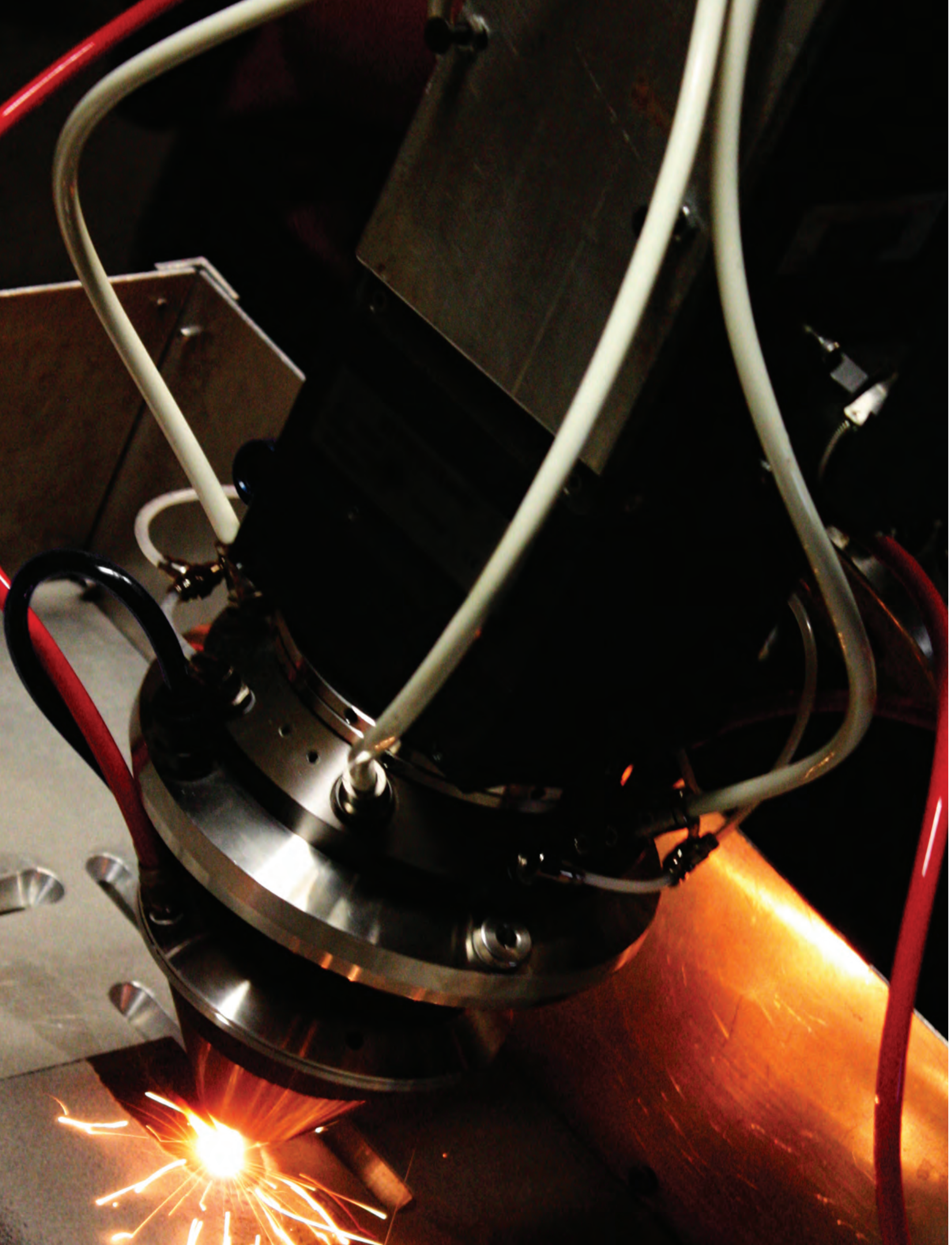

Additive Manufacturing, Abstract Assemblage, and Material Agencies

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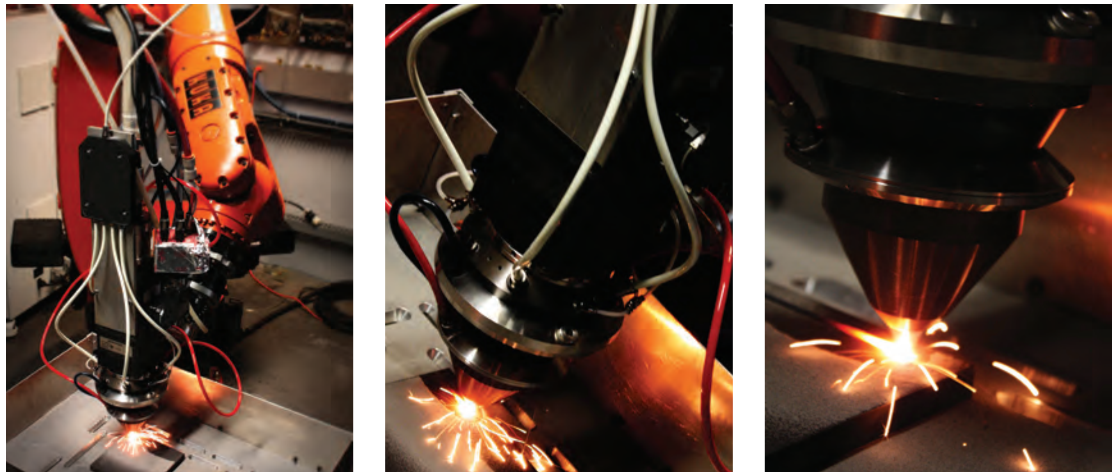
AN OVERVIEW OF ADDITIVE MANUFACTURING IN METALS

Within the last decade, a variety of systems for the additive manufacturing of metals have been introduced to the market. These can be loosely characterized according to the material deposition process, heat source used for fusing, and physical constraints of fabrication. The majority of these show little deviation from the first patents filed by Pierre Ciraud (1972) and Ross F. Housholder, and are fundamentally equivalent to selective laser sintering, or SLS (Beaman 1997). These 3-axis systems rely on a bed of metallic powder to support each subsequent layer as a heat source selectively fuses or welds the metal powder to the previously fused layers. After sintering, the build chamber lowers, and a new layer of fine metallic powder is applied. Like most rapid prototyping technologies, this process allows for design complexity unachievable through conventional manufacturing processes.

The second classification of additive manufacturing systems is differentiated according to the way material is delivered. These direct metal deposition, or DMD, systems deposit material precisely where needed and range from three to five axes. Since they fuse metal directly to the substrate material previously applied, they are less dependent on support material and offer significant decreases in build time. Among the most robust of these is the 5-axis LaserTec65, developed by the CNC machining systems manufacturer DMG-Mori. This 5-axis system is based on their existing machining systems design, features 5-axis, additive/subtractive operations, and offers a notably larger build area than most powder supported machines. This approach is commonly referred to as hybrid manufacturing. In general, additive manufacturing of metals is restricted to near-net shape fabrication. This is partially attributed to the resulting surface roughness and tolerances associated with mated surfaces. Because of this, components must go through post-processing before completing their production time. Utilizing hybrid manufacturing minimizes coordination between these processes and allows for additional complexity since both processes can alternate during fabrication.

A third class of systems extends from previous research and development within Southern Methodist University's Research Center for Advanced Manufac-

Figure 1: Robotic workcell for research based on free-form direct metal laser sintering (DMLS). Features include coaxial powder delivery, 4kW fiber laser, and high-speed monitoring CCD. Dual powder hoppers supply powder at numerically controlled rates for inline control of material composition.



turing and builds upon the patents of Dr. Radovan Kovacevic (2006). This system is similar to the previous classification in regards to material delivery, but utilizes a 6-axis robotic arm to control the deposition paths (and in some cases feature an additional tilt-rotary build platform manipulator). Because this system is not fully enclosed or self-contained, the build area is restricted only by the robot's range of reach and allows much larger structures than proprietary machines. Additional axes allow for greater degrees of freedom and flexibility for medial path planning (Dwivedi et al. 2006). Medial path planning is not limited to slicing along the z-axis. In this case, sections are sliced and paths are organized along the medial axis of predominant features within the component's geometry (Dwivedi et al. 2007). Paths may also be organized to move freely along complex surfaces relative to perpendicular normals. Path planning for these systems becomes increasingly complex, but allows advantages in regards to topological complexity without the aid of sacrificial support material.

While there has been considerable improvement to the control of process parameters, dimensional tolerances, and resulting mechanical properties, the application of additive manufacturing in metals to architectural research has seen little attention compared to the enthusiasm demonstrated by a larger body of architectural research based additive manufacturing in other materials (Warton et al. 2014). Among the few cases published is the work of Joris Laarman and IAAC's MX3D-Metal,[1] which draws some similarity to the robotic processes noted previously. This project presents a novel approach to path planning, but the wire-fed MIG welder proves insufficient for mechanical properties and controlled tolerances required for research leading to structural implementation. The Multithread collection by Clemens Weisshaar and Reed Kram[2] exhibited at the Istanbul Design Biennial 2012 serves as a potential precedent for metal structures that utilize 3D printed forms. These forms are then cast in steel using a lost-wax process (Kram et al. 2012). Similarly, Matt Hutchinson[3] of PATH investigates the coupling of off-the-shelf standardized stock with parametrically differentiated elements. A recent example investigating an architectural application of additively manufactured metals was released in June 2014. Arup and Salomé Galjaard[4] produced a 14 cm scaled connection prototype composed of maraging steel. This particular project begins to investigate topological complexities, whereas the previous projects gesture more toward mass differentiation. In each of these three cases, the project promotes the effective application of AM and metals to structural connecting members, as well as synthesis between structural performance and aesthetics. Aside from Laarman, these projects operate in the more conventional file-to-fabricator workflow and rely on the proprietary powder supported machines with a size limitation typically under a cubic foot.

Despite this apparent limitation in size, several independent contractors and research institutions have developed technologies where a modest architectural scaled execution is feasible. Researchers at Northwestern Polytechnical University of China have demonstrated that additive manufacturing is effective for metal components as large as 3.1 meters and have validated their process through rigorous mechanical testing (Huang et al. 2014). Their test case, LSF wing spar cap strips, will be fabricated in TC4 (Ti-6Al-4V) alloy and is targeted for production on the Comac C919 by 2018.[5] Similarly, Sciaky Inc., a subcontractor of Lockheed Martin, markets its ability to produce parts with dimensions up to 19' x 4' x 4'.[6] It also claims to build up material at speeds approaching 250 cubic inches or 40 pounds per hour, significantly increasing the production speed achieved by the smaller powder supported systems.

EXPERIMENTAL SETUP

Building upon these various processes, a work cell comprised of a 6-axis Kuka KR-60 robotic arm, a 4 kW fiber laser, and a co-axial powder delivery system for the direct deposition of fine metallic powders has been assembled in the Research Center for Advanced Manufacturing (fig. 1). This work cell implements freeform sintering of metallic powder and is planned for extended capacity to produce functionally graded structural components comprised of heterogeneous alloys and coordinated subtractive milling. Multiple powder feeders allow for controlled composition and support the production of functionally graded components. The composition can be graded to achieve both aesthetic and performance-driven criteria, as well as to minimize cost by concentrating more expensive materials precisely where they are desired. The implementation of heterogeneous powder delivery requires calibrated powder control and monitoring (Mei et al. 2002). Commercially available powder delivery systems have been designed for purposes other than additive manufacturing. The difficulty with appropriating these systems arrives when precise control of very small amounts of material is needed. Most of the current systems are designed for feed rates higher than those required for powder-fed direct metal deposition. Within our center, research and development is underway to improve upon these systems and offer viable low-volume feed rates with precise monitoring and control for improved process stability, mechanical properties, and powder catchment efficiency (Liu et al. 2014). The experimentations presented here maintain feed rates that are at approximately .5 grams/sec or 4 pounds/hr. This is notably slower than Sciaky's claims, but is considered an acceptable trade-off for exploration of heterogeneous composition. This rate is nevertheless significantly faster than the differentiated lattice and node assembly prototypes produced using the powder supported ARCAM A2 Electron Beam Melting system shown in Figure 2.

THEORETICAL FRAMEWORK

The research methodology presented balances objectives within various disciplines of design research. Investigations explore a range of criteria, including fabrication constraints and mechanical and structural performance, as well as the aesthetic and formal consequences arising from the implementation of nascent technologies. This research methodology is coupled with an acknowledgement that form arrives into being at least partially from productive participation with material properties and the means of making as a mode of technê. Our view of technê can be characterized through a dynamic assemblage of interdependent material and machinic agencies that act upon the various aspects of a design artifact's revealing.

The notion of technê was essential to Aristotle's view of aesthetics and its role in poiesis or 'bringing into being'. For him, technê was centered on an informed and knowledgeable maker and the mastery of one's productive activity. "Technê involves a true alignment of the axis of potential/realization in human productive activity: it is concerned with bringing into being, by intelligible and knowledgeable means, objects whose existence depends on their maker" (Halliwell 1998). This traditional conception of artisan and the mastery of craftsmen is however distinct with regard to the proposed methodology and aligns itself more closely to a notion presented by Heidegger (1977). In his essay "The Question Concerning Technology," we are provided with an example of a silver chalice that owes its revealing to shared dependency between the silver as matter, the chalice as a signified object, and the silversmith's gathering together of acting elements. Barbara Bolt (2007) describes this shared dependency as "a play between the understandings that we bring to the situation and the intelligence of our tools and materials" and goes on to say, "This relation is not a relation of mastery but one of co-emergence". The dependencies described offer a clear route into engagement with these elements of agency and reorient the focus away from a strictly defined or clearly articulated outcome. Furthermore, this emphasis on interdependency gives way to the notion

Figure 2: Procedural lattice structures featuring variability within each element. a) This prototype was developed as a hypothetical design for a highly articulated structure where element design is informed by discrete loading criteria. b) Assembly prototype comprised of seven unique components. Automated design-to-fabrication enables the production of mass customized assemblies.

of technê as a participatory assemblage. According to Jane Bennett's (2010) analysis of Deleuze and Guattari, "Assemblages are ad hoc groupings of diverse elements exhibiting emergent properties." She continues: "Each member and proto-member of the assemblage has a certain vital force, but there is also an effectivity proper to the grouping as such, an agency of the assemblage."

Together, these ideas suggest the adoption of an approach directed toward the guiding forces within this abstract assemblage. The methodology proposed is signified through its participation with the material artifact as well as the apparatus employed to achieve an end and engages rigorously with the methods and mechanisms for making. If technê illustrates an alignment of potential with one's productive action, further engagement amplifies the domain of realization. Proactive commitments to the composition of material, mechanisms for production, and customization of design tools encourage dynamism within the manifold of possible outcomes.

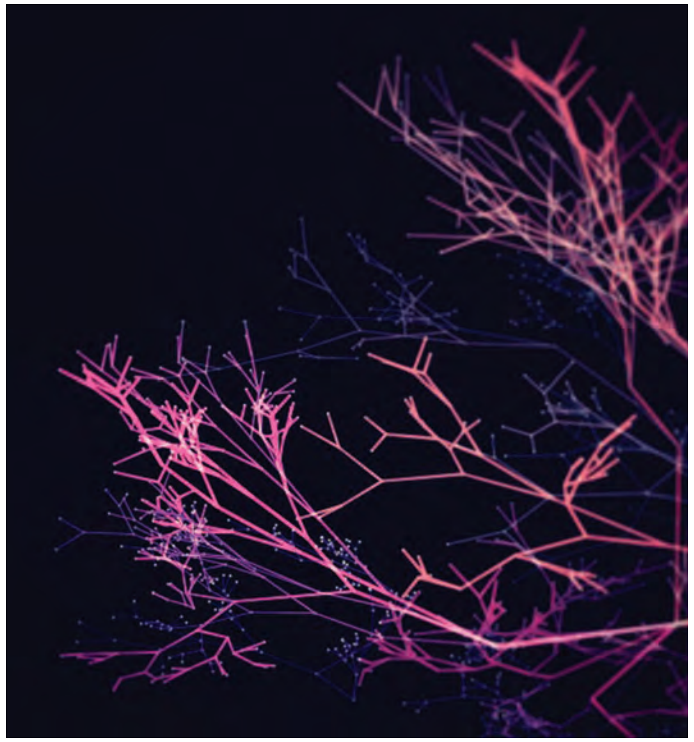
MULTI-SCALED PERFORMATIVE EXPRESSION

The notion that materiality has fundamental formal consequences was demonstrated within architectural theory and discourse as early as the nineteenth-century writings of Eugène Viollet-le-Duc. He clearly articulated enthusiasm for novel materials and believed that proactive involvement with industrial practices and methods of manufacture would enable the production of "new forms" (Hearn 1990). In response to the advancements of iron in his time, he writes: "Let us study its properties, and frankly utilize them, with that sound judgment that the true artists of every age have brought to bear upon their works." These beliefs manifest themselves within his work through expressions of structure, spatial organization, and ornamentation. Since then, refinement of metallurgical practices leading from wrought iron though ultra-high-strength steel have ushered in seminal contributions to the design and engineering of lightweight structures from Buckminster Fuller, Chuck Hoberman, Frei Otto, and Robert Le Ricolais. The high density, fracture toughness, and relative strength-to-weight ratios have made alloys a driving force for such explorations and have contributed greatly to the catalog of seeming weightlessness and transparency of structure. Additive processes for fabricating metal systems additionally offer a new era of design potential in regards to lightweight structures. In order to capitalize on this potential, intelligent design techniques must be employed.

A prototypical design approach has been adopted based on the form-finding methods of Frei Otto. The development of spring equilibrium algorithms loosely based on his tensioned spring models for optimized branching systems serve as the basis for global as well as nested organizations of material and spatial differentiation. Spring behavior modeled after Hooke's law is embedded within the individual elements of recursively generated branching systems. This provides the exploration of novel configurations and parametric control of both the organizational and behavioral forces driving the outcome. Initial conditions are set to determine branching depth, branching factor, and leaf factor (fig. 3). Stable relations between elements and nodes allow the system to relax into a state of equilibrium spanning between predetermined points of fixity. The organization of element relations provides additional benefit in regards to analysis. Once the system reaches equilibrium, structural matrix analysis using the finite elements method (FEM) is applied to determine local stresses and axial forces within the system. Reactions and nodal displacement can also be determined based on loading cases unique from the generative forces initially applied. The FEM feedback can then be used to inform cross sectional area and design constraints for each element and node component within the system. Once these parameters are determined, a meshing algorithm is applied to establish the volumetric boundary representation (fig. 4). Matrix analysis at this low-resolution stage provides an efficient approach for complex structures comprised of an abundance of dissimilar elements. Coordination of elements and node relations for large systems of this type can be tedious and prone to error. Through integration of algorithmic form-finding and matrix analysis, a multiplicity of design options can be explored with higher degrees of structural feasibility while alleviating error associated with coordinating these processes manually.

The abstract assemblage of material, means of making, and methods of design contribute to an endeavor for multi-scaled structural articulation. Together, this ensemble promotes and enables a precise and calibrated engagement at scales ranging through the organization of material composition, discrete connections, elements of assembly, and their diverse spatial distribution. The expression of complexity and synthesis of performance can traverse the full range of architectural scales while satisfying objectives to achieve visual nuance, intricacy, and delicate lightness. These optimizations are not entirely centered on functionality of structure; rather, they respond to desires for visual levity and animated suspension of multi-scaled fields of density. Stress accumulation and buckling resistance within these novel structures is essential, and design features to satisfy both visual and performance criteria must be developed. An essential feature of additive manufacturing processes is the ability to fabricate complex topologies with internal voids and stiffening members (fig. 5). The morphology of hollow bone structures found among birds represents an effective model for lightweight assemblies. The thin exterior wall in these structures is stiffened by an internal network of struts, and reduces the overall mass associated with its skeletal system. Unlike extrusion or built-up plate assemblies, similar features can be embedded within additively manufactured thin-wall cross sections without added complication during the fabrication process.

Prototypes testing this concept were developed starting from a solid hypothetical node subjected to



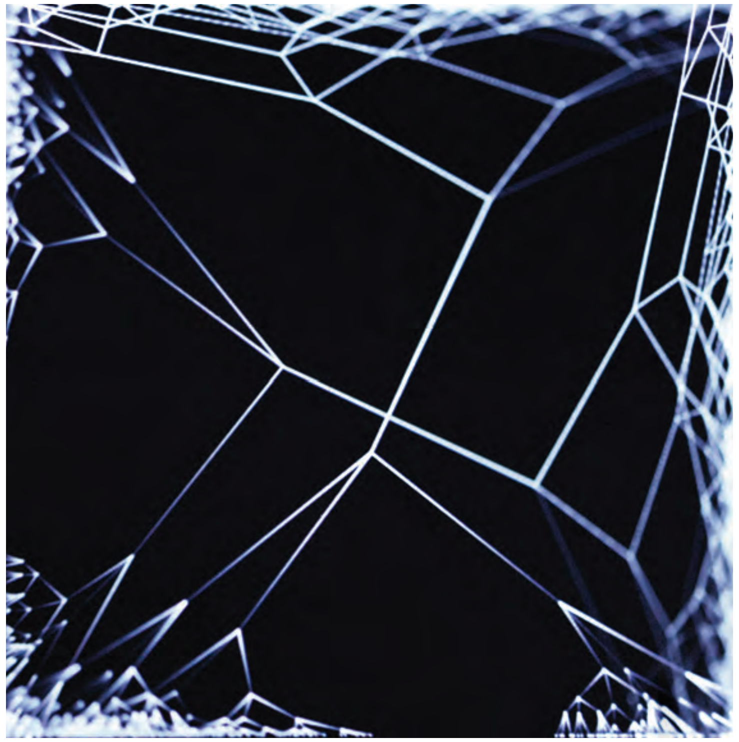


Figure 3: Examples of recursive branching structure with associative node relations. These relations allow for spring- and physics-based behaviors and structural matrix analysis. a) Color and thickness parameters can be linked to various modes of analysis for design feedback before applying mesh routines. b) Branching structures after spring equilibrium is obtained.

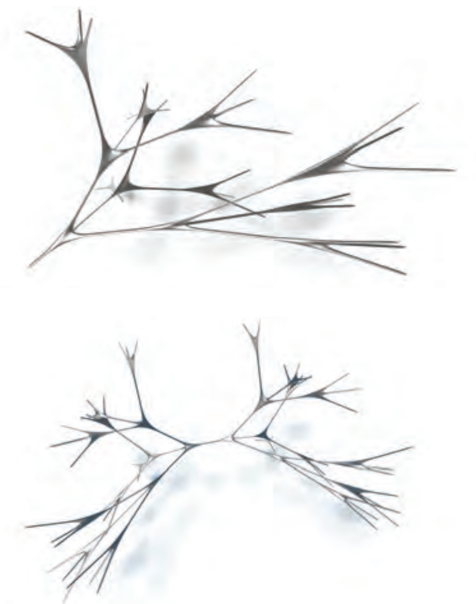
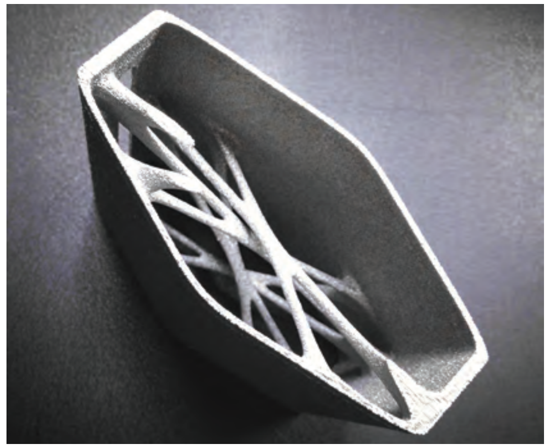


Figure 4: Results from cage-based meshing algorithm. Algorithm accepts arbitrary vectors with shared node relations as input and requires numeric input for parameters defining the cross section's geometry.



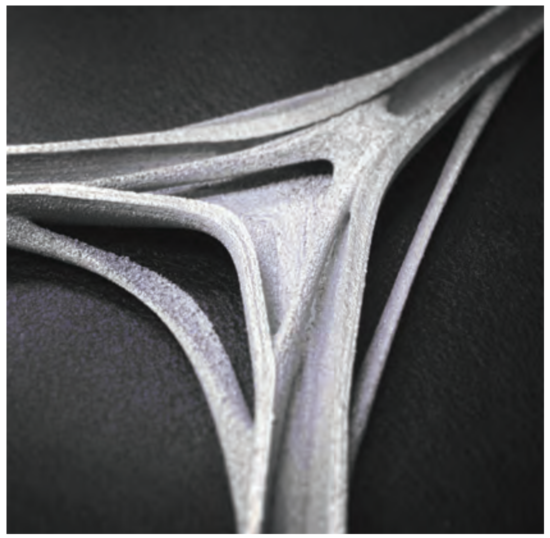


Figure 5: Cross section prototypes revealing internal lattice structures modeled after avian bone morphology. a) This 2" x 4" tube section has a principle wall thickness of 1/16". b) Variable wall thickness based on results from multiple iterations of FEM analysis and design.

Figure 6: Titanium Y-branch prototype produced using electron-beam melting (EBM).

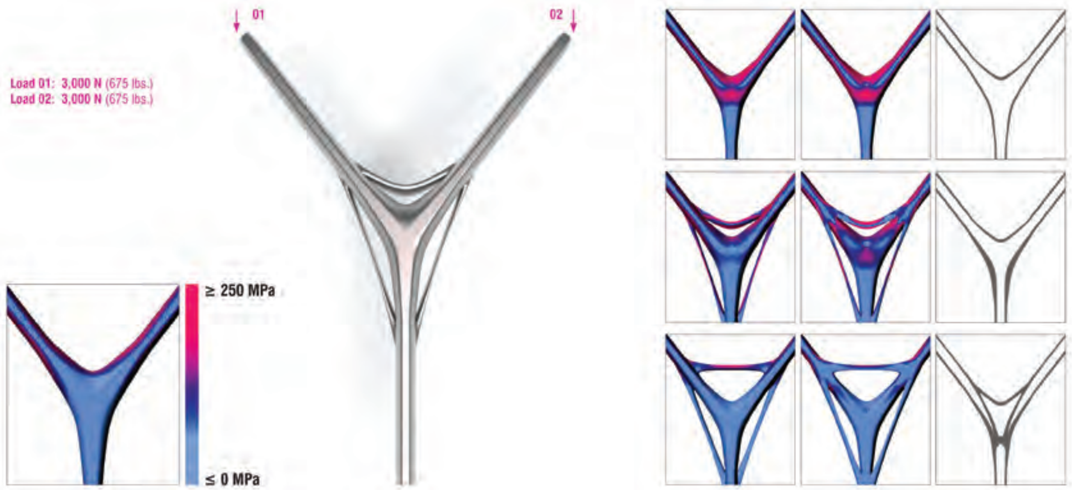


Figure 7: Stress accumulation observed in solid and uniform wall thickness designs inform subsequent iterations incorporating variable thickness and stiffening members.

FEM analysis (fig. 6). Resulting stress concentrations were compared between both solid and hollow versions. Thickness variations and reinforcing struts were incorporated in response to concentration patterns noted in the resulting gradient maps. The hypothetical load case consists of two 3,000 N forces and produced a maximum stress value of 315.57 MPa. The loading criteria were satisfied with a 34.6% reduction in mass. Maximum local displacement was reduced from 3.88 mm to 1.92 mm (fig. 7).

FUNCTIONAL INTEGRATION AND DESIGN FEATURES

In addition to apparent lightness stemming from optimization of structural performance, integration of building infrastructure provides opportunities to minimize visual clutter. The complexity achievable with additive processes further enables systems integration through a network of internal voids. These internal pathways can be designed to support infrastructure for rainwater harvesting and drainage, interior climate control, ventilation, and electrical and data transmission. Approaches that promote functional integration reduce the escalation of components used in construction. Over the last century, the trend has continuously moved toward an increase of infrastructural systems and assemblies that comprise the total structure (Kieran et al. 2004). This contributes to disproportionate increases in construction cost and systems coordination. Intelligent design based on additively manufactured systems could support the reversal of this trend or, at minimum, dampens its impact.

Interlocking and complex mated surfaces can be embedded within connecting elements, restricting improper assembly. Fastener-free, self-locking, and load-specific connection strategies can be designed for optimal assembly to potentially reduce construction schedules. A catalog of joinery types generally associated with wood and timber construction may prove applicable where previously infeasible due to traditional metal fabrication constraints. The connections developed for steel are inherent to the profiles and fabrication methods available; however, hybrid fabrication offers the potential to reconfigure the relationship between mating surfaces. This gives credence to alternative strategies modeled after the intricate interlocking found in Japanese joinery. The gooseneck tenon shown in Figure 8 would be infeasible within an assembly of stock steel profiles, but may serve as an appropriate model for connections between additively manufactured elements.

The "high-level functional integration" achieved through additive processes is noted by Achim Menges (2008) in his essay "Manufacturing Performance." In this examination, he presents the challenges of construction scaled implementation and the inverse relationship between scale and resolution associated with fabrication time. He effectively demonstrates the limitation of additive systems to provide material delivery rates that effectively operate in both high-resolution and bulk deposition. This challenge is particularly relevant for implementation of highly articulated components with functional integration. While this inverse relationship exists, metals are not challenged by this as significantly as the thicker load-bearing materials examined within his essay. The relative thinness and minimal mass required for metal structures alleviates some of this condition. A solution to this problem lies in the way material is delivered and fused within our proposed system. The laser used to fuse material is focused before passing through the coaxially delivered powder stream. Within most (if not all) additive manufacturing systems, the optics used for focusing is fixed and does not allow for in-line control during the fabrication process. A zoom homogenizer offers this type of control of the laser beam's size but is generally designed for applications such as heat treatment rather than cladding or deposition. Coordinated control of the beam diameter, laser power, and material delivery rates would enable nimble negotiation between states of high-resolution and high-speed bulk deposition. In addition, this feature provides more effective deposition for path planning based on dissimilar path width and can more efficiently deposit material within cross sections of non-uniform thickness.

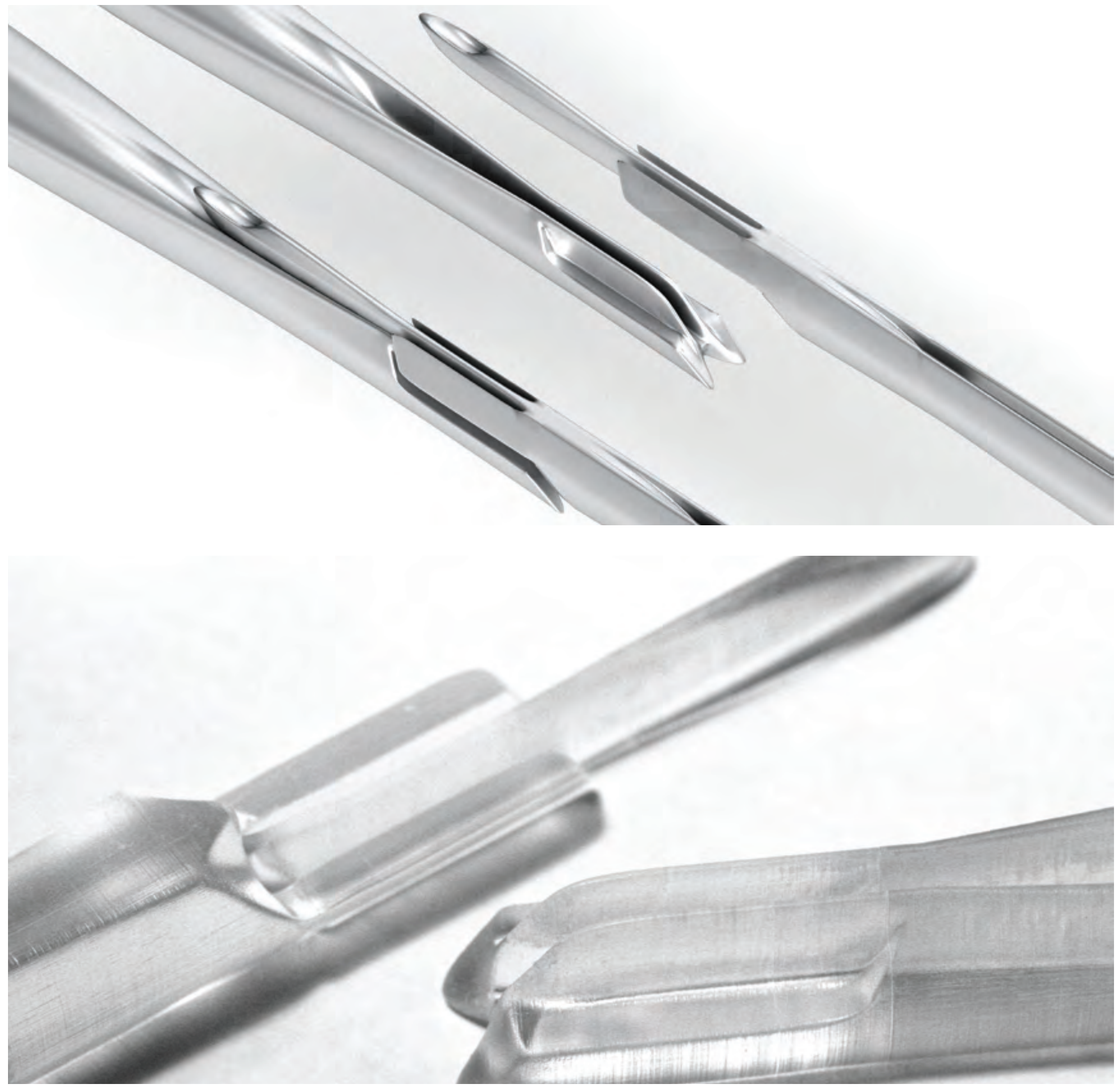


Figure 8: Connection strategy based on the gooseneck tenon observed in the joinery of Japanese woodwork. The prototype demonstrates effective self-locking and alignment of elements. An algorithmic design approach capitalizing on advanced manufacturing will enable solutions such as this.

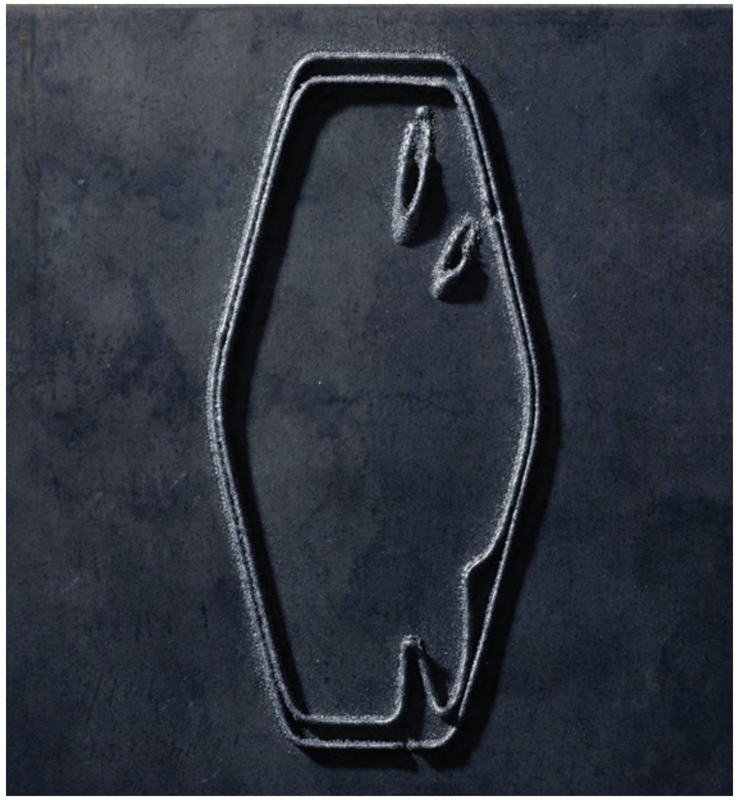


Figure 9: Experimental results from the initial contour-slicing algorithm demonstrated effects of signal timing delays and overbuild associated with inconsistency of velocity along path. Gaps produced by signal timing issues have been resolved, but further development is needed to regulate interdependent parameters based on real-time velocity feedback.

DIFFERENTIATED COMPOSITION

Building upon the resolution of design possible with additive processes, Neri Oxman (2010) proposes a more nuanced commitment to material through her theory of variable property design (VPD). VPD, as described by Oxman, places material first in a bottom-up approach. The relevance of this approach provides cues regarding the multi-scaled arrangements of spatial voids and heterogeneous material distribution. This approach applied to metals has compelling repercussions on the design of heterogeneous alloys and functionally graded structures. The metals used for direct metal deposition include (but are not limited to) aluminum, steel, and titanium. The micro-powders available provide a broad range of compositions designed to achieve localized mechanical properties. Through numerically controlled deposition rates, material properties can be modulated to address various design criteria and offer a high degree of structural performance. Base metals can also be combined with other alloying elements such as chromium, molybdenum, nickel, silicon, or tungsten carbide. These can be supplemented selectively to components comprised of several compatible alloys within a single direct-to-part fabrication process (Kovacevic et al, 2002).

Compositions can be designed to locally increase hardness, high creep/fatigue resistance, or fracture toughness to minimize damage or crack growth in regions subject to plastic deformation. Similarly, corrosive properties can be selectively determined to achieve functional criteria and/or aesthetic qualities. Insulated and conductive pathways may even prove feasible as embedded infrastructure. In addition to the mechanical properties noted, other physical properties can be modulated, including specularity, reflectivity, emissivity, and color. This can be achieved to promote sensual qualities or other aesthetically driven aspirations. Combined with surface treatment and other post processing applications, oxidization and bluing effects can have locally controlled responses. Each of these criteria has inevitable design implications for the element's cross section and surface appearance, potentially contributing to emerging affect at an organization level.

DESIGN THROUGH FABRICATION WORKFLOW

The integration of algorithmic design methods featuring optimization routines and FEM response mechanisms with file-to-fabrication processes presents notable challenges. For this reason, material- and fabrication-based research runs parallel to programming development of design-to-fabrication tools. These ad-hoc applications contribute to the testing and investigation process by augmenting the available toolset. As each component of research satisfies its objective, prototypical modules of code are integrated within a code library or framework written in C++. This design-to-fabrication framework serves as the backbone for a prototypical architectural scaled implementation of additively manufactured metal structures and extends from conceptualization of a global system incorporating structural feedback based on FEM analysis through discretization of node components, path planning, and signal control for robotic fabrication.

Preliminary path planning definitions developed in Grasshopper have been post-processed with the assistance of Kuka|prc, developed by Johannes Braumann. This application plug-in offers versatility and expedience for prototyping KRL programs and integrates seamlessly within a Rhino/Grasshopper platform. Workflow limitations related to computational efficiency are nevertheless apparent as part geometry's size and complexity increases. High-resolution paths are needed to fully describe the instruction sequences for fabrication of such parts. Similarly, the instructions generated test limitations for the robot controller (Gardiner et al. 2014). Unlike most operations for which industrial robots have been employed, additive manufacturing requires tighter path positioning tolerances and minimal variation in velocity during the deposition process (fig. 9). Vertical spacing of contours and tool orientation must be coordinated with deposition rates to ensure proper delusion for overhangs and unsupported inclines (fig. 10). Internal fill algorithms also require special attention in regard to

Figure 10: Studied for unsupported inclines and overhangs. Investigations have been based on three approaches: vertical axis of tool orientation, tool orientation based on slope, and coordinated orientation between tool and part manipulated tilt-rotary platform.

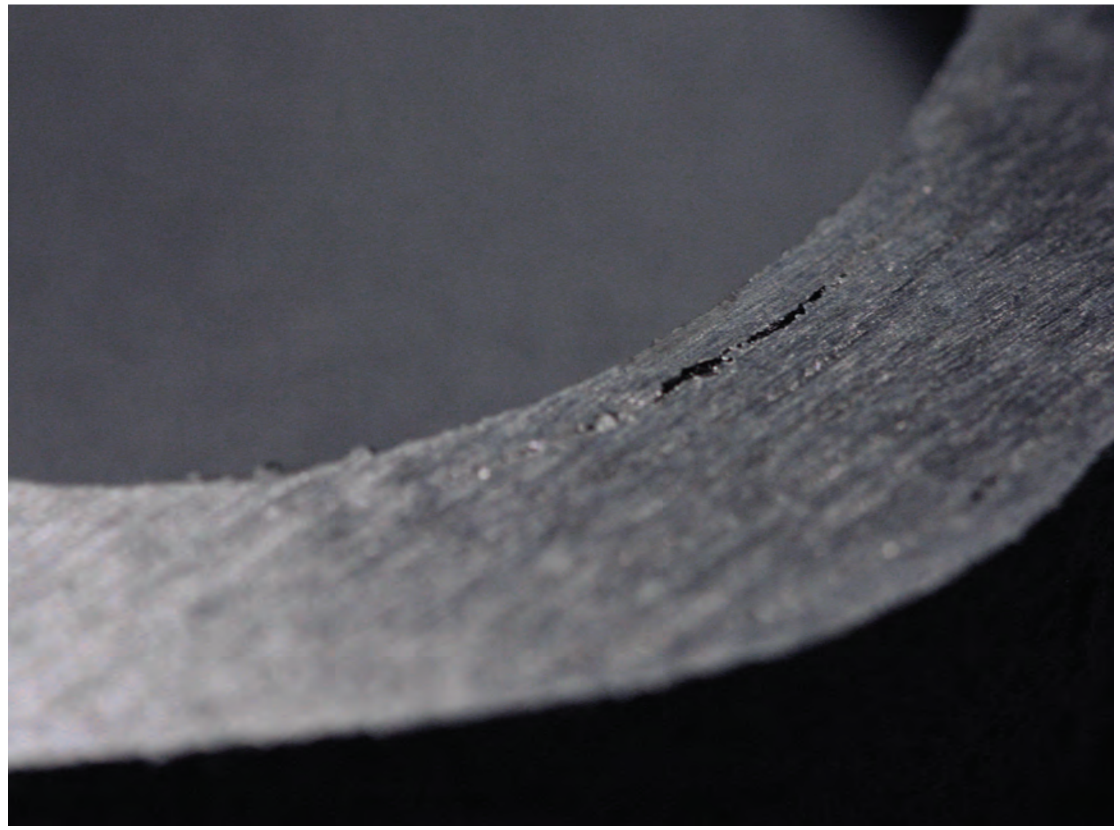


Figure 11: Hatching or fill algorithms for cross sectional path planning. The results show porosity encountered when paths are not properly spaced for delusion between adjacent passes. This is particularly evident in areas where paths diverge related to increased wall thickness. Further research is targeted for use of zoom optics to provide inline control and variation of path width.

spacing to eliminate porosity that adversely affects the mechanical properties (fig. 11). These factors contribute to lengthy instruction files that exceed sizes supported by Kuka's KR-C2. This limitation is partially alleviated by breaking instruction files into smaller chunks of code. To achieve this, a KRL parser was developed to divide instruction files according to specific tokens within the program. These subdivisions are then compiled into separate batches of instruction and formatted into subprograms, which can be called from a corresponding master program that is also automated during the read/write process.

Due to the apparent lag associated with performing these calculations for a single node, the potential to automate this process for large collections of nodes is improbable and certainly computationally inefficient within the current workflow. Added complexity and increases in KRL instruction needed to describe material composition on a point-by-point basis further compound the limitation of the current workflow. These limitations are not unique to this platform, and in general most CAD/CAM software fails to anticipate design processes implementing heterogeneous composition (Knoppers et al. 2010). While these limitations represent challenges, solutions are being researched. One example that may serve as a model for implementation is being developed by Andrew Payne and Panagiotis Michalatos (2013). Their proposed software introduces several compelling approaches that extend well beyond the scope of this paper, but a fundamental shift towards graphics processing and shader-based calculations offer clear computational advantages.

CONCLUSION

The proposed system for hybrid additive and subtractive manufacturing presented yields an expanded domain for design research. Structural performance and the design of lightweight structures are key areas for implementation of additively manufactured metals. The ability to integrate various functions and calibrateheterogeneously composed alloys locally demonstrates significant implications for the synthesis of aesthetics with performance-driven criteria. Technê as an intelligible participation between maker and matter contributing to poiesis is evident. Further investigation of this theoretical framework can only provide resolution to our understanding of the dependencies at play. Driving potential for emergence through material engagement must, however, be demonstrated empirically through a larger body of research based on this methodology, as well as through refinements to the proposed manufacturing systems. While current investigations show promise, many challenges must be addressed before the realization of intricate and high-resolution structural systems comprehensively exemplify many of the features discussed.

ENDNOTES

1. http://www.dezeen.com/2014/02/21/3d-printing-robot-by-joris-laarman-draws-freeform-metal-lines/

2. http://www.kramweisshaar.com/projects/multithread

3. http://patharc.com/portfolio/re_stock

4. http://www.dezeen.com/2014/06/11/arup-3d-printed-structural-steel-building-components/

5. http://aviationweek.com/commercial-aviation/comac-c919-have-3-d-printed-titanium-spars

6. http://www.sciaky.com/additive_manufacturing.html

REFERENCES

Bolt, B 2007, 'Material thinking and the agency of matter', *Studies in Material Thinking*, vol. 1, no. 1. Available from: http://www.materialthinking.org/sites/default/files/papers/Barbara.pdf

Beaman, JJ, Barlow, JW, Bourell, DL, Crawford, RH, Marcus, HL, & McAlea, KP 1997, *Solid freeform fabrication: a new direction in manufacturing.* Kluwer Academic Press, Boston.

Bennett, J 2008, *Vibrant matter*: a political ecology of things. Duke University Press, London.

Ciraud, PA 1972, *Process and device for the manufacture of any objects desired from any meltable material.* FRG Disclosure Publication 2263777.

Dwivedi, R & Kovacevic, R 2006, 'An expert system for generation of machine inputs for laser-based multi-directional metal deposition', *International Journal of Machine Tools & Manufacture*, vol. 46, pp. 1811–1822.

Dwivedi, R, Zekovic, S, & Kovacevic, R 2007, 'A novel approach to fabricate uni-directional and branching slender structures using laser-based direct metal deposition', *International Journal of Machine Tools & Manufacture,* vol. 47, pp. 1246–1256.

Gardiner, J & Janssen, S 2014, 'Free fab development of a construction-scale robotic formwork 3D printer' in *Robotic Fabrication in Architecture, Art and Design* 2014, eds W. McGee and M. Ponce de Leon, Springer, New York, pp. 131–146.

Halliwell, S 1998, *Aristotle's poetics*, University of Chicago Press, Chicago.

Hearn, MF 1990, 'Applying new architectural principles' in *The architectural theory of Viollet-le-Duc: readings and commentary*', ed MF Hearn, MIT Press, Cambridge, pp. 231–237.

Heidegger, M 1977, *The question concerning technology and other essays*, trans. W Lovitt, Garland, New York.

Huang, W & Lin, X 2014. 'Research progress in laser solid forming of high-performance metallic components at the state key laboratory of solidification processing of China', *3D Printing and Additive Manufacturing,* vol.1, no. 3, pp. 156–165.

Liu, S, Farahmand, P, & Kovacevic, R 2014, 'Optical monitoring of high power direct diode laser cladding', *Optics Laser Technology*, vol. 64, pp. 363–376.

Kieran, S & Timberlake, J 2004, *Refabricating architecture: how manufacturing methodologies are poised to transform building construction*, McGraw Hill, New York.

Kovacevic, R, Mei, H, & Ouyang, J 2002, 'Rapid prototyping and characterization of a WC-(NiSiB alloy) ceramet/tool steel functionally graded material synthesized by laser cladding', *Rapid Prototyping of Materials, The Minerals, Metals & Materials Society, Warrendale.*

Knoppers, R, Gunnink, JW, van den Hout, J, & van Vliet, W 2010, 'The reality of functionally graded material products,' *TNO Science and Industry*, The Netherlands, pp. 38–43.

Kram, R, & Weissharr, C 2012, 'Force feedback', *Domus*, no. 957, pp. 54–59.

Mei, H, Valant, M, Hu, D, & Kovacevic, R 2002 'The characterization of the performance of a new powder feeder for laser based additive manufacturing', in *Solid Freeform Fabrication Symposium Proceedings: August 2002*, University of Texas, Austin, pp. 448–457.

Menges, A 2008, 'Manufacturing performance', *Architectural Design*, vol. 78, no. 2, pp. 42–47.

Oxman, N 2010, 'Structuring materiality: design fabrication of heterogeneous materials', *Architectural Design*, vol. 80, no. 4, pp. 78–85.

Otto, F 2009, *Occupying and connecting: thoughts on territories and spheres of influence with particular reference to human settlement,* Edition Axel Menges, London, pp. 68–69.

Payne, A & Michalatos, P, 2013, 'Working with Multi-scale Material Distributions', in *ACADIA 2013 Adaptive Architecture: Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture*, eds P Beesley, O Khan, & M Stacey, ACADIA/Riverside Architectural Press, Cambridge, pp. 43–50.

Tapia, G & Elwany A 2014, 'A review on process monitoring and control in metal-based additive manufacturing', *Journal of Manufacturing Science and Engineering,* vol. 136, no. 6.

Warton, J, Dwivedi, R & Kovacevic, R 2014, 'Additive manufacturing of metallic alloys: an architectural case', *Robotic Fabrication in Architecture, Art and Design 2014*, eds W. McGee and M. Ponce de Leon, Springer, New York, pp. 147–161.

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