Gemini: Engaging Experiential and Feature Scales Through Multimaterial Digital Design and Hybrid Additive–Subtractive Fabrication

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Abstract

Gemini is a chaise lounge constructed using hybrid fabrication involving 3D printing of a textured polymeric skin combined with CNC milling of a wooden chassis. The texture of the chaise was inspired by the seed geometry of the Ornithogalum dubium flower and designed using a computational implementation of an inhomogeneous Poisson process. The 3D-printed texture was informed by the weight distribution of a person with the goal of delivering structural support and comfort on the one hand and maximizing the absorption of sound emanating from exterior sources of noise on the other. Gemini is the first functional object produced using the Stratasys Objet500 Connex3 color multimaterial 3D printer including the Tango+ soft material. It represents one of the first cases of a hybrid additive–subtractive manufacturing approach, which combines the strength of both of these techniques.

Introduction

Printing for the Human Experience: Additive–Subtractive Manufacturing Across Scales

GEMINI—AN ACOUSTICAL "twin chaise"—spans multiple scales of the human existence extending by metaphor from the warmth of the womb to the stretches of the Gemini zodiac in deep space. It recapitulates a human cosmos: our body—like the Gemini constellation—drifting in space. In this project we explore interactions between pairs: sonic and solar environments, natural and synthetic materials, hard and soft sensations, as well as subtractive and additive fabrication. The design is rooted in the mythical relationship between twins: one is mortal—born of man—the other divine. Made of two material elements, a whole that is bigger than the sum of its parts, like the sun and the moon, like Adam and Eve, the chaise forms a semi-enclosed space surrounding the human with a stimulation-free environment, recapitulating the ultimate quiet of the womb as it echoes our most inner voices. The calming and still experience of being inside the chaise invokes the prenatal experience of the fetus surrounded by amniotic serenity, an antidote to the stimuli-rich world we live in. This is achieved through the combination of a solid wood-milled shell housing and an intricate cellular skin made of sound-absorbing material.

Gemini is the first functional design to implement Stratasys's Connex technology using 44 materials with unique preset mechanical combinations varying in rigidity, opacity, and color as a function of geometrical, structural, and acoustical constraints.[1,2] Gemini, the object, is designed as a reclining chair offering structural support and comfort for the human body. Gemini, the experience, is designed as an acoustical chamber offering a stimulation-free environment for quieting the thinking mind.

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Figure 1. Gemini, 2014 (top view). Designed by Neri Oxman in collaboration with Prof. W. Craig Carter (MIT Department of Materials Science and Engineering) for the "Vocal Vibrations" exhibition at the Le Laboratoire, Paris, France. Sponsored and 3D printed by Stratasys with Objet500 Connex3 color, multimaterial 3d printing technology. CNC milling by SITU Fabrication. Photo: Michel Figuet.

Figure 2. Gemini, 2014 (side view). Designed by Neri Oxman in collaboration with Prof. W. Craig Carter (MIT Department of Materials Science and Engineering) for the "Vocal Vibrations" exhibition at the Le Laboratoire, Paris, France. Sponsored and 3D printed by Stratasys with Objet500 Connex3 color, multimaterial 3d printing technology. CNC milling by SITU Fabrication. Photo: Michel Figuet.

Design

Biological Inspiration

The 3D-printed surface was designed to absorb the reflections of sound or electromagnetic waves and insulate from exterior sources of noise. In this respect it can be considered a habitable anechoic chamber.[3] The texture of the chaise is inspired by the seed geometry of the *Ornithogalum dubium* flower, characterized by a tightly packed cellular structure with interlocking "fingers" attaching one cell to its neighbors.[4] This geometry enables an increased surface area-to-volume ratio, maximizing the number of bounces a wave makes within the structure. With each bounce, the wave loses energy to the 3D-printed material and thus exits with reduced signal strength. A micrograph of the *O. dubium* flower seeds (Figure 3) reveals a pattern of star-shaped interlocking units, varying in size, number of interlocking units or fingers, and in local height. For the surface of the chaise, the purpose was to create a texture that is inspired by the biological specimen mapping its geometrical logic and properties onto the chair surface.

The 3D-printed texture was informed by the weight distribution of an average person sitting on the chair with the goal of maximizing structural support and comfort. The form of the cellular units, their rigidity, opacity, and color were informed by anatomical curvature data of the human body and anticipated physiological comfort. Negotiating between, and optimizing for a multiplicity of objective functions, including structural support and comfort, posed a challenge from a design perspective—how to deliver an optimal solution across multiple design criteria.

Computational Approach

Problem statement. Designing Gemini called for a multifunctional "skin" that can simultaneously act as an integrated structural surface, an acoustical barrier, and a comfortable cushionlike shell. In order to accommodate for the multiplicity of requirements, we developed a computational approach that enabled the generation of a multifunctional surface, its design directly informed by intrinsic material properties of the 3D-printed substrate as well as the desired extrinsic requirements. Moreover, this approach was designed to assimilate experiential and feature scales through multimaterial digital design and fabrication.

Technical approach. Given that the design objective involves multifunctional features and property gradients on

Figure 3. Left: Polychromatic scanning electron micrograph illustrating the surface detail of a seed from the sun star, *Ornithogalum dubium*. Micrograph: James C. Weaver, WYSS Institute, Harvard University. Right: Gemini, detail. Photo: Yoram Reshef.

different length-scales representing average quantities, the challenge was to come up with a computational process that would allow us to computationally vary the properties of the texture across multiple length scales. The process we used is intimately connected with a specific physical phenomenon that involves gradients and a multiplicity of materials. Through an iterative computational mapping process, the designer mediates between these two distinct physical entities—the natural phenomenon and the object itself.

The mechanical and acoustical properties of the 3D-printed texture devolve quantities and their gradients from the density, size, shape, and material choice of each cell. These quantities and their gradients arise from the algorithmic evolution/simulation of natural processes such as reactions to pressure distributions, capillary flow, and the biology of cell colonies. For example, the density of cells on the chair's surface derives from an estimate of the pressure distribution due to a sitting body and a simulation of the diffusion of that pressure within the chair's surface. The morphology and shape of each cell derives from an algorithm that, simultaneously, maximizes the interlacing contact between neighboring cells and minimizes the distance of any part of the cell to its root structure. Algorithms for material choices for each cell are generated so as to optimize for structural integrity and user comfort. Thus, the resulting object represents a mapping of a large set of quantities onto a two-dimensional object manifold embedded in three dimensions.

Such projection progressing from a higher dimensional space to a lower dimensional space would involve a loss of information unless one could increase the dimension of the object manifold by introducing the notion of multifunctionality or multiproperty fabrication. However, to date digital fabrication approaches are limited in their ability to deliver multifunctionality.

Multimaterial printing allows assigning more than a single property or function to every point on the object manifold, thereby enabling high spatial frequency, property control, and multifunctionality.[1,5] In this way, a framework emerges that allows all degrees of freedom of the natural or biological phenomenon to be represented by the object. This salient feature presents the opportunity to develop a computational approach that allowed us to introduce property gradients and multifunctionality across scales.[6,7]

Weight-based cell density. The chair morphology was constructed as a parametric surface $[x(u, v), y(u, v), z(u, v)]$, where (u, v) is a rectangular subspace of R^2. A two-dimensional Delaunay triangulation was constructed from points generated from an inhomogeneous Poisson process in (u, v) subspace. The set of point locations was constructed using a probability density that derives from a solution to the diffusion equations with initial conditions, $C(u, v, t=0)$. These initial conditions were generated from an estimate of distribution normal load $P(u, v)$ $[n_x(u, v), n_y(u, v), n_z(u, v)]$. The point-set (u_i, v_i) was generated from a random variate of the probability density $P(u, v) \alpha C(u, v, t=t_{\text{final}})$. The Delaunay triangulation was constructed from the (u_i, v_i). A "Delaunay star" was constructed at each vertex as follows: each line segment connecting two vertices was subdivided into two line segments with fractional lengths, f and $(1-f)$, with random variate f obtained from uniform distribution between 3/8 and 5/8. Each star, S_i, consists of all subdivided line segments abutting vertex $V_{i.}$ Each star, S_i, was rotated by an angle R_i obtained from a random variate of a uniform distribution within $(-\pi/6, \pi/6)$. The resulting stars were used as the generating sets for a "shape-based Voronoi construction." The shape-based Voronoi construction is obtained by locating the set of points, P_i, which are closest (with the Euclidean norm) to a given set, S_i (here taken to one of the Delaunay stars). The boundary B_i of each set, P_i, was used to obtain level sets for each closed boundary curve, $(u_B, v_B)i=C_i(t=0)$. As illustrated in Figure 4, the shape-based Voronoi construction mimics the base structure of the *O. dubium* cells.

To obtain the lofts, each level set was used as an initial condition for motion by curvature.[8] Motion by curvature, as illustrated in Figure 5, produces an evolution of the base structure to a circle disappearing at a point. The timelike variable t was mapped as a scaled offset $t(n_x, n_y, n_z)[C_i(t)]$ from a loop on the chaise $(x, y, z)[C_i(t)]$, where each $C_i(t)$ is the level set $(u_B, v_B)i$ at time t. Motion by curvature has the effect of producing inward motion where curvature is positive and outward motion where curvature is negative. Because any border of two neighboring cells has a curvature that is positive with respect to a particular cell and negative (with equal magnitude) with respect to that cell's neighbor, the motion of one loop initially follows, but eventually diverges from its neighbors to produce lofts in Rhino.

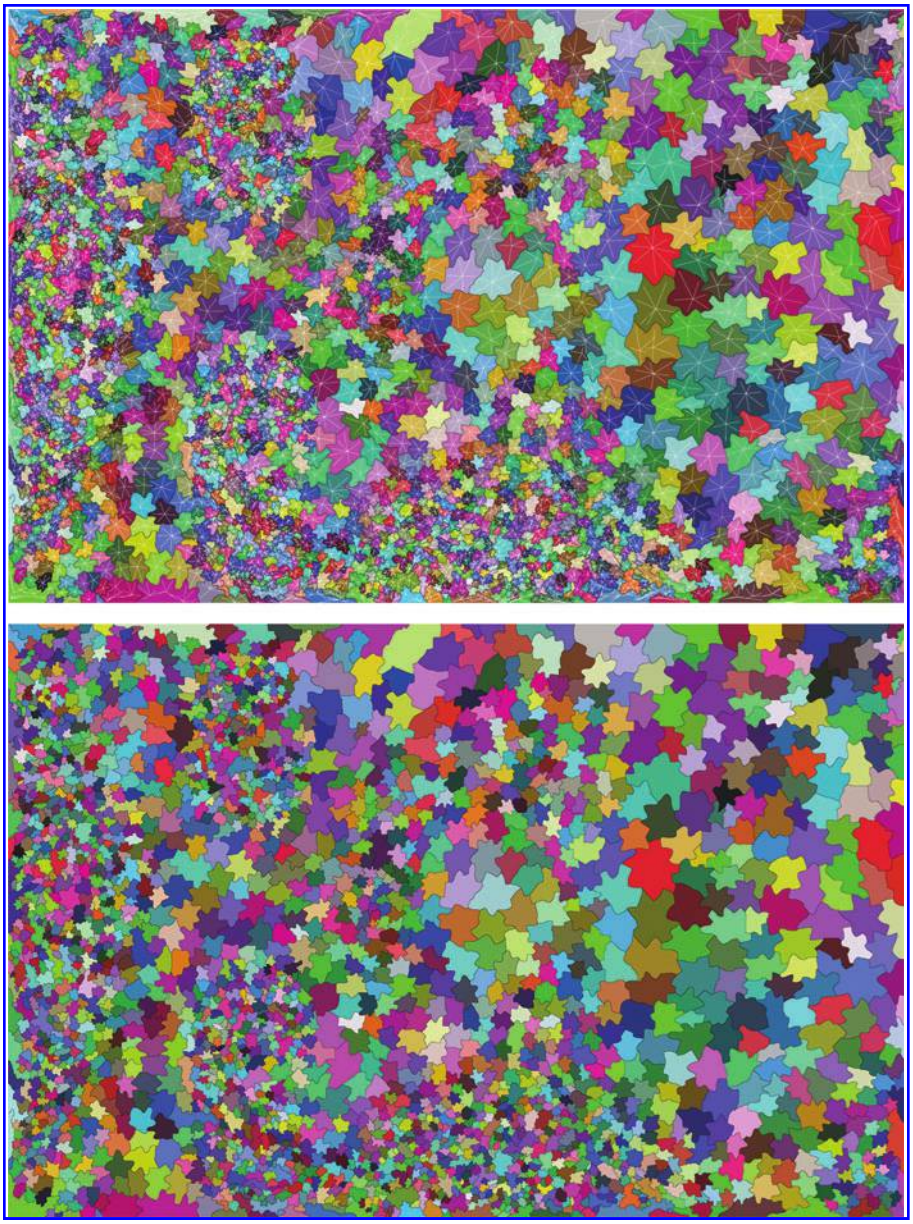

Figure 4. Shape-based Voronoi inspired by the sun star, *O. dubium*. Star-shaped cells were extracted from the two-dimensional Delaunay triangulation (*top*). The resulting stars were used as generating sets for a "shape-based Voronoi construction" (*bottom*).

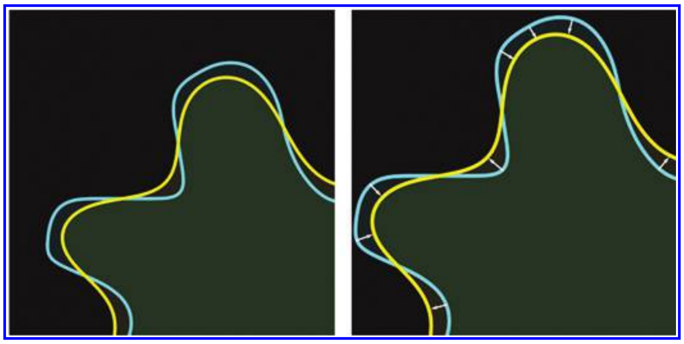

Figure 5. Motion-based curvature produces an evolution of the base structure ("cell") to a circle disappearing at a point, producing the effect of inward motion where curvature is positive and outward motion where curvature is negative.

This evolution produces structures that are morphologically similar as can be seen in Figure 6. All computation was performed using Mathematica and the Wolfram Language (Mathematica, Version 9.0, 2012; Wolfram Research, Inc., Champaign, IL). The timelike sequence of loops was used as data structures for RhinoPython script.[9,10]

Hybrid Additive–Subtractive Manufacturing: Materials and Methods

Technology

Gemini is the first functional object produced using the Stratasys Objet500 Connex3 color multimaterial 3D printer including the Tango+ soft material. It also represents one of the first cases of a hybrid additive–subtractive manufacturing approach that builds on the strength of both of these techniques. The printer combines multiple printing materials that are simultaneously deposited to create the 3D part. As a result, it enables the design and production of a variety of material properties within a single build (Figure 7). The user can selectively position multiple materials within a single 3D model and can even combine three materials to create composite digital materials with distinct, predictable properties. The Objet500 Connex3 is a unique triple-jetting system based on the PolyJet technology and can combine three base materials to build as many as 1200 material combinations within a build envelope of 500 × 400 × 200 mm. This enables a large array of material combinations and mechanical properties within a single build, including rigid, flexible, and translucent materials. For Gemini, two rigid and one soft material were used. The stiff materials were Stratasys' rigid opaque VeroMagenta and VeroYellow (tensile strength 50–65 MPa, elongation at break 10–25%, flexural strength 75–110 MPa); the soft material was Stratasys' rubberlike TangoPlus material (Shore A-27, elongation at break 170–220%). The combination of these 3D printing materials enabled the production of parts with 44 different predefined combinations, defined by Dr. Daniel Dikovsky, digital materials team

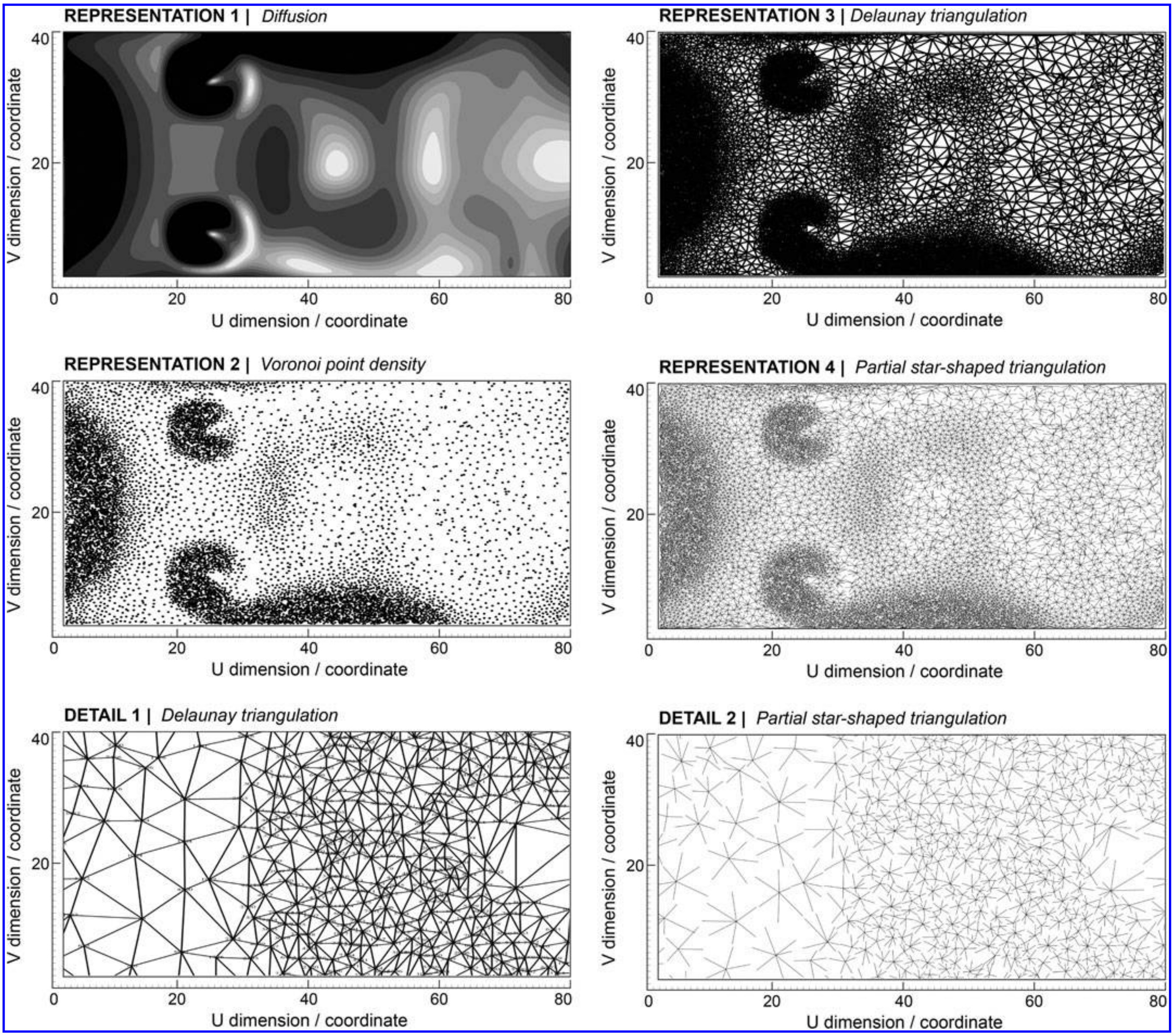

Figure 6. Morphologically similar structures in the following sequence: (1) reaction–diffusion, (2) Voronoi point density, (3) Delaunay triangulation, and (4) partial star-based triangulation.

leader at Stratasys. A print mode of 1200 DPI (at *X*-axis) and 600 DPI (at *Y*-axis) resolution and 30 mm on the *Z*-axis was specified.

Materials Selection

Additive fabrication. In this project a Connex3 printer was used to produce multimaterial parts, while manipulating material characteristics across the surface area of the chaise accommodating to local fitness criteria. Overall, the geometry was composed of a flexible substrate with protruding units or cells. Each cell was assigned a unique digital material that represents a predefined combination of three basic Objet resins—two of them producing rigid colored plastic resins and the third producing transparent rubberlike material. The mix ratio between the three materials droplets within the unit geometry determined its physical properties. Controlling the mix ratio allowed controlling the color, transparency, and rigidity of a unit. Transparency and rigidity were both dependent on the Tango+ concentration, while the color was informed by the ratio between the two colored rigid materials, Vero Magenta and Vero Yellow.

Viscoelastic properties were modified given the large difference in the dynamic absorption properties of the Vero and Tango+ materials. We assume that the sound absorption can be related to the tan delta of the material, that is, the ratio between loss modulus (E'') and storage modulus (E'). The Tango+ should therefore exhibit high absorption having

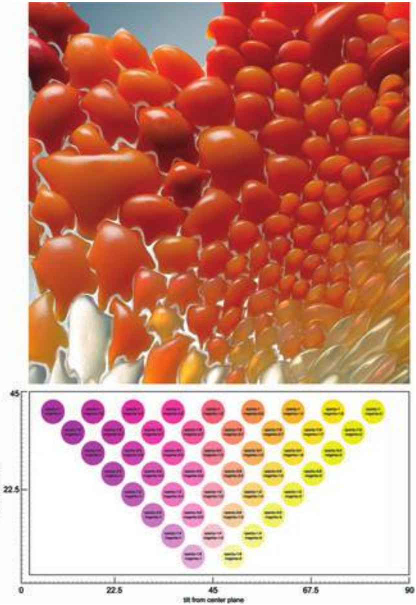

Figure 7. Stratasys Connex3 material selection chart: each cellular component was assigned a unique digital material representing a predefined combination of three basic materials: Vero Magenta, Vero Yellow, and Tango+. Top photo: Yoram Reshef.

tan delta of 0.8, while Vero should exhibit much lower absorption having tan delta of 0.2 (measured @6 Hz, 25°C, measured using DMA, TA Instruments, Q800). Consequently, the mixing ratio between the stiff material and the soft material produced large variations in sound absorption and caused nonacoustic trivial behavior when applied to the Gemini shell.

Subtractive fabrication. Brooklyn-based SITU Fabrication constructed the chassis of the chaise using subtractive wood milling. This portion of the chair comprised a variable thickness surface ranging from 1.5″ through the legs and center to 0.5″ at the edges. The form was generated digitally using Rhino software. It was then divided into 1.75″ sections with staggered seams and carefully placed dowels. The sections were first CNC milled in 2D out of 4′ × 8′ slabs of cherry. The profiles were glued to create the rough massing of the chaise creating a "stepped" mass. The masses were then milled smooth with a large five-axis CNC router. Finally, milled sections were glued together, hand-sanded smooth, and sprayed with a thin polyurethane clear coat.

Length Scales and Functionality

The design includes a number of length scales ranging from a large structure made of wood to the much finer 3D-printed surface. Each scale was designed to support a unique functionality, be it shape retention and structural support or weight distribution and sound-absorbing properties: (1) On the meter scale, the chaise forms a semiclosed anechoic-like chamber with curved surfaces that tend to reflect sound inward. The surface structure scatters the sound and absorbs it and, in the absence of large planar surfaces, reduces the amount of sound that would otherwise bounce back to the source. (2) On the centimeter scale—a scale that corresponds to the wavelength of sound—the 3D-printed inner "skin" is designed as 3D doubly curved cells that scatter and absorb sound effectively given their geometry (i.e., the sound tends to bounce from one "cell" unit to another till it gets absorbed) and high surface area-to-volume ratios. The features of the chaise are on the order of the wavelength of sound, and they therefore interact strongly with sound and get absorbed effectively. (3) On the smallest scale, the properties of the digital materials also contribute to the absorption of sound. These materials are elastic in nature, varying in durometer (and therefore sound absorption) as a function of curvature. The length scale of the acoustic properties is a combination of the frequency (for each reflected "note"), the elastic modulus of the material, the material density, the absorbed sound frequency, the storage as well as loss moduli (E' and E''), and the density. Surface areas that are curved more than others are assigned elastic properties, thereby increasing absorption around local chambers.

Conclusions

Gemini represents a hybrid additive–subtractive design of an acoustical "twin chaise." By fusing subtractive CNC milling and additive manufacturing approaches, wood and polymer are combined in a structure that spans multiple scales and textures aimed at addressing both experiential as well as functional design objectives. The design itself is rooted in the mythical relationship between twins: one is mortal—born of man—the other divine. The design explores the relationship between them: somber and playful, natural and human-made, rigid and compliant, subtractive and additive.

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Author Disclosure Statement

No competing financial interests exist.

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