From Design to Interaction: an overview of 3D Printing interactive prototypes

Kongpyung (Justin) Moon *

Industrial Design, KAIST, jkpmoon@kaist.ac.kr

3D printing technology has revolutionized the prototyping process by enabling fast and cost-efficient creation of functional prototypes. These prototypes have the potential to be disruptive as they allow testing user interaction under a range of conditions. The advancements in 3D printing functional parts will allow users to print beta prototypes that actuate, sense, and process information, enabling for rapid manufacture of initial ideas and products. This workshop paper includes how a material property and its reaction to heat can be leveraged to control functions such as resistance, leading to the creation of 3D printed fuses and switches, which opens up wide research opportunities to explore and develop 3D printed processors that can be integrated into objects during the printing process.

CCS CONCEPTS • Insert your first CCS term here • Insert your second CCS term here • Insert your third CCS term here

Additional Keywords and Phrases: Insert comma delimited author-supplied keyword list, Keyword number 2, Keyword number 3, Keyword number 4

ACM Reference Format:

First Author's Name, Initials, and Last Name, Second Author's Name, Initials, and Last Name, and Third Author's Name, Initials, and Last Name. 2018. The Title of the Paper: ACM Conference Proceedings Manuscript Submission Template: This is the subtitle of the paper, this document both explains and embodies the submission format for authors using Word. In Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY. ACM, New York, NY, USA, 10 pages. NOTE: This block will be automatically generated when manuscripts are processed after acceptance.

1 INTRODUCTION

3D printing, additive manufacturing (AM) technology, has revolutionized the prototyping process by enabling the fast and cost-efficient creation of look-and-feel prototypes. Functional prototypes (a.k.a. beta prototypes) have the potential to be disruptive because they allow testing product performances under a range of conditions. 3D printed parts in functional prototypes act as a shell that is assembled with electro-magnetic actuators (servo, stepper, DC motors), printed custom board (PCB) with integrated chips (IC), and various sensors, forming "functional" and "interactive" prototypes.

This work was presented at the **CHI2023 Workshop [WS2] - Beyond Prototyping Boards: Future Paradigms for Electronics Toolkits**
CHI '23, April 23-28, 2023, Hamburg, Germany

However, 3D printing and assembling a passive shell with other electronic components is time-consuming. It requires a wide range of knowledge and expertise in electronics and physical computing that hinders many makers and creators from rapidly prototyping and testing their ideas.

HCI researchers have developed 3D printing techniques for functional objects with various materials and printing methods to address this problem. For sensing technique *Capricate* [1], *MetaSense* [2] and *Flexibles* [3] introduce 3D printing conductive filament such as a capacitive sensor to detect touch [3], hover [1], and joystick control [2] just with 3D printed materials. *Thermorph* [5] and *ShrinkCells* [6] demonstrates how 3D-printed object can be actuated without any motors attached. 3D printing meta-material structures enable the creation of interactive hinges [7], textures [6] and mechanical logic gates [8] with various design structure topologies. On the other hand, attaching additional tool-head on CNC plotter such as component placer [18] allows to fabricated interactive objects that can be activated after laser-cutting process. These advancements in 3D printing functional parts will eventually allow users to 3D print a functioning prototype that actuates, senses, and process information, enabling creators and makers to manufacture their initial ideas and products rapidly.

Despite advancements in 3D printing input and output techniques, instructing components such as switches and transistors that can form fundamental building blocks of digital circuits are yet explored in digital fabrications. This workshop paper will discuss the possible research direction of 3D printing electro-switch and transistors by 3D printing carbon and copper-based materials and controlling the current flow via selective Joule-heating. 3D printing electro-switches with other 3D printable materials (e.g. PLA and ABS) will contribute to the vision of 3D printing functional and interactive prototypes that can be used and tested straight from the machine.

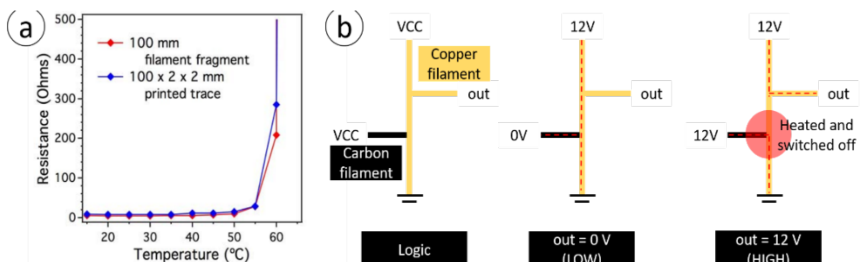

Figure 1: a) resistance temperature relationship [16], b) primitive logic circuit design diagram

2 HEAT AS A STIMULATION TO ACTIVATE MATERIAL PROPERTIES

Heating is one of the most common and effective methods used in the 3d printing process to melt and extrude thermoplastic filament to create a custom 3D object (i.e. Fused Deposition Modeling (FDM) and Fused Filament Fabrication (FFF)). Heat can also be applied, globally or locally, after the printing process to change its shape [8] and properties, such as the resistant value of a conductive filament [6]. For instance, *TF-Cell* [8], *Thermoforming Circuit Board* [9], and *Meltables* [10] apply hot air on the printed surface and manually modify the geometry of printed parts. *Thermorph* [5], *4DMesh* [11], and *A-line* [12] sink printed objects into hot water (>70C) to trigger self-morphing properties in thermo-reactive polymers. On the other hand, *Hotflex* [13] and *Exoform*[14] embed external electronic heaters (copper wire) inside a 3D-printed object to locally produce high temperatures for a shape-changing effect. ShrinkCell [6] and Printed Paper Actuator [15] introduce 3d printed heaters with carbon-based conductive filaments. Furthermore, [6] controls the temperature of a conductive heater by designing and printing a geometry with various cross-section areas.

3 3D PRINTING REUSABLE FUSES AND SWITCHES WITH SELECTIVE HEATING

Heat can also modify non-visible material properties, such as the resistivity of conductive filament, enabling granular control of current flow. The variable resistance change through heat will fabricate a 3D-printed fuse and switch that can be applied to functional prototypes. The copper-based resin filament from *Electrifi* [16] stops conducting when it's above the melting temperature (60C) as the resin expands and stretches the copper chain. It recovers to its initial resistance when the temperature cools down (<50C), and this property can be repeated over time. With its material behavior under different temperatures, we can construct a hybrid material topology with carbon-based conductive filament that heats a copper geometry. Effectively, the heat produced from the carbon filament will trigger the resistance change over copper geometry, opening a wide research possibility for designing and 3D printing switch, relay, transistor and logic gates that can be repetitively used over time. So far, we have tested two topology types, one with isolated circuit – which carbon and copper-based materials have independent power supply, and connected topology (Figure 1.b) which carbon-conductive material is attached to the copper circuit. We have tested both topology with 12V with 50mA current limit and repeated heating and cooling process over 3 times. The experiment requires rigorous systematical study procedure to demonstrate full feasibility of the switch and transistor, yet our primary test shows promising aspect of the 3D printed circuit for future applications such as custom designed switches for game controller and soft-robotic gripper with custom switches and relays for its actuation. Overall, Technical and design finding in this study will contribute to the ultimate vision of 3D printing interactive and functional prototypes.

4 DISCUSSION AND CONCLUSION

The fabrication process of integrating electronic components without the need for a traditional assembly process will make it possible to produce complex, customized, unique prototypes faster, more efficiently and cost-effectively. Thus, research on 3D printing reusable fuses, switches and logical gates with composite polymers are vital to achieving a larger vision of printing embedded circuit for interactive prototypes.

To specify the full applicability of 3D printed fuses and switches, dept technical evaluation and exploration are necessary, such as ampere range, rating, and opening time based on the cross-sectional area of a 3D printed geometry. The topology design has to be further explored to find the optimal patterns for specific base geometry, as identically functioning switches and fuses can be in different shapes.

In Conclusion, this position paper envisions a rapid fabrication process of functional prototypes that can actuate, sense and process data straight from the 3D printer. Research and Development innovation on 3D printing functional objects will allow makers and creators to build and evaluate their ideas with lower cost and risk for a more challenging concept.

5 AUTHOR INFORMATION

Kongpyung (Justin) Moon is a PhD candidate at KAIST, advised by Prof. Andrea Bianchi. His research intersects the Human-Computer-Interaction and digital fabrication for functional prototypes. Particularly, He is interested in additive manufacturing custom-shaped electronics for programming and controlling 3D printed materials. His research goal is to expand the affordance of 3D printed objects, from rapid prototyping complex geometries to functional products with embedded electronics, allowing researchers and designers to fabricate an interactive prototype. As a part of this, he presented "ShrinkCells: Localized and Sequential Shape-Changing Actuation of 3D-Printed Objects via Selective Heating" at UIST 2022 technical paper session.

ACKNOWLEDGMENTS

This research was supported by the 4th BK21 through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(MOE)((NO.4120200913638)

REFERENCES

[1] Martin Schmitz, Mohammadreza Khalilbeigi, Matthias Balwierz, Roman Lissermann, Max Mühlhäuser, and Jürgen Steimle. 2015. Capricate: A Fabrication Pipeline to Design and 3D Print Capacitive Touch Sensors for Interactive Objects. In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15). Association for Computing Machinery, New York, NY, USA, 253–258. https://doi.org/10.1145/2807442.2807503

[2] Jun Gong, Olivia Seow, Cedric Honnet, Jack Forman, and Stefanie Mueller. 2021. MetaSense: Integrating Sensing Capabilities into Mechanical Metamaterial. In The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21). Association for Computing Machinery, New York, NY, USA, 1063–1073. https://doi.org/10.1145/3472749.3474806

[3] Martin Schmitz, Jürgen Steimle, Jochen Huber, Niloofar Dezfuli, and Max Mühlhäuser. 2017. Flexibles: Deformation-Aware 3D-Printed Tangibles for Capacitive Touchscreens. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). Association for Computing Machinery, New York, NY, USA, 1001–1014. https://doi.org/10.1145/3025453.3025663

[4] Byoungkwon An, Ye Tao, Jianzhe Gu, Tingyu Cheng, Xiang 'Anthony' Chen, Xiaoxiao Zhang, Wei Zhao, Youngwook Do, Shigeo Takahashi, Hsiang-Yun Wu, Teng Zhang, and Lining Yao. 2018. Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). Association for Computing Machinery, New York, NY, USA, Paper 260, 1–12. https://doi.org/10.1145/3173574.3173834

[5] Kongpyung (Justin) Moon, Haeun Lee, Jeeeun Kim, and Andrea Bianchi. 2022. ShrinkCells: Localized and Sequential Shape-Changing Actuation of 3D-Printed Objects via Selective Heating. In Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22). Association for Computing Machinery, New York, NY, USA, Article 86, 1–12. https://doi.org/10.1145/3526113.3545670

[6] Alexandra Ion, Robert Kovacs, Oliver S. Schneider, Pedro Lopes, and Patrick Baudisch. 2018. Metamaterial Textures. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). Association for Computing Machinery, New York, NY, USA, Paper 336, 1–12. https://doi.org/10.1145/3173574.3173910

[7] Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch. 2016. Metamaterial Mechanisms. In Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16). Association for Computing Machinery, New York, NY, USA, 529–539. https://doi.org/10.1145/2984511.2984540

[8] Donghyeon Ko, Jee Bin Yim, Yujin Lee, Jaehoon Pyun, and Woohun Lee. 2021. Designing Metamaterial Cells to Enrich Thermoforming 3D Printed Object for Post-Print Modification. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21). Association for Computing Machinery, New York, NY, USA, Article 671, 1–12. https://doi.org/10.1145/3411764.3445229

[9] Freddie Hong, Connor Myant, and David E Boyle. 2021. Thermoformed Circuit Boards: Fabrication of highly conductive freeform 3D printed circuit boards with heat bending. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21). Association for Computing Machinery, New York, NY, USA, Article 669, 1–10. https://doi.org/10.1145/3411764.3445469

[10] Andrew O. Sageman-Furnas, Nobuyuki Umetani, and Ryan Schmidt. 2015. Meltables: fabrication of complex 3D curves by melting. In SIGGRAPH Asia 2015 Technical Briefs (SA '15). Association for Computing Machinery, New York, NY, USA, Article 14, 1–4. https://doi.org/10.1145/2820903.2820915

[11] Guanyun Wang, Humphrey Yang, Zeyu Yan, Nurcan Gecer Ulu, Ye Tao, Jianzhe Gu, Levent Burak Kara, and Lining Yao. 2018. 4DMesh: 4D Printing Morphing Non-Developable Mesh Surfaces. In Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18). Association for Computing Machinery, New York, NY, USA, 623–635. https://doi.org/10.1145/3242587.3242625

[12] Guanyun Wang, Ye Tao, Ozguc Bertug Capunaman, Humphrey Yang, and Lining Yao. 2019. A-line: 4D Printing Morphing Linear Composite Structures. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19). Association for Computing Machinery, New York, NY, USA, Paper 426, 1–12. https://doi.org/10.1145/3290605.3300656

[13] Daniel Groeger, Elena Chong Loo, and Jürgen Steimle. 2016. HotFlex: Post-print Customization of 3D Prints Using Embedded State Change. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). Association for Computing Machinery, New York, NY, USA, 420–432. https://doi.org/10.1145/2858036.2858191

[14] Fang Qin, Huai-Yu Cheng, Rachel Sneeringer, Maria Vlachostergiou, Sampada Acharya, Haolin Liu, Carmel Majidi, Mohammad Islam, and Lining Yao. 2021. ExoForm: Shape Memory and Self-Fusing Semi-Rigid Wearables. In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (CHI EA '21). Association for Computing Machinery, New York, NY, USA, Article 249, 1–8. https://doi.org/10.1145/3411763.3451818

[15] Guanyun Wang, Tingyu Cheng, Youngwook Do, Humphrey Yang, Ye Tao, Jianzhe Gu, Byoungkwon An, and Lining Yao. 2018. Printed Paper Actuator: A Low-cost Reversible Actuation and Sensing Method for Shape Changing Interfaces. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). Association for Computing Machinery, New York, NY, USA, Paper 569, 1–12. https://doi.org/10.1145/3173574.3174143

[16] Multi3D. 2022. Electrif Conductive Filament. https://www.multi3dllc.com/product/electrif/

[17] Williams, N.X., Bullard, G., Brooke, N. *et al.* Printable and recyclable carbon electronics using crystalline nanocellulose dielectrics. *Nat Electron* **4**, 261–268 (2021). https://doi.org/10.1038/s41928-021-00574-0

[18] Martin Nisser, Christina Chen Liao, Yuchen Chai, Aradhana Adhikari, Steve Hodges, and Stefanie Mueller. 2021. LaserFactory: A Laser Cutter-based Electromechanical Assembly and Fabrication Platform to Make Functional Devices & Robots. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21). Association for Computing Machinery, New York, NY, USA, Article 663, 1–15. https://doi.org/10.1145/3411764.3445692