ABSTRACT
The research presented here investigates an approach to FDM freeform 3D printing that fully utilizes simultaneous x, y, and z axis movement for the production of designed artifacts. Most freeform printing techniques create bands of space-frame-type structures, often defined by structural pursuits. Here, a form responsive method (FRM) is used, which exploits the design opportunities of synchronized three dimensional movement, depositing extrudate in patterns of lines and curves that embrace functional, aesthetic and tectonic qualities, influenced largely by an industrial design perspective. The system allows the designer complete control of the pattern and deposition of the material in relation to the printed artifact. The form and details are designed concurrently by direct manipulation of the toolpath whilst considering material deposition and structural integrity. This method of working requires intimate understanding and control of both software and hardware to craft the artifact to the desired design. Different aspects of the technique and challenges are described and discussed through a range of artifacts of different scales from utensils to furniture items.
INTRODUCTION
Freeform 3D Printing
Freeform 3D printing provides new opportunities and approaches to building additive 3D forms. Currently, one of the main types of additive manufacturing (AM) is fused deposition modeling (FDM). This method melts and extrudes filament of thermoplastic material through a fine print nozzle and deposits thin layers of material which build up to form 3D geometries. Freeform 3D printing retains some inherent novelties from FDM printing, using the same computer numerical control (CNC) machine capabilities in conjunction with material extrusion to build 3D forms, but no longer relying on planar layering methods. Instead, it employs self-supporting build material that solidifies upon extrusion to create free-standing strands of material in space. These are generated from the toolpath of the CNC machine which exploits the freedom of simultaneous x, y, z axis movement. Through this process, the need for support material diminishes. Resourcefully designed, the path the extruder head follows can become increasingly economic in material use and printer movements.

BACKGROUND
Form Responsive Method
Current applications of freeform 3D printing are predominantly in the architectural domain employing the flexibility of robotic arms. These projects often explore large-scale building solutions for complex structures, taking a structural space frame approach in creating three-dimensional printed forms. These are defined by automated dispersing algorithms and are reflective of the traditional slicing processes, building from the ground up. Projects such as Wire Print by Mueller et al. (2014), Ai Build (2016) Branch Technology (n.d.) Iridescence Print, Helm et al. (2015) use a distinct banding approach as their process in order to break up large geometries into layers of spatially printable bands. The benefit of this is, as in traditional 3D printing, almost all geometries can be run through a slicing system, and turned into printable information.

The research here takes intended forms and structures into consideration from the onset, informing bespoke material deposition and thereby differentiating the process from any automated, banded or layering methods. Figure 2 illustrates the form responsive method (FRM), which fully utilizes simultaneous x, y, z axis movement with regards to the intended form. FRM disregards the requisite that surface or solid forms need to be delineated prior to considering material deposition. Instead, artifact specific approaches have been applied to consider both form and material deposition concurrently. Artifacts are now fundamentally defined by repetitious lines used to create a toolpath which determines the geometries of the three dimensional built form.

When taking this approach to artifacts, through an industrial design perspective, the FRM presents an opportunity to embrace functional, aesthetic and tectonic applications of material, prospering upon the predominantly structural pursuits currently in the field. On the Industrial Design Society of America’s website, NC State Industrial Design Program states:

Industrial Design (ID) is the professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer. (IDSA 2017)

Incorporating these qualities and understanding that the manufacturing method has needs, requirements, constraints and limitations allows the designer to become an informed mediator between user and the manufacturing method. The language between these, in this case, is G-code, informed primarily by the toolpath, extrusion settings and speeds.

Craft/Digital Craft
Craft is known as a skill, art, or dexterity for doing or making something. Pye states that craftsmanship is inclusive of the workman using any kind of technique and apparatus in which the quality is not predetermined, but depends on the judgment, dexterity and care which the maker exercises as he works (1968). Technology is now embraced as an aid for the workman. It could be argued that, in digitally crafting materials, the designer and the machine become the mutual maker.

The linear tectonics and stair-stepping qualities created from FDM printing processes often form undesirable surface qualities, a trade off between build speed and quality. However, by using freeform printing and the FRM to create printed artifacts, this can be overcome through bespoke deposition and computational processes. Furthermore, by disregarding current assumptions that
printed geometry must first be defined by a solid form or surface and sliced using algorithm-based layers or space frame systems. Opportunities arise to explore diverse and unique sets of print tactics that incorporate craft qualities through the digital control of motion, speed and extrusion rates. By engaging industrial design sensitivities, this research seeks to create visual, tactile and textural expressions of the making process to enhance the printed product both visually and structurally.

Cross-discipline Freeform Strategies and Approaches

This research commenced with an in-depth study of state-of-the-art freeform techniques at the time of the initial investigation (July 2016–May 2017). From the information gathered, a matrix was developed to allow analysis of the techniques, materials and processes used with sixteen notable spatial printing projects evaluated (Figure 3). The majority were in the architectural domain using robotic arms, with others selected as they were closely aligned with the intent of this research.

Although the aforementioned projects use 3D bands that build up cumulatively, other projects from the architecture research community, use a similar approach but explore more variability in toolpath and material deposition in response to the geometries at hand or the requirements of the object. Prime examples include the Spacewires project and Curvvoxels project (Gilles and Manuel Jimenez 2016), and two notable exemplars that use multi-extrusion tools, Freeform 3D Printing: Towards a Sustainable Approach to Additive Manufacturing (Oxman et al. 2013) and Robotic Multi-dimensional Printing Based on Structural Performance (Yuan et al. 2016). Another project of interest, although not a freeform project as it employs a mould, is “Robotic-Enabled Stress Line Additive Manufacturing” which uses simultaneous movement to create curvaceous lines defined by finite element analysis (FEA) to create 2.5D-surface layered structures (Tam et al. 2016).

Whilst there are multiple precedents showing the discovery of impressive qualities, possibilities and applications for spatial printing methods using 6-axis robotic arms for the creation of complex architectural geometries with real world application, there are other groups undertaking experimental freeform projects from the maker community, such as Filament Sculpture (Lia, 2014) and Vessel Experimental G-Code (Lobser, n.d.). These start to digress beyond traditional layer-based printing techniques and
Grasshopper/Silkworm was adapted through a converter to an .x3g file compatible with the MakerBot printer. A Grasshopper script was developed to define print head location, speed of movement (F-speed), extrusion rates (E-rate) and temperature settings. A series of extrusion tests were conducted to ascertain optimum performance of unsupported printing across gaps (bridge test using N1) (Figure 4) and arc movements (Figure 5). Different E-rates and F-speed relationships were ideal for different sized arcs; therefore, identifying the best-printed arcs of each radius allowed the researcher to understand the relationship between the values and the correlated lines length(s), and the optimum settings could be calculated (Figure 6). Through visual analysis of the test samples, the speed of F100 was found to be the optimum print movement value for the longest arc segments, and an E-rate of between 0.25 to 0.3 times the line length performed the best (Figure 6). The second custom nozzle (N2) was used for the arc tests; it had the same diameter orifice as N1 (0.8 mm), but the protrusion was increased to 17.5 mm to begin to show how more variability in settings and material deposition can be used for rich visual and tectonic qualities, often exhibiting some loss of control/precision but embracing serendipitous findings. By amalgamating these concepts and successes, our research here begins to understand the value of this technique in the spaces between the micro and macro, the tinkerer and the engineer. An industrial design perspective provides a new set of guidelines and proprieties to interpret the process through.

METHODS
Experimentation and Optimization Tests
Initial testing was carried out using a MakerBot Replicator 2X with some adaptations and modifications to maximize the printer’s ability to work spatially and to gain control over the printer’s motions and material deposition. This included making custom print nozzles to allow greater spatial movement before collisions with the built form would occur. The first custom nozzle (N1) protruded from the body of the print head 13 mm and had an orifice of 0.8 mm diameter. In addition the G-code output from Grasshopper/Silkworm was adapted through a converter to an .x3g file compatible with the MakerBot printer. A Grasshopper script was developed to define print head location, speed of movement (F-speed), extrusion rates (E-rate) and temperature settings. A series of extrusion tests were conducted to ascertain optimum performance of unsupported printing across gaps (bridge test using N1) (Figure 4) and arc movements (Figure 5).
Arc test results, showing optimum settings for F-speed and E-rates in relationship to segment length and direction.

Findings: extrusion rates in relationship to segment length, twice in opposite directions to evaluate directional pull.

Early Grasshopper script used for print testing on the MakerBot.

6 Arc test results, showing optimum settings for F-speed and E-rates in relationship to segment length and direction.

7 Findings: extrusion rates in relationship to segment length, twice in opposite directions to evaluate directional pull.

8 Early Grasshopper script used for print testing on the MakerBot.

avoid collision with the built arcs. It was also discovered that the E-rate on the paths moving downwards (negative Z movements) needed to be slightly decreased compared to upward motions. This is due to the gravitational pull on the filament, meaning that excess filament was printed during downward motions. This is compared to the upward motions during which the slight tension between the nozzle and printed geometry counteracts gravity. A comfortable adjustment for negative motions was to multiply the calculated extrusion rate by 0.8.

The arc tests proved it was possible to print self-supporting strands spatially with the MakerBot Replicator 2X using standard ABS 1.7 mm diameter filament. Once established, the optimum settings were found to create physical structures that very closely approximated the original digital delineation. The final settings produced prints with minimal deviation from the expected print height in the z direction, no more than 1 mm, but with a small amount of deviation in the y direction, dependent on the direction that the arc was printed in.

After these initial optimization tests, three groups of abstract design experiments (Figure 9) were used to find and explore opportunities for spatial printing through the proposed form responsive method using a Grasshopper definition (Figure 8). The three groups were as follows:

- The Minimal Base Adherence series, which tested techniques to avoid reliance on the base plane/raft or relying on large quantities of support structure to build complex forms.
- The Dynamic Layering series, which sought to pursue the opportunities arising from structures built through combinations of accumulative layers and spatial deposition.
- The Structures, Patterns and Tectonics series, which sought to test the impact of surface patterning on material integrity, with a focus towards influence on structure. It explored how direction, interaction, and density would impact the structural or mechanical qualities of a print. Tectonics and aesthetics were considered, with influence from the form.

These experiments began to express how simple, bespoke processes could create new material qualities through freeform 3D printing. Many specific qualities were found in the experiments, and the integration of these were used to further increase opportunity for the FRM. More general opportunities exposed were:
The ability to create variable material qualities, both locally within a single print, and over separate artifacts
Freedom to define materiality and tectonic qualities for specific purposes
Largely diminished need for support material and less wastage of material
Greater control over visual, physical and tectonic impact of material deposition
Ability to easily create open or mesh-like structures (compared to standard FDM)
Visual patterning as a cue for the artifacts use and structural integrity

Machine Adaptation, Computational Development and MendelMax Settings
Following the tests and the abstract design experimentation, the requirements and abilities of the spatial printing process were more intimately understood. Computational systems were improved in response to the knowledge gained. At this stage, a MendalMax printer was acquired and used for the remaining duration of the research as this printer allowed for larger geometric freedom in the Z-axis direction. In addition, it could be run from direct G-code output from Grasshopper/Silkworm via Repetier. Two new nozzles (N3 and N4) of different lengths, protruding 25.5 mm (N3) and 21 mm (N4) were trailed. N3 had an orifice diameter of 0.6 mm and N4 a diameter of 0.7 mm. Again, 1.75 mm ABS filament was used and the N4 nozzle performed better and was used for the remainder of the study.

APPLICATION BASED EXPERIMENTS
To further understand how freeform 3D printing could be embraced through an industrial design perspective, a number of application-based exemplars were identified to span common industrial design product areas, specifically a utensil and a range of furniture items. Simple archetypes with non-complex 3D forms were used as the research focused on new approaches to material deposition and the FRM. Here we present two furniture items and the kitchen utensil set.

Furniture Design Experiments
With the intension to explore the FRM at a larger furniture scale, 1:5 scale samples were designed and made to test a range of toolpath strategies. These parametric furniture
design experiments were broken down into furniture components, exploring two different seat forms with distinctive structural configurations/strategies and one common leg system with variable density (Figures 10 and 11). The chair pattern system, seen in Figure 10, explored a rotational FRM pattern with opposing directions of material connecting at intersections, thus creating variability in layer densities from the center to the periphery. The pattern system used in the design in Figure 11 explored configurations where volumetric material flowed transversely over form in a primarily linear direction. The strategy employed on the legs facilitated the printing of open Freeform structures and FDM 2.5D printing conjointly to create cumulative dense patterns for vertical load and open bracing structures.

Variable Density: Solidity and Open Structure, Kitchen Utensil Set (KUS)

By digitally crafting through curves as opposed to solids, material becomes controllable down to the single print strand. To explore varying levels of structural dispersion a three-part kitchen utensil set was chosen. Each component within the set presented unique requirements for density with respect to its intended use, ranging from dense areas to light open meshes (Figure 12).

RESULTS AND DISCUSSION

Through the utensil- and furniture-based exemplars it was understood how widely impactful material deposition is to the integrity of the printed artifact. Interesting visual, physical and tectonic qualities were revealed through the different configurations of deposition and it became evident that many more could be explored. Only a handful of techniques were explored comprehensively with overlays of repetitious lines, three-dimensional layering, and other patterning techniques being given precedent.

To evaluate the success of freeform printing, the sieve element from the set of kitchen utensils was printed using a standard FDM process on an UpBox printer. Through this
comparison, the disparity of reliance on support material became explicit. As illustrated in Figure 13, the amount of material is vastly reduced when using the FRM approach with its self-supporting build material, compared to the mass of excess material required for FDM prints using standard slicers. The removal of these support structures also impacted the quality of the print in many areas where it could not be removed at all. The FRM-printed sieve is shown in use in Figure 14 on the next page. The time comparisons and linear material usage should also be noted, see the caption for Figure 13.

The step between delineating the general design of deposition and executing the desired tectonics to a reasonable standard proved to be a highly interactive process and demanded a very intimate relationship with the manufacturing device. The development of a design became a negotiation between desires of the designer and the limitations of the printer. A conversation of design iterations continued until the craftsman (the designer) the workman (the printer) and the material could agree upon a solution. This dialogue allowed the authorship of making to be reclaimed and the printer to become a palpable tool for actualizing digital craft. Diversity in digital techniques resulted in diversity in artifacts, both between prints, and locally within single designs.

As discussed earlier, many of the published freeform projects investigate pragmatic architectural structural issues with less concern for aesthetic resolution, with some concealing the printed structure deep within the fabric of the building. If the FRM were to be applied at an architectural scale, it would seek to avoid the separation of building parts into structural and non-structural elements but would adopt an integrated, homogenized tectonic approach. Furthermore, as a construction method, the value lies in the synergy between material deposition, functional/structural requirements and aesthetic control through the precise manipulation of the toolpath. The aesthetic expression is defined by the skill, judgment and sensitivity of the designer or architect. It could be called “digital dexterity” where the built design is masterfully crafted through code with the
explicit intent to integrate a high level of aesthetic refinement and resolution. Furthermore, the making process is biomorphic in nature and is fluid, both in its ability to be adaptive or customized and in its visual expression. As with nature, it is economic with material usage and matter is placed only where needed. Although reliant on a mould construction system, the ICD/ITKE pavilion (Doerstelmann 2015) illustrates economic use of material through digital robotic fabrication at a larger scale. If the technical issues of scaling up the freeform form responsive method were overcome with further research conducted in the field, larger scale constructions could enhance the built environment with future bespoke toolpaths having the potential to offer new expressions of materiality and aesthetics.

CONCLUSION
This research started with an in-depth survey of all the freeform research projects published at the time, mid 2016 to early 2017, which analyzed project processes, methods and outcomes. Most focused on architectural pursuits, with the notable exception of Laarman’s metal Dragon Bench (Friedman Benda 2014). Due to the broad nature of the survey, this research project became interdisciplinary, as generative software techniques used in architecture were cross-pollinated with concepts and approaches from industrial design. In addition, looking at freeform 3D printed artistic expressions in the maker space further enriched project concepts.

The outcomes of this study are proof of concept and the next step in the program is to scale up by utilizing our large ABB robotic arm and a recently completed custom filament extruder. In the next few months we will be printing one of the furniture pieces full size. The structural performance is likely to be compromised by the ABS material used and it is in this area that much more material research needs to be undertaken to produce multi-material filament (Oxman et al. 2013) or blends of materials that are designed for the specific requirements of freeform 3D printing, be they plastic or other materials.

The research here shows that by utilizing the form responsive method and directly working with toolpaths the deposition of material can be defined to new levels of control, resulting in digitally crafted artifacts with novel qualities (Figure 15). The method proved to be highly...
economic in terms of time and material usage. By scaling up in size and with the increased dexterity of six axes of robotic movement or more, further design opportunities exist and could be explored in a range of designs in a number of fields. Further integration of a range of structural systems used in architecture, including FEA, may yield a greater diversity of deposition qualities and could move towards closer synchronization between structural performance and aesthetic resolution.

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REFERENCES


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