Hybrid Fabrication of Physicalizations

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Abstract
Historically, visualizations have been manually constructed and designed by graphic designers, facilitating some of the cognitive benefits of constructive visualizations. Today, researchers are investigating how digital fabrication techniques can allow people to quickly yet expressively author digitally-designed objects. This workshop paper discusses an application of *hybrid fabrication* – systems where a human and a computer collaborate to author a physical artifact – to the creation of *physicalizations*. We believe that hybrid fabrication of physicalizations can offer opportunities for reflection-in-action around datasets, while still resulting in an accurate physical representation of data.

Author Keywords
Physicalization; Reflection-in-Action; Fabrication.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

Introduction
Physical representations of data (or, *physicalizations*) are an accessible mode of data representation that leverages people's multi-sensory interactions with objects to provoke reflection on data. However,

another way that physicalizations provoke reflection on a dataset is through participation in constructing physicalizations[3]. People perform "reflection-in-action" [5] as they create a physical prototype of a visualization, building deeper intuition about the data itself.

In practice, manually creating physicalizations still has its weaknesses – humans are not efficient at accurately translating abstract data into a physical representation. As a result, Information Visualization and Human-Computer Interaction researchers have proposed tools to facilitate the creation of Physicalization. This has led to tools that automate (e.g., [4]) or assist (e.g., [7]) the process of generating digital designs for physicalizations, that are then created using digital fabrication machines. However, this automated design tools prevent people from more actively participating in actual constructing the physicalization.

Recently, HCI researchers have begun to explore the grey area between manual and automated fabrication techniques. In a *hybrid fabrication* system, both a human and a machine participate in creating a physical object. This leverages the strengths of computer-controlled fabrication (producing accurate geometry), while the human participation introduces interpretive flexibility or replaces the need for complex control. By leveraging the strengths of both manual and computer-controlled fabrication, HCI researchers have created hybrid systems that result in more creative output[2], expressive iterative prototyping[10] and computer-assistance for hand tools[1,6].

In the context of constructing physicalizations, hybrid fabrication presents an opportunity to reintroduce reflection-in-action into the practice of authoring data-driven artifacts. In a hybrid system, the computational side can handle complex datasets and produce accurate geometry; the human, meanwhile, can be invited to participate in authoring features at critical opportunities for reflection-in-action around the data itself.

Examples

In the following section, we discuss two physicalizations that could be created using hybrid fabrication techniques discussed in past work.

3D Doodled Water Globe

Instead of having a 3D printer handle all object creation, or having a human follow instructions manually[2], a human could take turns with a machine, manually adding to a physicalization as needed. For example, a 3D printer could produce the bulk of a data sculpture, while indicating where to add your own ornamentation. This is similar to the approach where a machine might go back to 'repair' or add on to an existing plastic structure [8], except that a human is able to communicate their intent during the 'repair' instead of precisely-defined and machine-executed geometry.

For example, a geography instructor could bring a set of small 3D printed globes into their class. Pairs of students would receive one of these globes, a 3D Doodler, and a projection system that could track the position and orientation of the globe, and project instructions on exactly where to 'build' data using the 3D Doodler. Using the 3D Doodler, students could add plastic filament to the existing physicalization to represent the amount of water usage per capita in different countries. The 3D Doodler could also track (or limit) how much filament it has extruded, allowing the quantity of material to be more tightly paired with the underlying dataset.

'Pen Pal' Wall
A classroom of 5th grade students in Canada has a "sister" classroom in Japan; each student has a corresponding 'pen pal' in the other country to whom they write emails as part of a cultural exchange. The teachers of the two classes decided to create physicalizations in each location to represent the 'pen pals' in the remote classroom. The teachers take photographs of each student, and generate a dataset of 'silhouettes'. Using Shaper[11], each student takes their turn, tracing their pen pal's shape along the wall. Each time their pen pal sends a letter, the student can continue to 'edit' the wall using augmented physical tools[6] to create a sequence of holes that represent the length of the letter. While the final physicalization is relatively anonymous, the student will have participated in creating and adding the data associated with their pen pal. This helps them identify the silhouette and datasets that are relevant to them in the midst of an otherwise ambiguous physicalization.

Discussion
There are several common threads present in these examples:

Balancing Turn Taking
In the above examples, the human and the machine take turns in creating the physicalization. However, this interaction needs to be balanced such that the human cognitively engages in the task. If a human views their job as "babysitting" the machine, then a fully-automated process would be better than a hybrid fabrication approach. With careful interaction design, the human should feel as though the machine is a helpful scaffold for them to learn how to create a physicalization[9].

Tracking Human Involvement
While the machine and the human take turns in 'editing' the object, the machine must continuously tracking the human's involvement and actions. This allows the machine to know where and how it should intervene in creating the physicalization. The machine can also check the accuracy of the human's actions against the data itself.

Data Experiences in Fabrication
Hybrid fabrication of physicalizations offer targeted moments for people to reflect on data, as it is being authored in the physicalization. HCI researchers have an opportunity to craft more interactive data experiences that are situated in the overall task of hybrid fabrication. For example, a system that is aware of the human's 3D Doodling on the Water Globe could present more detailed information about the water consumption in the particular region of the world where filament is being added.

One Machine, Multiple Humans
Hybrid Fabrication is not necessarily limited to operation by a single human; a group of people can participate in creating a physicalization (such as in the 'Pen Pal' Wall example). The machine can help coordinate the efforts of individual people, ensure that the group is consistent in how data is represented and ensure the overall accuracy of the physicalization. This results in a physicalization where each individual participated reflection-in-action on the specific data

points that they helped construct. The act of creation would help them recognize the data points that they played a role in creating, while maintaining relative anonymity for the data points that they did not construct themselves.

About the Participant

Lora Oehlberg is an assistant professor in Computer Science at the University of Calgary, and a member of the Interactions Lab (iLab). Her research focuses on technologies that support collaboration and creativity, particularly in the context of fabrication and product design. She completed a PostDoc at INRIA-Saclay, and has a PhD in Mechanical Engineering from the University of California, Berkeley. She has published in the Human-Computer Interaction research community, as well as at Engineering Design research venues.

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