論 文 の 内 容 の 要 旨

論文題目

Study on Functional Design of Printable Electronic Circuits and Mechanical Devices

(印刷可能な電子回路および機械部品の機能設計に関する研究)

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Digital fabrication has enabled the democratization of manufacturing on a large scale. The fact that powerful fabrication tools such as 3D printers, laser cutters, and inkjet printers are placed into the hands of end-users makes it possible for anyone to design, customize and fabricate almost anything. The digital fabrication which can be considered as a process of fabrication personification has opened a whole new range of possibilities. Especially, users such as small companies, hobbyists, and researchers have been taking advantage of these tools to accelerate the design to production iteration.

However, whether it is an addictive or subtractive manufacturing process, the current digital fabrication tools are only focusing on the morphing of the object. How to fabricate a fully functional object is still questionable to researchers in many different fields. The integration of actuation and sensor components into those printed objects has not been fully explored yet. Without these input and output channels, the product of the digital fabrication process will be limited to being a static model. Adding active components to the fabricated object will enhance its functionality as well as its interaction with end-users. Adding these components in a single process with the morphing process will further revolutionize the impact of digital fabrication on making stuff, and magnify its adoption among a broader range of user base.

This dissertation will focus on reporting our exploration in the use of a variety of functional inks, including sintering-free silver nano-particle ink and ultra-violet (UV) cured resin, to embed rich featured functionality into printed objects. We will go from the 2D printing of electronic circuits with silver nano-particle ink, through 3D printing with the integration of electronic circuits in a single pass, to the printing of a frictional anisotropic surface to fabricate soft-bodied robots.

In the 2D printing of electronic circuits using silver nano-particle ink, we proposed and developed a Traveling Salesman Problem based auto-router to evenly distribute electric current to multiple light-emitting diodes (LEDs) wired by conductive ink printed traces. The problem of lighting up a bunch of LEDs is more troubling than it sounds. The intrinsic resistance of silver nano-particle ink makes it much more difficult to balance the brightness of all LEDs, even with an electronic circuits design expert. Our auto-router helps to automatically generate the conductive patterns to wire multiple LEDs, average their brightness without any additional resistors.

Moving from 2D to 3D printing, we challenged the problem of fabricating and integrating electronic circuits in 3D printed objects. We first realized the fabrication of double-sided electronic circuits with silver nano-particle ink on double-sided photo papers. The interconnections between two layers are attained by making via-holes with felting needles. The next step in the 3D printing field is to integrate electronic circuits into 3D printed objects in a single process. We combined the laminated object manufacturing (LOM) technique with our silver nano-particle ink inkjet printed electronic circuits to achieve this goal. Before printing, the 3D model will be sliced into multiple layers in the design software. Embedded electronic circuits are decomposed and printed on paper with silver nano-particle ink. By stacking these papers one-by-one, we fulfilled the goal of integrating electronic circuits into 3D printed objects.

Stepping on top of these building blocks, we explored the print-ability of sensors and actuators for rapid prototyping soft-bodied robots with an all-printed paper caterpillar robot (Paper Caterpillar) as an example. Our Paper Caterpillar consists of a plastic film with silver nano-particle ink printed heater on top of it. As the plastic film is a multiple layers structure, when heated up by the printed heater, the difference in the coefficient of thermal expansion of each layer makes the whole structure bend. By controlling the on-off of this heater, we are able to make it crawl forward. The bending of the plastic film will induce a change in the resistance of the printed heater, and we can use this change as a feedback of the bending angle. Thus, our robot is able to detect the alternation of its surrounding environment and switch its locomotion gaits to best fit the change of the environment.

In addition to printing electronic circuits, we also studied the fabrication of soft-bodied robots with different mechanical properties materials. Being inspired by the scales on the skin of a snake, we proposed a designing scheme to achieve an all-printed wriggle soft-bodied robot by computationally patterning high and low friction material to the ventral side of the robot. This patterning creates a frictional anisotropy underneath the robot. When generating a traveling wave along the body of the robot, we are able to make it undulate forward.

Going from 2D, through 3D, and approaching robotic printing, we are aiming at lifting the difficulty of digital fabrication along with amplifying the functionality of the fabricated objects. We take this chance to vision a future where a user can easily print a fully functional object in just a single process. It is the future where anyone can make almost anything, and that thing is not only standing statically but actively interacting with the surrounding environment and humans.