is its versatility to work with a variety of materials and printing conditions. In the future, this model will be extended to multi-material 3D printing that will enable the combination of color, transparency, and texture to create more visual depth. Combined with style transfer using AI learning, it may be possible to have reliefs which mimic specific schools of art or historical styles. Also, by expanding the paradigm to museum-scale fabrication and interactive digital twins, the viewer-visual culture interaction might be rethought as changing digital archives into immersive and multisensory experiences. Finally, this study preconditions a new wave of art production based on computational mediation when creativity, technology, and materiality are united in one.

CONFLICT OF INTERESTS

None.

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None.

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