Nanotectonica SEM-GAN

The Strange Materiality of Subvisible Bodies

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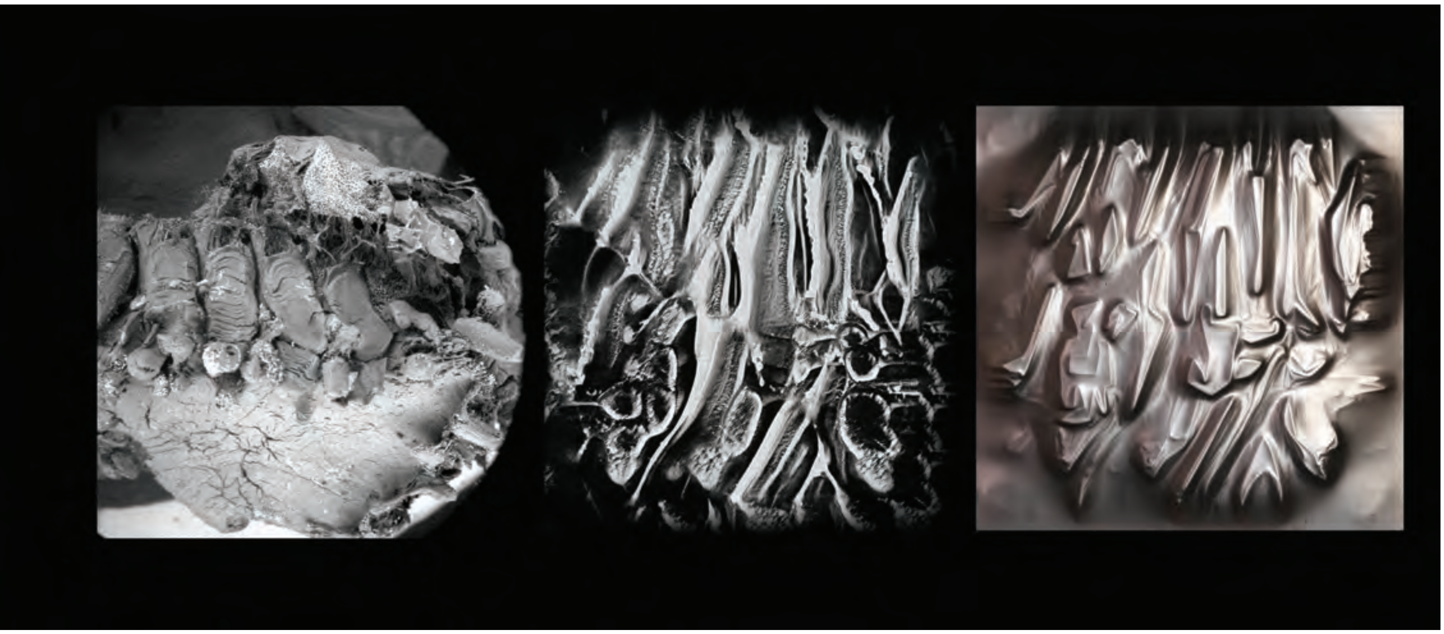


1 Left: Scanning Electron Microscopy (SEM) image

Middle: Generative Adversarial Network (GAN) image

Right: Robotic Incremental Metal Formed (RIMF) steel relief

ABSTRACT

Nanotectonica is an architectural research project that examines the convergence of nanotechnology and contemporary design tools. The present study, *Nanotectonica SEM-GAN,* focuses on two processes for image production, one based in the field of nanotechnology and the other in machine learning: Scanning Electron Microscopy (SEM) and Generative Adversarial Networks (GAN). It establishes commonalities of these routines as they pertain to aesthetics and design methodology, and it explores methods of spatializing and materializing images produced in their interaction. The study of transposing rich image material to three-dimensional geometry and material artifact is considered relevant not only to the particular study at hand, but also to the general problem of image-based machine learning techniques when applied in the spatial design disciplines. A third process, Robotic Incremental Metal Forming (RIMF), advances the aesthetic language of SEM-GAN through the sculptural method of the relief. Analogous to the electron beam probing minute bodies in nanoscopic imaging, the end effector impresses robust steel plates in robotic fabrication.[1]

The study elaborates a "strange materiality," identified in SEM imaging, enhanced through GAN, and materialized via RIMF. It refers to the inherent unfamiliarity of subvisible expressions that are made visible through the scanning electron microscope. SEM visuals are generally misperceived as black-and-white photography, yet they are not produced with light (photons) but with electrons (matter); hence, the strange materiality of the aesthetic quality—the infinitesimal manifestation of things rendered visible in total darkness. Materialism here refers to the mind-independent existence of objects under observation. Strangeness hints at expressing the vibrant agency of their invisible matter through appropriated aesthetic methods such as SEM and GAN.

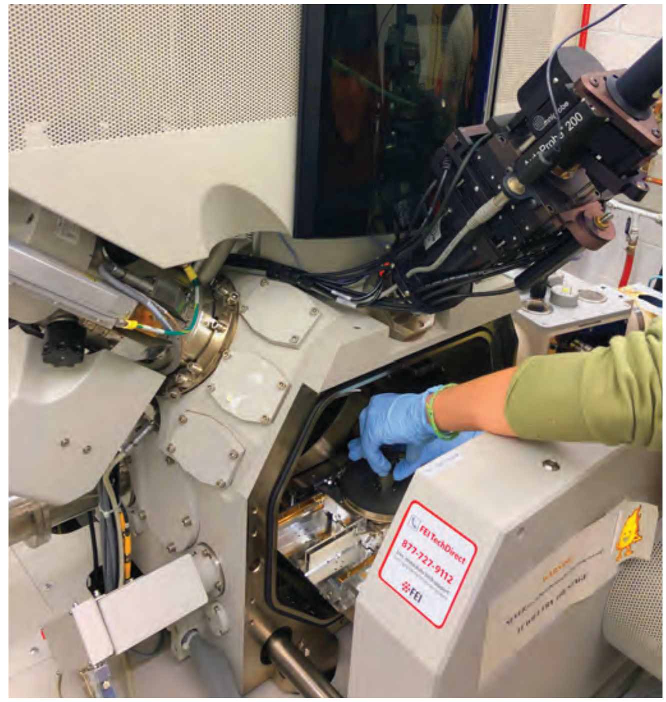
INTRODUCTION

The study begins by discussing parallels in the operating processes of the Scanning Electron Microscope (SEM) and Generative Adversarial Network (GAN) applications, and it explores their potential for a non-deterministic and collaborative design method, here referred to as speculative design.[2] SEM and GAN applications both entail blind procedures, which momentarily suspend control by the human operator either through a certain degree of autonomy granted to the machine in training (GAN) or through indirect observation (SEM) [see *Blind Probing* section of this paper].

In addition to operational parallels, the study establishes aesthetic commonalities found in images produced by the SEM and GAN processes. It argues that both share a particular visual language with an intrinsic quality of "strange materiality." Images produced by the scanning electron microscope and those generated by adversarial networks express spatial effects through gradient pixel fields that depict shade and shadow and work without line graphics; both relate inputs that are not visible per se. However, GAN and SEM visuals differ in two fundamental ways. First, GAN applications process as well as produce digital images, whereas SEM produces images from subvisible physical specimens. Second, GAN sources and produces the entire digital spectrum of color, while the SEM operates without light and thus without color [see *SEM Operation*]. SEM grayscale images render smooth gradients into blurred fields and produce an often moody atmosphere, while GAN images evoke dreamlike scenarios; both depict strange worlds as they relate to an invisible source.

In *Nanotectonica*, strange materiality refers to the inherent unfamiliarity of subvisible expressions that are made visible through the Scanning Electron Microscope. The SEM visuals are generally misperceived as black-and-white photography, yet they are not produced with light (photons) but with electrons (matter). Hence, the strange materiality of the aesthetic quality—the infinitesimal manifestation of things rendered visible in total darkness by a direct matter-to-matter reading, and granted novel expression via GAN manipulation. Materialism here refers to the mind-independent existence of objects under observation. Strangeness hints at expressing the vibrant agency of their invisible matter through appropriated aesthetic methods such as SEM and GAN.[3]

While identifying inherent aesthetic commonalities produced by SEM and GAN operating separately, the study explores the two techniques in conjunction. Here SEM images function as source material for the GAN operation, and together they serve two parallel modes of inquiry. The first is a continuation of the aesthetic discussion (above) and attempts to amplify the established effects, i.e. the unfamiliarity of the subvisible



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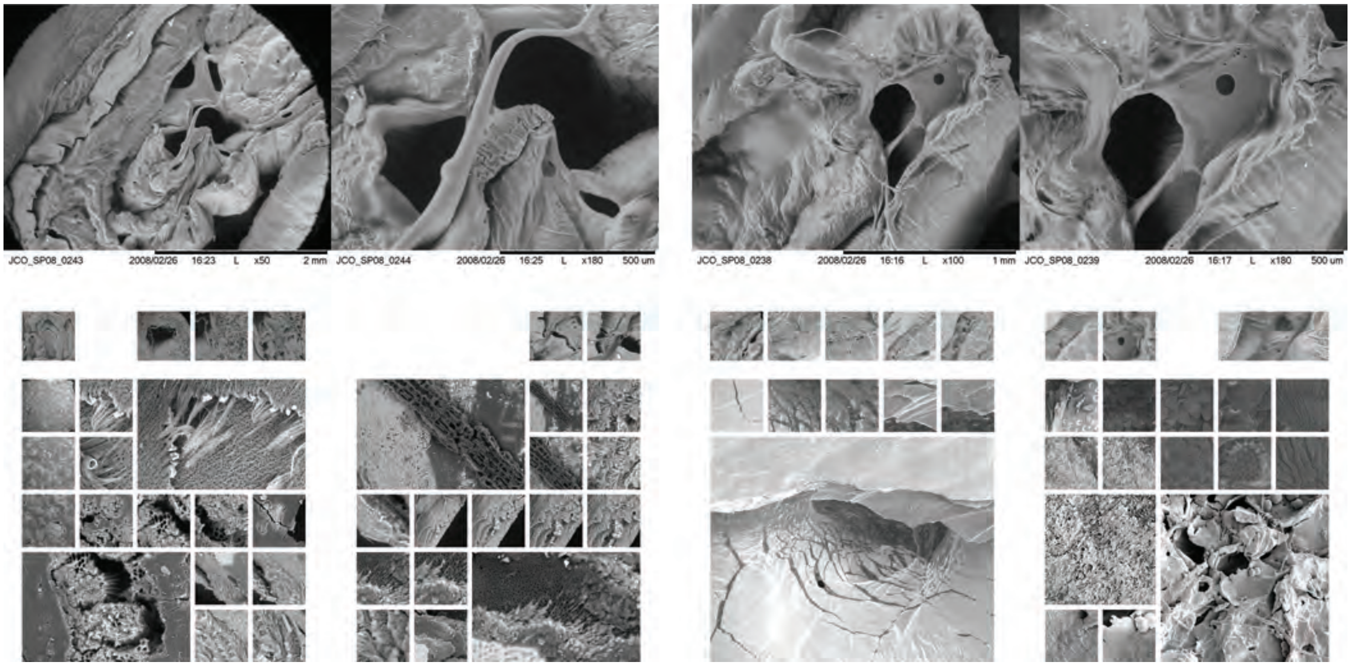
2 Scanning Electron Microscope: FEI, Helios NanoLab650; *Nanotectonica* at The New York Structural Biology Center, 2019

3 Robot: ABB IRB6700 *Nanotectonica* at The Consortium for Research and Robotics, hosted by Pratt Institute, 2022



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world is heightened by machine intelligence; GAN estranges the SEM image further.[4] The second utilizes the GAN as a taxonomic and archival operator of the SEM image collection Nanographia.[5] By training the GAN with a vast data set of SEM-produced image material, the study explores new modes of taxonomy making. Here, a non-human actor is invited to advance “open taxonomies” of the subvisible world [see *SEM-GAN Taxonomy*]. As a technical consideration, the study compares two different methods of training a GAN engine on the Nanotectonica SEM image library [see *Comparing Methods*].

Subsequently the study turns towards the problem of image spatialization and critically discusses various methods of transposing 2D image data to 3D geometry. With this Nanotectonica, SEM-GAN aims to contribute to a particular aspect of the discourse in the spatial design disciplines (architecture, and urban-, fashion-, and industrial design, etc.) relating to the use of image-based GANs. Initially the study takes three approaches to image spatialization: working with image stacks to generate monolith geometry; with multi-dimensional orthographic image projection to generate sculptural form; and with image displacement mapping to generate topographic relief. It concludes that sculptural relief is the preferred method for elevating the inherent aesthetic qualities of SEM-GAN [see *Image to 3D*].

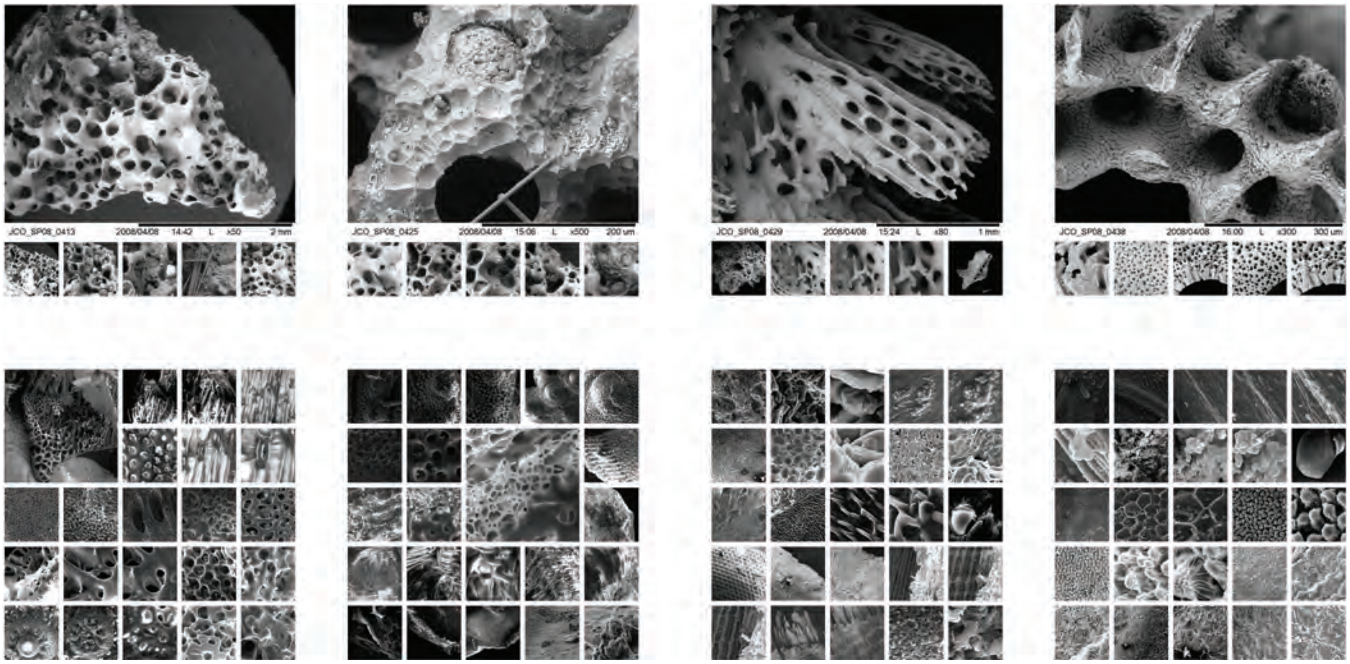
Finally the study explores and advances Robotic Incremental Metal Forming (RIMF) as a method for fabricating sculptural reliefs derived from the SEM-GAN process. For relative flexibility in the robotic metal forming process, initial material tests were performed with aluminum panels. The fabrication aspect of *Nanotectonica SEM-GAN* currently focuses on light-gauge steel panels for RIMF, as the material expression of the resultant relief panels most directly corresponds to, and elevates the aesthetic qualities identified for SEM-GAN; in particular through its dark graphite qualities in matte finish [see *Metal Forming*].

BACKGROUND

Nanotectonica

The present study—*SEM-GAN*—is embedded within the larger design research project *Nanotectonica*, which examines the relationship between natural and architectural systems through the convergence of nanotechnology and contemporary design tools.[6] Nanotectonica is the encompassing term for the design research into the structures, aesthetics, and design ramifications of the Nanoscale, which originated as project-based investigations within our architectural practice around 2000, and then developed into a series of academic seminars beginning in 2007.[7] The nineteenth installment of this seminar is currently conducted as an advanced technology course Arch 720AP Nanotectonica directed by Jonas Coersmeier at Pratt Institute, School of Architecture, with participating graduate students James Nanasca, Man Hin Ivan Yan, and external consultant Ezio Blasetti.

A design research and production project that studies structures and organizations at multiple scales, *Nanotectonica* utilizes computational techniques to design, construct, and build novel material systems, intricate assemblies, and architectural artifacts.[8] The design research employs



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4 Selection of SEM images from the Nanographia archive

5 Selection of SEM images from the Nanographia archive

nanotechnology, specifically the scanning electron microscope (SEM), and digital tools of analysis for a deeper understanding of structures at various scales. The investigation is not limited to the phenotypic expressions, but seeks to decipher organizing and form-building principles. While the SEM is used as an instrument for the analysis of subvisible structures, it also serves as a model for a speculative design method, Blind Probing, which operates outside of the duality of the generative and determinative routines.[9]

Early findings of the *Nanotectonica* project were presented at ACADIA 2010 (Coersmeier 2010), during the conference at The Cooper Union and in the parallel exhibition at Pratt Institute. These early findings focused on a research, design, and fabrication process chain that entailed electron microscopy, parametric design, CNC flip milling, and fiberglass construction.[10]

SEM Operation (Technical Context)

Electrons have a shorter wavelength than visible light, and thus electron microscopes can detect smaller objects than optical microscopes. The Scanning Electron Microscope (SEM) images a sample by probing it with a focused beam of electrons that scans across its surface; in response, the sample emits secondary electrons which carry information about the properties of the specimen surface. This information is recorded and mapped into images that represent the surface morphology of the sample. Unlike other types of electron microscopes, the SEM has a significant depth of field, which allows it to produce two-dimensional imagery with three-dimensional visual qualities reminiscent of those achieved in photography. In the absence of light, secondary electron shadows sculpt spatial effects, rendered in grayscale pixel fields.

SEM Aesthetics

Nanotectonica embraces the SEM as a prolific machine for aesthetic production. The aesthetics of the SEM are based in part on the device's particular ability to produce spatial effects in the absence of light and shadow. While other types of electron microscopes generate flat images that evoke a sense of abstraction, SEM-based images hold an intrinsic quality of realism. Ever so close to black-and-white photography, these grayscale images often render smooth gradients into blurred fields and produce a kind of detached, moody atmosphere.[11] There is an uncanny quality to these images, which momentarily suspends the association with photography. The representational qualities of the SEM visuals enhance the inherent strangeness of the subvisible object, which itself is never seen directly and is shaped by unfamiliar forces.[12] SEM representation plays with the familiar and unfamiliar, describing an alien world in visually accessible terms. In *New Landscape in Art and Science*, Gyorgy Kepes (Kepes et al. 1956) describes how the gross world of regular sense perception can be connected to the subtle world by scientific instruments, and he establishes a relationship between images produced by these devices and those of contemporary abstract art. Images produced by the SEM often suggest just this relationship to artistic expression, in the form of strange materiality.

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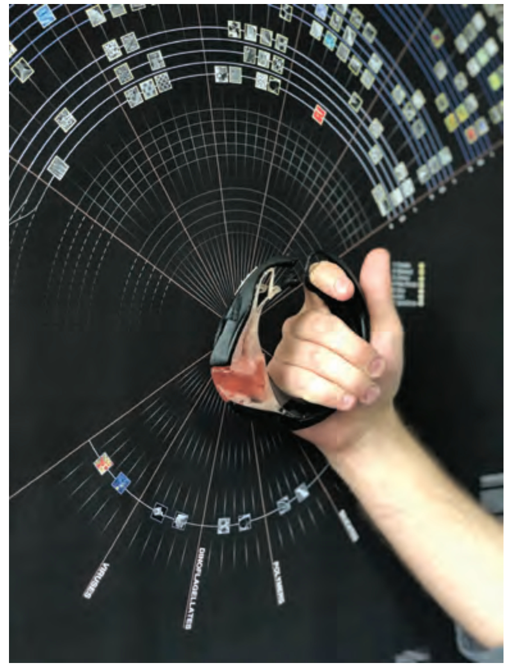

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SEM Taxonomy

Nanotectonica explores the innovative potential of open taxonomies in the architectural design process. The formation of taxonomies is considered a creative act in itself, as it directs the search within an infinite space of possible structures; it gives texture to this space and provides momentary orientation. We refer to taxonomies here not in the sense of standard biological classifications, but as systems of structural and architectural commonalities crystallized in the sorting of rich nanographic material.[13] Accordingly, the terms used in these taxonomies do not adhere to biological nomenclatures, but refer to architectural expression.

This study approaches classification via taxonomy and not typology, despite the usual association of typology with architecture, and taxonomy with biology.[14] Taxonomy classifies according to observable and measurable characteristics, having no idealized point of reference (datum). Typology on the other hand refers to concepts rather than empirical cases, to idealized constructs rather than objects of reality. *Nanotectonica*'s model of design relates to speculative realities more than it does to ideal types, and so privileges the taxonomic approach over the typological.

SEM-GAN

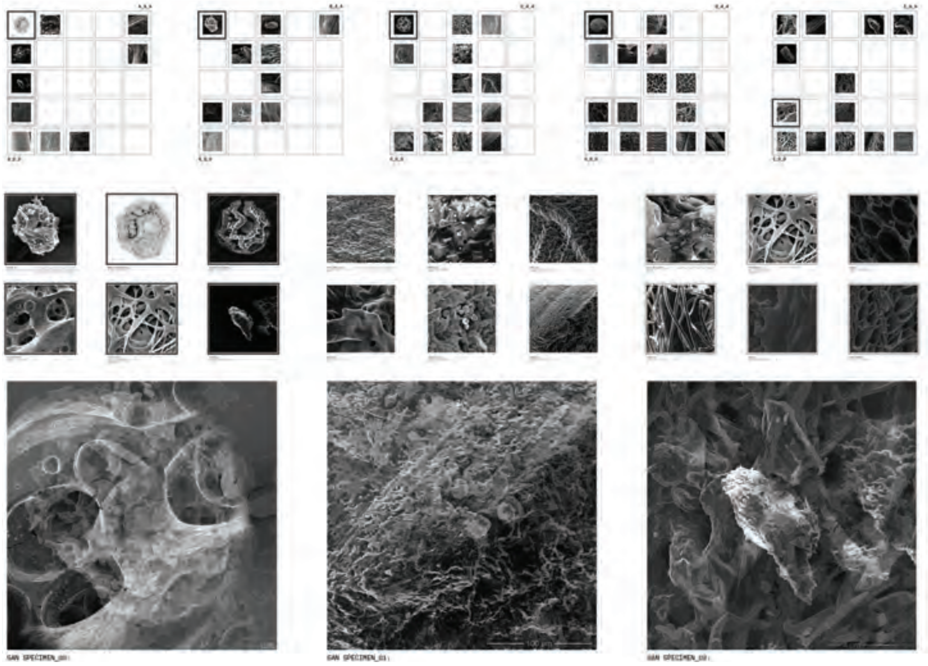
SEM-GAN Taxonomy

The study explores the potential of GANs to advance open classifications for objects and structure of the subvisible world. The study explores new modes of taxonomy making by training the GAN with a vast data set of SEM-produced images and considering the generated images in terms of species relations. While the SEM catalog refers to a finite set of physical specimens, the images produced through machine learning processes suggest an infinite number of synthetic species that display similar formal characteristics as the source material. With GAN the definitions of these common attributes are generated through statistical analysis. Taxonomic identifiers are not limited to matrices of humanly crafted parameters but they are generated in an open field of commonalities. This advances the idea of open taxonomies and their speculative potential in the design process, as it liberates it further from the model of standard architectural classifications (typology).

GAN Technology (State of the Art)

StyleGAN is a style-based GAN (Generative Adversarial Network) architecture yielding data-driven unconditional generative image modeling (Karas et al. 2020). Improving on a previous iteration of StyleGAN, Karas et al. further develop NVIDIA's StyleGAN into StyleGAN2 that refines the GAN architecture's overall image quality and control of image generation. At the time of conducting this research, StyleGAN3 was released by NVIDIA, but was not utilized due to the proliferation of StyleGAN2, and readily available scripts from the likes of Jeff Heaton (Heaton 2022) and companies like RunwayML (Runway AI, Inc. n.d.).

In the last five years there has been an unprecedented interest in architectural design research with GAN and machine learning tools. These techniques were first introduced in speculative design studios taught by architects such as Karel Klein in 2018, and their use became ubiquitous in academic



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6 SEM Taxonomy, indexical

7 SEM taxonomy, radial

8 SEM-GAN taxonomy *Prototype*: images from the Nanographia archive are arranged according to formal commonalities, represented specimens manually hybridized

research in a very short period of time. Early works that speculate on the creative design potential of these tools include the academic studios and practices of Matias del Campo, Kyle Steinfeld, Daniel Bolojan, Garbiel Esquivel and others. At the time of writing this paper, we are witnessing a massive acceleration in the production of machine learning applications. Tools like Nightcafe, Wombo, Midjourney, and DALLE that work primarily with text or images as input have millions of active users everyday. The research presented in this paper is also part of this acceleration. To our knowledge, no other researcher is working specifically with images or datasets from the nano scale for purposes of machine learning for design.

Comparing Methods

The study compares two different methods of running a StyleGAN2 engine trained on the same SEM Nanotectonica archive library. With a myriad of Python scripts available, the study tested one from Jeff Heaton at University of Washington St. Louis (Heaton 2022), and RunwayML's web-based StyleGAN2 interface. RunwayML's StyleGAN2 allowed the options of pre-trained discriminator datasets of faces, cats, vehicles, etc. Training the Nanotectonica archive with RunwayML's pre-trained vehicle discriminator dataset resulted in more "SEM-like" aesthetics with discernable objects and fields that the study pursued.

The differences between Heaton's StyleGAN2 script, and RunwayML's StyleGAN2 output are seen in stark contrast below (Figure 11). Heaton's method resulted in field-like conditions almost exclusively, as well as producing a green tint from grayscale SEM images. The pretrained discriminator from RunwayML generated more recognizable "SEM-GANs", leading the research to select RunwayML as its StyleGAN engine of choice. While not the sole subject of the paper, there is much to be gained in Nanotectonica research by training our own discriminator of SEM images to then allow a StyleGAN to more successfully generate SEM-GAN imagery.

The Synergetic SEM-GAN Workflow

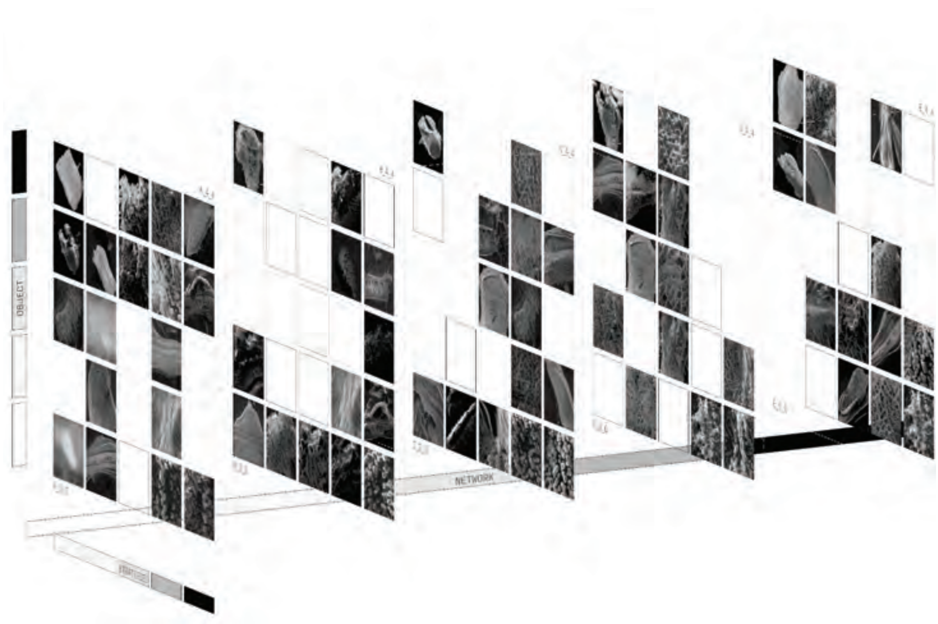
The investigation and production of the SEM-GAN images quickly found credence in a hybrid workflow. Human command over the images gave way to machine driven outputs, with said digital outputs guided by human intuition and selection. This method expressed in itself the logic proposed by Kepes regarding art and science [see *SEM Aesthetics*] in which the human eye injects artful finesse into the project, while the computational procedure remained objective in the process. This partnership fundamentally anchored the methodology of how we began to perceive these new creatures, as not one or the other, but a product of human-machine interactions, which generated SEM-GAN images of strangely foreign yet familiar worlds.

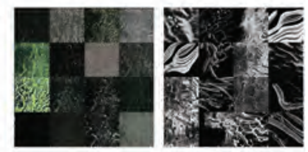
IMAGE TO 3D

State of the Art (Existing Research)

The problem of deriving 3D artifacts from image material is as old as the (spatial) design disciplines themselves. Since machine intelligence technology first arrived in design via image-based GANs, this problem has been given a particular status in recent disciplinary discourse. The research presented in this paper builds upon previous work from one of its authors with focus on the computational generation of 3D

9 Nanotectonica SEM-GAN: GAN images generated from Nanotectonica SEM Archive Nanographia





10 Nanographia SEM images are scored and organized on a matrix of structural commonalities

11 (left) Nanotectonica SEM archive dataset trained using Heaton's Google Collab StyleGAN2; (right) Nanotectonica SEM archive dataset trained using RunwayML StyleGAN2

form from image based machine learning tools.[15] Early work on specific machine learning techniques for the encoding and generation of 3D form includes the work of Hiroharu Kato from the University of Tokyo[16] (Kato et al. 2018). Today's advanced digital tools, such as those discussed by Chan from Stanford University and NVIDIA, allow for the "[u]nsupervised 3D generation of images and 3D shapes using collections of single-view 2D photographs…" (Chan et al. 2021). Tools like these have been making their way into architectural research. As an example, a recent project by Kyle Steifeld for the Venice Biennale titled "Artificiale Releivo" attempts to train a GAN model with 3D information embedded in semi-transparent depth map representations. The more accessible tools in 2D-to-3D generation reside in mesh and NURBS modeling softwares, as those softwares are relatively user friendly.

Three Methods for Image to 3D

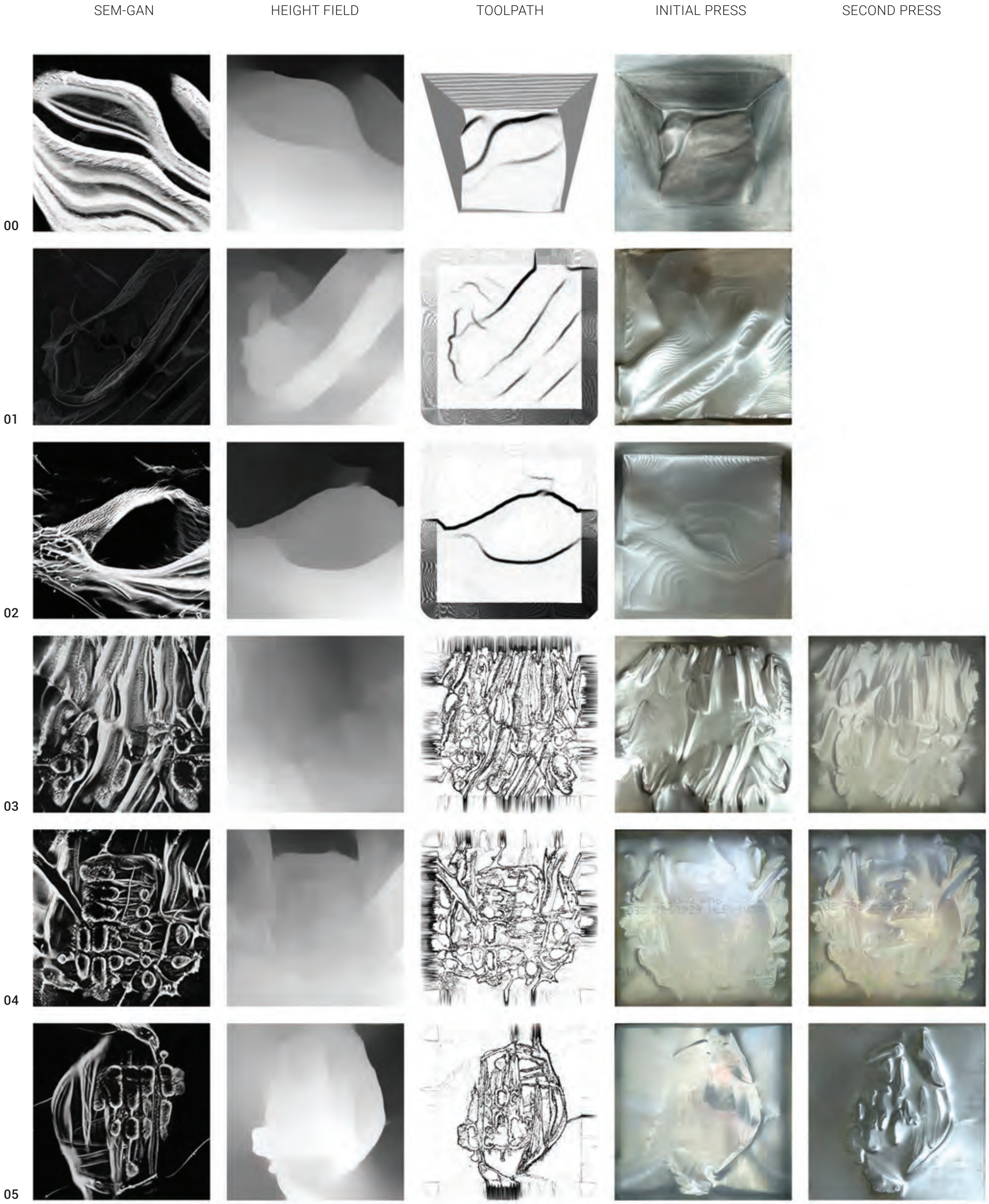
A readily available and contemporary method of turning 2D images into 3D is the use of voxelization softwares. This initial study leaps from image to 3D by transposing unprocessed SEM-GAN imagery into mesh geometry.[17] Stacking images along a guiding curve (which in this initial case is oriented to the *z*-axis) allowed for the 3D geometry to be generated based on light and dark values of the stacked SEM-GAN images. The slicing of images along the *z*-axis results in an eroded column-like structure (Figure 13 left). While aesthetically interesting, this 3D generation deviated from the research agenda and qualities of the SEM imagery and was not further pursued.

Another attempt was made of translating an image to 3D via image projection into a voxelized field (Figure 13 center). Compared to the stacked method, the projection allows a network of light and dark values of three images along the *x*-, *y*-, and *z*-axis to generate geometry based on guiding curves. Like the stacked method, this guiding geometry of two circles and a vertical curve produced a column-like structure but with a less eroded effect than the stacked method. The column-like forms and eroded aesthetics were discontinued to pursue methods that would produce geometry and aesthetics closer to the source material of the generated SEM-GANs.

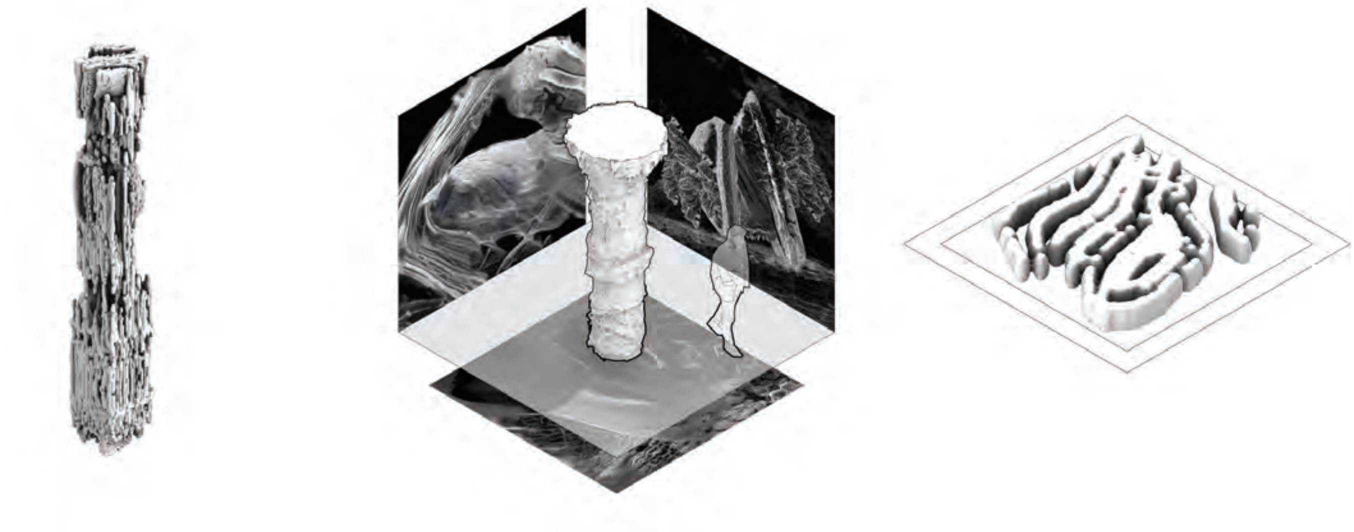
Still using voxelization software, the study pursued the extrusion of light and dark values of the chosen SEM-GAN image into a displacement-mapped mesh geometry. Some images translated into mesh geometry better than others depending on the values of adjacent dark and light pixels. A large difference between adjacent pixel values resulted in "sharp" or "spiked" meshes (Figure 13 right), rendering the geometry incompatible with fabrication. The method of voxelized displacement-mapped meshes began to produce geometry closer to the aesthetic qualities discussed in the research, so other methods furthering displacement-mapped geometry were pursued.

Displacement Method: Monocular Depth Estimated SEM-GAN Images

Focussing on the displacement geometry, the research looked at turning SEM-GAN images into a NURBS surface instead of a voxelized mesh geometry. Filtering the images through a Monocular Depth Estimated machine learning engine via RunwayML produced smoother and less "spiked" geometry. Figure 12 displays the translation of the chosen SEM-GAN image, filtered through the Monocular Depth



12 SEM-GAN specimen and operation matrix



13 (left) Sliced SEM-GAN 3D object; (center) Projected SEM-GAN 3D object; (right) Displacement SEM-GAN 3D object

estimating software, and ultimately translated into a surface that retains the surface continuity of the source image. A clear lineage of image-3D is established and primed to turn into a physical artifact.

The relief became the most effective process in capturing the aesthetic qualities of the SEM-GAN images. Relief is also the most conducive of the chosen fabrication method of robotic incremental metal forming (RIMF), enabling the setting of a toolpath derived from the Monocular Depth Estimated SEM-GAN Surface and hand tailored to achieve the greatest possibility of success. This focus allowed us to set the main agenda as a 2.5D image production, revealing the most direct and authentic/accurate translation of the image from a 2D plan into the intended 3D object.

METAL RELIEF

RIMF State of the Art

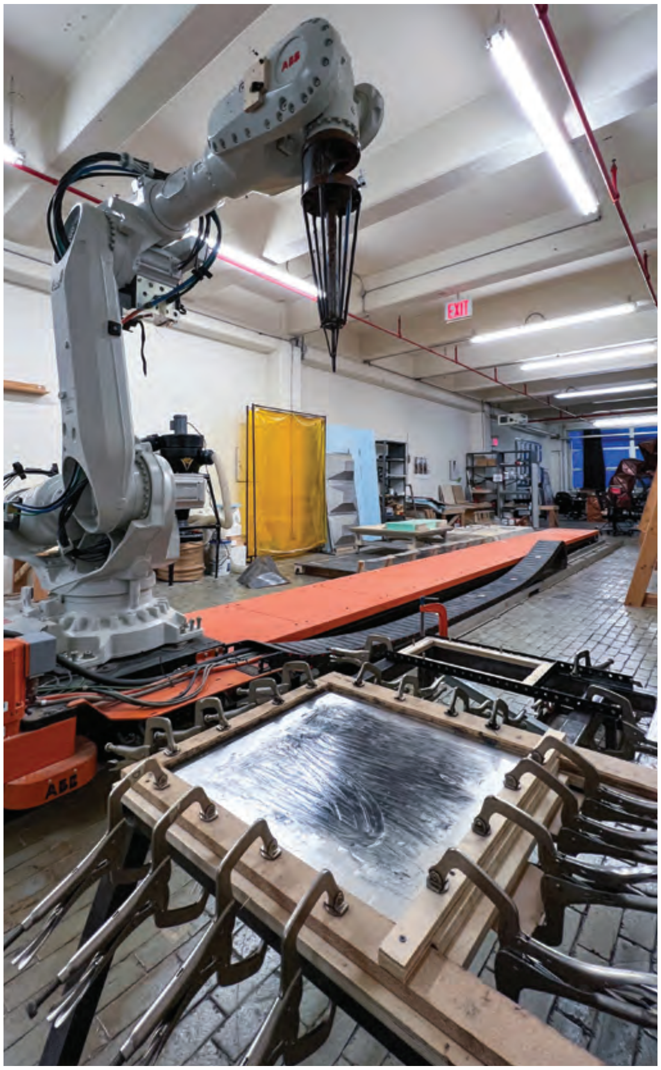
Robotic Incremental Metal Forming (RIMF) is a well documented fabrication method of turning flat sheet metals into formed pieces, first pioneered by Schrafer and Schraft (2005). Ammar Kalo and Michael Jake Newsum (Kalo and Newsum 2014, 2) take RIMF further by pressing non-planar components to aggregate an assembly of self-similar parts. More recent research done by Cui et al. (2022) rigorously details methods of finite element analysis and 3D scanning that can be deployed to minimize geometric inaccuracies with RIMF. The goal of this study is not primarily to expand upon the work in RIMF or StyleGAN separately, but to explore design potential and aesthetic richness in the interaction of these processes.

Toolpathing and End Effector

Toolpathing to press the SEM-GAN imagery is generated by contouring the surface using the outputs from the Monocular Depth Estimated Images. Kalo and Newsum (Kalo and Newsom 2014) illustrate that a spiral toolpath allows for constant engagement of the end effector and alloy(s) being pressed. Other tool path generations that were not spiraled resulted in visible seams once pressed into the alloys. A constant acute angle of 30 degrees measured planarly from the inside of the pressed form was found to be the most reliable angle to press the relief (Figure 16). Neglecting to adhere to this prescribed angle led to the tearing of the steel [see *Material*] as the material would be stretched inconsistently.

The end effector traces the path of the spiralized toolpath, acting as a displacer of the steel sheet. Similar to how the computer using the monocular estimated depth method will read the light and dark values of pixels and assign them corresponding heights, the end effector and robot work in a choreographed routine stretching the sheet. The current 1 foot and $11\frac{1}{4}$ inches long end effector is constructed of a steel frame that interfaces with ABB 6700 baseplate and a hardened carbide tip to engage with the stock. Using a 2 ft by 2 ft sheet, the end effector was able to press both steel and aluminum into $2\frac{3}{4}$-inch depths while maintaining the alloy's integrity. In this current research the longer end effector, which allows for deep reliefs, was not utilized, but future research could leverage the reach of the end effector by pressing larger stock (Figures 12, 13).

Aligning with the research of Kalo and Newsum (2014), this study also performs multiple toolpath operations on a single



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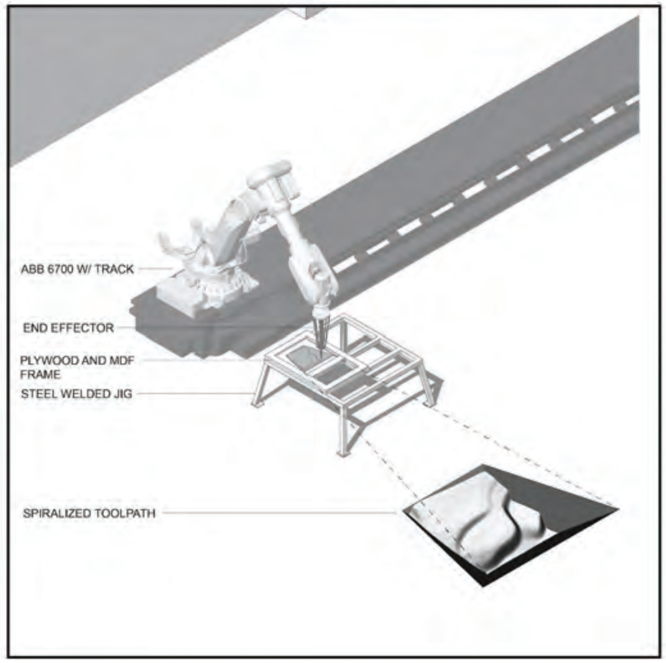

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sheet with the aim of producing detail-rich steel panels representative of the SEM-GAN images. The research found that select panels prompted a “second act” to enhance resolution. Specimens 03-05, served as good candidates for “second acts” due to highly varied and high contrast images. The first spiralized toolpath resulted in a global press, wherein the general 3D shape was pressed by visualizing some low resolution detail of the SEM-GAN. The “second act” allowed for the inclusion of localized and higher resolution details to be pressed. Select geometries local to a given specimen were manually culled, translated into spiralized toolpath geometry, then pressed into a higher resolution steel form.

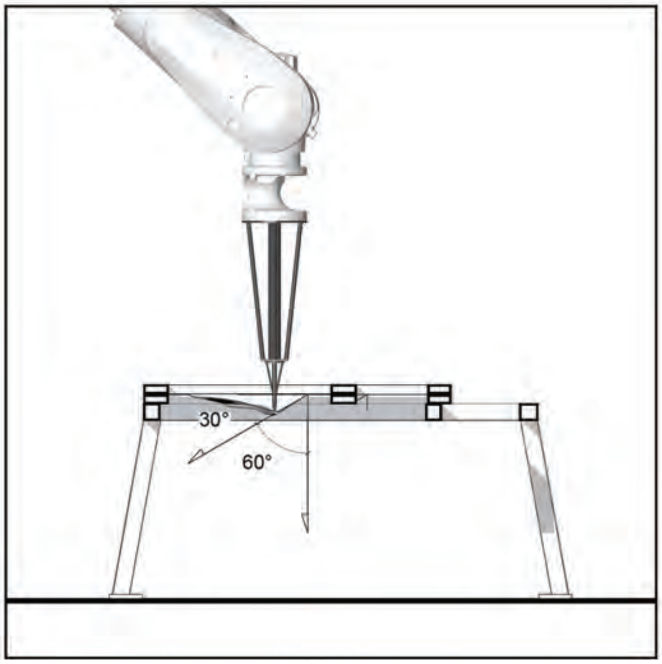
Material

Aluminum at 14 gauge and 1/16-inch thick, and steel at 22 gauge and 1/32-inch thick were tested in this research project. Aluminum afforded more malleability when compared to steel, and allowed for more successful pressing of the toolpath generated with minimal risk of tearing the sheets. However, the aesthetic qualities found in steel aligned more directly with the research agenda, and SEM imagery (Figures 22-25), so ultimately steel was pursued and tested on large (24 in x 24 in, 22 ga sheets) and small (12 in x 12 in, 22 ga sheets) scales. Testing allowed us to visually quantify the stress limits of the steel through observation of its physical responses when pressed, revealing the material’s breaking points. The material choice led to the codifying of aesthetic properties that drew from SEMs. Specifically steel’s inherent aesthetic qualities referenced the language that emerged under the scanning electron microscope, with highlighted bright spots and deep graphite coloring on matte fields.

Human–Robotic Fabrication

The synergetic SEM-GAN workflow previously detailed was extended into the fabricating portion of the paper’s research, where we found a fine balance between trusting the robotic arm to perform as programmed, but made manual adjustments through human hands and mounting points to address the stress symptoms exhibited by the pressed alloy. The choreography quickly reinforced the idea of a partnership in which the operating agents made an action and the other reciprocated with a response—a production method that relied on the strengths of the two partners to push and pull against the mounted alloy in order to guarantee the greatest chance of success in pressing the relief.

The robotic arm possessed the proficiency and payload to stretch the anchored metal sheet, but was constrained by the programmed input and its sensors that rejected the shifting and pinching moments of the material as it was stressed to



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14 ABB IRB6700 with clamped steel sheet setup

15 Diagram of setup [see Figure 14]

16 Diagram of Robotic Incremental Metal Forming (RIMF) section [see Figure 17]

17 RIMF in operation

its limit. The human, on the other hand, lacked the ability and power of the robotic arm, but played tandem to the process through monitoring the audible and visible stressing of the steel that is evident to human senses but inaccessible to the robot's digital sensors. Addressing the live conditions by applying more machining lubricant or shifting the mounting clamps allowed for greater tolerance and shifting of the material and ensured the greatest chance for the routine to be completed without material failure.

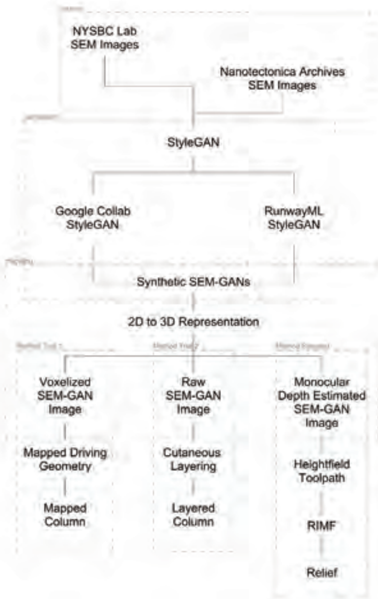
This partnership codified the SEM-GAN as a collaborative; with a focus upon subvisible structures (SEM) hybridized through machine learning (GAN) training that is directed towards a three dimensional and aesthetic production as a workflow of human-machine interface (Figure 19).

CONCLUSION

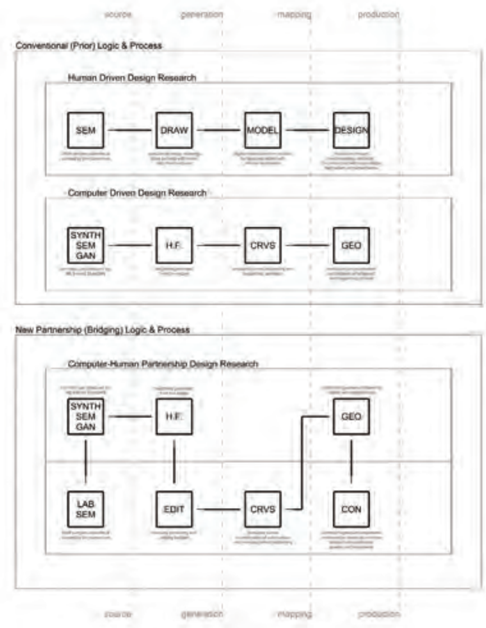
Nanotectonica SEM-GAN develops a strange materiality, first identified in subvisible (physical) expressions imaged by the Scanning Electron Microscope, and carried through the process of Generative Adversarial Networks, to the physical artifact of metal relief. It addresses the three processes—SEM, GAN and RIMF—in interaction. While the study advances specific techniques for each one, it principally contributes to a cross-process knowledge base as it pertains to design methodology and material aesthetics.

The study elaborates a model for human-machine-material collaboration in design research and production. It ascribes design agency to all three actors, who perform an open dance rather than a scripted routine.[18] With this the study critically discusses the algorithmic project in architectural discourse, which typically sets up a dichotomy between the generative and the compositional design method.[19] *Nanotectonica SEM-GAN* aims at disrupting these categories and offers an integrated model for design.

The general problem of deriving 3D artifacts from image data is approached by assessing three methods of spatialization along two criteria—the immediacy of a method and



18 *Nanotectonica SEM-GAN* research map



19 Comparing linear design model with the human-robotic integrated model

the relevance of an output geometry to a given material and fabrication system.[20] The direct translation from image to relief via the method of displacement stays close to the source data, while it generates topographic relief rather than tectonic artifact. As this study is invested in exploring a particular aesthetic language migrating across various media, the immediacy of this method proved to be significant.[21] In a next stage the study will explore this proximity in practical terms, by developing a direct routine for robotic material displacement based on SEM-GAN image data.[22]

Future *Nanotectonica* research seeks to capture three dimensional material information in parallel to training GAN discriminators in 2D and 3D. Recent advances in computer graphics and microscopy, as well as the democratization of fabrication tools and autonomous processes, will allow *Nanotectonica* to explore the multidimensional qualities of matter further. In microscopy, the Focused Ion Beam-Scanning Electron Microscope (FIB-SEM) allows for the three dimensional tomography of matter. In computer graphics, Neural Radiance Fields (NeRF) provide three dimensional reconstructions with only few 2D image inputs to produce volumetric representations. In the field of robotic fabrication, multi-material 3D printing and weaving will expand the geometric and tectonic translations between mediums that this study engages with. Future design research will include some of these techniques to explore new models of engaging with the strangeness of subvisible matter.

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NOTES

1. In 1665 Robert Hooke published *Micrographia: or Some Physiological Descriptions of* <u>*Minute Bodies*</u> *Made by Magnifying Glasses. With Observations and Inquiries Thereupon*.
2. "Collaboration" here refers to the interaction between human designer and machine. The term 'speculative design' was "popularized by Anthony Dunne and Fiona Raby as a subsidiary of critical design. The aim is [..] to design proposals that identify and debate crucial issues that might happen in the future. Speculative design is concerned with future consequences and implications of the relationship between science, technology, and humans" (attributed to Dunne and Raby 2014, from Wikipedia article "speculative design" as accessed June 2022).
3. Our philosophical influences include new materialists such as Manuel DeLanda and Jane Bennett. Our aesthetic references draw from art historical categories of the "strange" (Herbert Grabes), the "weird"

(Mark Fisher), and the “uncanny” (Sigmund Freud and Anthony Vidler)

4. Russian formalist Viktor Shklovsky coined the term “defamiliarization” in his 1917 essay *Art as Device* in which he writes: “The purpose of art is to impart the sensation of things as they are perceived and not as they are known. The technique of art is to make objects ‘unfamiliar’....”

5. “Nanographia” is the term used for the Nanotectonica archive of original Scanning Electron Microscopy images produced since 2007. It comprises 1,665 images produced in various electron microscopy labs including the New York Structural Biology Center, the Interdisciplinary Nanostructure Science and Technology, University Kassel, Germany, and the Nanotectonica SEM lab at Pratt Institute [ct. *Micrographia* (Hooke 1665)]

6. Nature is capitalized to indicate that the term itself is subject of the larger research project’s inquiry. Nature is considered an artificial construct that refers to various and changing concepts. *Nanotectonica* discusses these concepts as they pertain to ecological thinking and building, and the architectural mandate in the midst of a global climate crisis. It points at the problem of distinguishing Nature from technology, investigates a new understanding of living systems, and offers an integrated reading of the term “Natural structures.” *Nanotectonica* critically discusses ideas of bionics and biomimicry, and rejects scientific and design methods that idealize and reduce Nature to an empirical field for investigation. In parallel *Nanotectonica* conducts historical studies that refer to a lineage of naturalists, microscopists, and engineers that have advanced ecological thinking and building.

7. Architectural practice by Gisela Baurmann and Jonas Coersmeier. Academic seminars at Pratt Institute, Undergraduate Architecture (2007-2012,) Graduate Architecture GAUD (2013-2022;) University Kassel School of Architecture, Digital Design Department Jonas Coersmeier (2008-2009.)

8. Design research in *Nanotectonica* refers to three linked modes of inquiry: the first invests in the concept of design itself, an ontology of design. It discusses the problem of the “creative act” in its relation to media and methods, and offers a design methodology as testing ground for this discourse. The second engages in project-based research production. This includes historical references and cross disciplinary sources for cognitive and material models in support of a specific design agenda. The third entails original research production, the work with the Electron Microscope, which simultaneously is the most concrete and speculative form of research here: concrete as it borrows its technical routine and device from the natural sciences and produces tangible (visible) results; speculative as it turns away from objectifying and recording nature and instead proposes the multi-dimensional and interactive operations (the blind folded dance) with the electron beam as a model for the moment of design. As such it offers answers to disciplinary questions posed in the first mode, the concept of design (Coersmeier 2020).

9. Blind Probing: “The work on the electron microscope provides access not just to the world of subvisible structures, but through its unique operating procedure to the obscure moment of design innovation. It can help externalize and thus prepare for theorizing this moment. [..] The process is blind in two respects: Firstly, it happens in the dark; light does not enter the scene, but an electron beam like a white cane scans the probe space. Secondly, the exploration is conducted without an overview or perceptual reference to the specimen. In a process of constant reorientation, local scans only gradually assemble a sense of object gestalt....” (Coersmeier 2020).

   SEM Method: “In *Nanotectonica* the Scanning Electron Microscope (SEM) does not embody the purely analytical routine of the scientific method. Instead, it operates as a model for design, both as a conceptual model for the moment of design innovation, as well as a practice model for speculative design sensibility. The former refers to the non-deterministic character of the blind search. In this model the search is conducted in a vast space of design potential, that comprises immanent yet unrealized forms and ideas. The search is not indiscriminate, as design intention structures the space, nor is it globally directed, as the intention acts like the electron beam locally and in real time. The latter model is a design trainer and refers to the actual work on the scanning electron microscope. We conduct electron microscopy laboratory sessions in order to gain first-hand experience in operating the SEM. While the work on the machine is initiated by the desire to explore subvisible structure and to produce images of a particular aesthetic quality, it serves as a training exercise that helps develop a light touch for design speculation. The work in the SEM-lab induces an instantaneous flow of mediate interaction with material, a state of focused distraction conducive to design” (Coersmeier 2020).

10. See *ACADIA 10: LIFE in:formation, On Responsive Information and Variations in Architecture, Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). New York 21-24 October, 2010.*

11. In some instances they feature sharp-edge, high-contrast depictions of specimens and evoke the strange illuminant effect common in astrophotography. Highlights are blown out by bursts of locally charged electrons rather than solar radiation.

12. Morphologies of the subvisible are less subject to gravitational force than those of the visible world. Electromagnetic force produces different forms.

13. Taxonomies of architectural expressions: the associations formed in this process are unconstrained by established species’ relations, and occasionally they run in parallel but often counter to them.

14. At the end of the eighteenth century Jean-Nicolas-Louis Durand set out to systematize architectural knowledge. He developed a theory of ‘type,’ a kind of science for architecture, we now call typology (Durand 1799-1801).

 

20 (left) SEM-GAN Specimen 05; (right) Global RIMF relief

15. Early experiments in translating the 2D output of styleGAN and cycleGAN into 3D form were conducted by Hang Zhang in the research studio of Ezio Blasetti and Cecil Balmond in Spring of 2019 using similar computational techniques: Serial Stack, Multiview. The research was later published in a paper titled "3D Architectural Form Style Transfer Through Machine Learning" by Hang Zhang and Ezio Blasetti.
16. The researchers explore the potential of the integration of a mesh renderer into neural networks in their paper "Neural 3D Mesh Renderer" (Kato et al. 2018).
17. *Monolith*, a plug-in for Grasshopper3D, and is described by its author, Andy Payne as a "voxel-based modeling editor…and three dimensional voxel based image processing with the aim of allowing a very fine level of control over volumetric material distributions…" (Payne 2017).
18. During the process of imaging (SEM), the observed specimen responds to the electron beam by changing its surface topography and thus the recorded image; during the phase of artifact production (RIMF), the behavior of the pressed steel plate induces adjustments in the robotic fabrication setup in real time. In each case the material disrupt and direct human-machine interaction. The Robot and GAN are considered autonomous systems and ascribed (artificial) design intelligence.
19. We first explored the convergence of nanotechnology and contemporary design tools at a time when the idea of generative architecture re-emerged in the context of digital technologies. We refer to this moment as the algorithmic project in architecture, and we discuss it critically in this design research. It is argued that the search for generative design methods, along with the critique of compositional and allegedly more deterministic methods, had been part of architectural discourse since the early twentieth century. "Self-generation has been a consistent goal in architecture for over a century" (Mertins 2004). Since the advent of the algorithmic project at the end of the past century, architectural effects of the generative method have been widely privileged over compositional qualities, and the two have been considered incompatible. Compositional qualities have been associated with a higher degree of direct, top down engagement by the designer, operating at the level of design expression, while generative qualities have been seen as the result of operations at the scripted substrate of the design engine.
20. Testing three methods of image-to-3D—image stacking, 3D projection, and displacement mapping—the study determines that displacement is the most relevant for the purpose of this study. "Immediacy" here refers to the direct translation of image to topography, as well as to the conceptual proximity of the geometric method to the chosen fabrication method (RIMF.)
21. In the context of additive or subtractive fabrication methods, or projects that foreground the logic of tectonic assembly, other methods of moving from image to 3D, including the two alternatives studied here—stacking and projection—may be more relevant.
22. Displacement mapping translates grayscale value to changes along the normals of a surface, analogously the robotic arm impresses topographical changes to the metal surface. At the current state the study identifies this conceptual proximity of displaced geometry and displaced material, while the practiced translation from one to the other remains mediated, as it entails several steps of 3D geometric authoring and the standard practice of robotic toolpathing.

21 (left) SEM-GAN Specimen 03; (right) Localised RIMF relief

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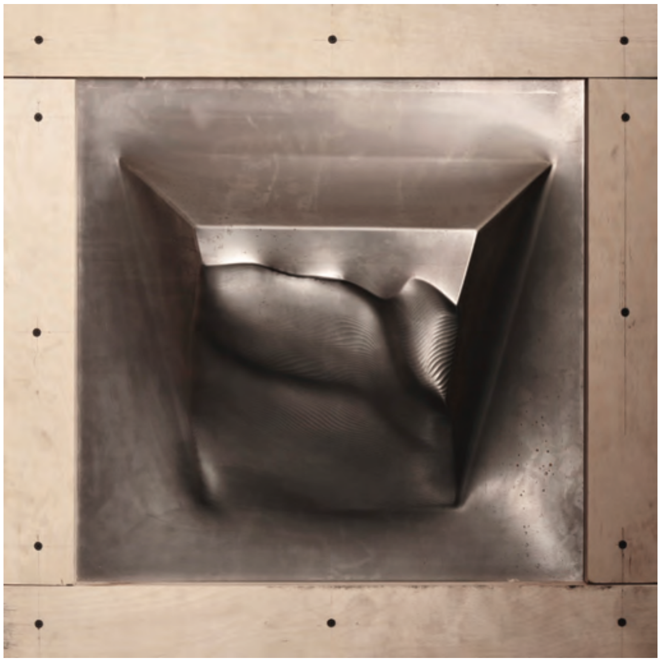

22 Specimen 00, RIMF steel relief secured with metal fasteners in birch plywood

23 Specimen 05, RIMF steel relief secured with metal fasteners in birch plywood

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24 Specimen 04, RIMF steel relief secured with metal fasteners in birch plywood

25 Specimen 03, RIMF steel relief secured with metal fasteners in birch plywood

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26 RIMF steel surface, Specimen 00

27 RIMF steel surface of Specimen 03