Data-Things: Digital Fabrication Situated within Participatory Data Translation Activities

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ABSTRACT
This paper explores a design-led approach to digital fabrication which situates it in participatory data translation activities to demonstrate that this technology can find application beyond its use as tool for manufacture. We present two contrasting design contexts in which, respectively, data from conference twitter conversations and craft practitioners' movements are translated into interactively generated and fabricated physical artefacts. We argue that direct involvement in such digital fabrication activities can help people invest meaning into artefacts and facilitate social interaction and reflection upon their activities, while encouraging practitioners to incorporate new forms into their own work. On this basis, we reconsider digital fabrication within data translation activities as situated along an extended 'trajectory of use' in which reflective, meaningful 'data-things' can be created.

Author Keywords
Digital fabrication; 3D printing; research through design; data materialisation; data translation; making; craft

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

INTRODUCTION
Digital fabrication is a widely researched topic in the HCI community with areas focusing on FabLabs [2, 18], DIY maker culture [9, 23], personal fabrication in the home [6, 13] and as interactive tools [15, 25]. More recently, research has also started to explore more varied perspectives on the role of digital fabrication in HCI [14]. Notably, a research area has opened out exploring the possibilities and values of digital fabrication situated within interactive making activities in different settings.

For example, Ogawa et al. [17] have studied what they call *Social Fabrication*, a shared experience of digital fabrication. They suggest two essential elements for realising it, (a) the "setting of a proper frame and topic and motivation" and (b) "a way to illustrate both individual and collective perspectives" [17, p.58]. Relatedly, Nissen et al. [16] studied a shared souvenir making activity where digital fabrication technologies were used to make a variety of artefacts representing individual and collective views on an art exhibition. The shared fabrication activity facilitated conversation and reflection concerning the exhibition and engendered curiosity in the fabrication technologies themselves. This work points to the value of embedding digital fabrication into a visitor's trajectory through the exhibition as not just a means for the making of souvenirs but for enriching the whole experience of the visit.

In contrast to these public settings, a domestic context is studied by Khot et al. with their *SweatAtoms* [8] – a system for situated digital fabrication in people's homes, allowing them to personally generate "material representations" [8, p.3835] of different aspects of their physical activity. With their more personal approach to fabrication and physical data representations the authors suggest that there is an opportunity for design researchers "to print things from data" [8, p.3843] to incorporate digital fabrication in their HCI design and research practices. This area of context specific, situated digital fabrication opens up a new design space to investigate digital fabrication situated in other contexts and experiences that have not yet been explored.

The current paper extends this emerging concern to study digital fabrication as a process embedded within social activities. While it is valuable to gain practical insight into the applicability and utility of digital fabrication technologies across many different contexts, Nissen et al. make a more radical argument for embedding fabrication within shared activities. By making fabrication a shared process, it is possible for participants to invest meaning in artefacts which they might not do if confronted with something mass-produced. It is not just that the artefact can be personally tailored. Participating in making creates a richer view on the skills and know-how involved in making, the technologies used, their rationales and any research issues surrounding them, as well as providing an occasion for conversation and reflection on the context in which the making is done. Following Ingold [7], Nissen et al. argue that artefacts made this way take on the character of 'things' connected to their circumstances of making, rather than alien 'objects' created by mysterious processes. While it has long been a value expressed by those who practice

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participatory design (see Ehn's classic formulation in [3]) it is only recently that researchers [16, 17] have pointed to the value of participation in digital fabrication.

We wish to further this concern for making digital fabrication a visible, accountable process potentially open to participation. In particular, we wish to explore settings which foreground the translation, into digitally fabricated form, of data of personal significance. It is a commonplace observation that much contemporary everyday activity yields data which can be captured and analysed, whether these data be the content of social media postings or the measurements given by a personal health monitor. Increasingly, we hear of the so-called 'quantified self' [19] or 'personal informatics' [12] to encapsulate this phenomenon. The critical examination of this trend and topics such as what we mean by the very idea of data lie beyond the current paper. Instead, we wish to see how our interest in shared fabrication processes can open out new possibilities for the experience of personally relevant data – data relevant to an activity or skill which is currently engaging the participants.

In this paper, we present two cases where we have created participatory fabrication activities so as to explore how they impact differentially on our design concerns and research interests. They contrast in various ways, deliberately, so that we can begin to investigate the broad application and implications of our approach. In one, we situate digital fabrication within a public setting, a conference. In the other, we study a craft which is typically practiced in intimate, domestic settings, crochet. At the conference, we conducted a short-term study with many participants, while our work with craft practitioners is a much more extended relationship with a few. At the conference, we worked 'in the wild' in the broader conference setting which did not principally concern digital fabrication, while the craft practitioners' engagement with us was much more focused, driven in part by a mutual interest in craft skills. At the conference, we experimented with translations based on data sources which are already public, while with the craft practitioners we used techniques to elicit data related to the execution of their craft. While these studies differ in terms of setting, time-frame, scale, focus, mutual interest and data provenance, we have approached both with a concern to make our digital fabrication practices open and accountable so as to explore the meanings people invest, discover or create in things and data. We conclude this paper with a comparative account of these contrasting contexts, especially noting where we have been less successful, to help us develop some concepts which might guide future investigations in the HCI community of data translation within participatory fabrication activities.

CONFERENCE TWEET TRANSLATIONS

Context and Study

This first case study took place at a national conference about future digital technologies called *Thinking Digital.* The event encouraged us to situate a digital fabrication activity within its programme. The attendees are a small but very involved community which every year engages with one another and the organisers who are an integral part of this community. In particular, discussions and conversations are broadcast via Twitter through an often trending hashtag #tdc14. After investigating twitter data from the previous year's conference, we decided to explore how online social interactions could be translated into physical forms to engage attendees in offline conversations.

For this purpose we developed an algorithmic design system that would translate overall conference and individual tweets into wearable artefacts that might resource attendees' interactions with one another. In order to be suitably engaging for the technology savvy audience, we decided to use a 3D printer. These decisions guided our design as we needed to take into account constraints such as fabrication duration and transportability [cf. 16]. After initial explorations of different techniques for tweet data translation, we decided on a wearable 'clip' shape. This depicted the timeline of tweet behavior over the course of 24 hours. The number of tweets per hour was computed and 'graphed' as a pair of 'ridges', for all conference tweets (bottom) and the individual's (middle). For example, the shape in Fig.1a shows the tweet activity of the 24 hours prior to midday of the second conference day. The collective tweets (bottom) with the most current amount of tweets on the left and going back in time towards the right. A spike of tweets can be seen in the morning session with minimal amounts of tweets during the night falling off after the previous evening's activity. In comparison, this individual's tweets (middle) show their tweet behaviour aligning with the evening and morning activity but showing more individual activity during the night. Using the Twitter API, we collected all hashtagged tweets throughout the conference in real time using a custom script in Processing (www.processing.org) which algorithmically generated 3D models (Fig.1b) when a Twitter handle was entered.

Figure 1 (a) Fabricated physical shapes (b) digitally generated

At the start of the conference, we introduced the project on-stage to encourage attendees to visit our fabrication stand in the hall of the conference venue (Fig. 2). We wished to make shape generation and fabrication as transparent as possible. However, it was clear that attendees would have limited time to engage with these activities. We therefore focused on keeping the process fairly simple for

participants. Upon entering their Twitter handle, their shape was digitally generated on screen and discussed before being printed on the 3D Printer. Participants were invited to watch and engage with the printing process for their shape or optionally return to collect it later.

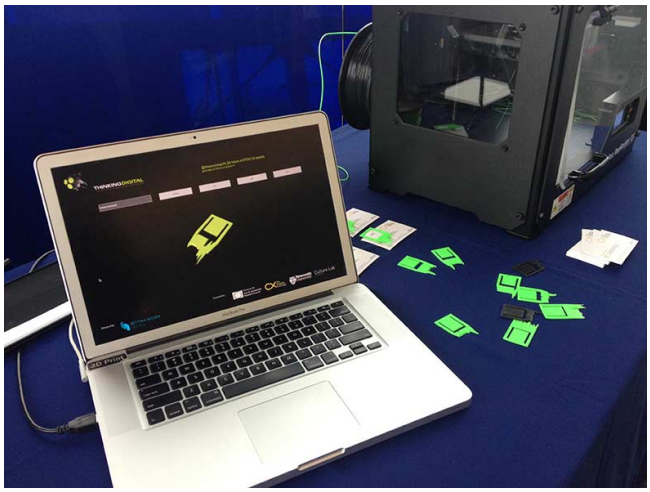

Figure 2: Fabrication stand with Makerbot and software

Observations

Over the course of the two-day conference, 24 people participated from diverse backgrounds – from computer programmers and business people to creative workers and cultural organisation representatives. We recorded each participant's engagement with the fabrication activity alongside informal conversations with attendees and participants. We took field notes and other forms of ad hoc observation. Overall the idea of generating a personalised shape from one's tweets was positively received with a surprisingly large amount of interest by the attendees, both online (via hashtag) and offline (attendee visits). Unpacking this general positive reaction, we analyse a number of features of interest.

Use, Value and Behaviour

When their shapes were generated and fabricated, the majority of participants were very enthusiastic about their shape, with one of the participant spontaneously hugging one of the researchers in excitement. With only four participants not returning for their shapes, the overall response was positive. The participants were predominantly eager to generate their shapes and equally interested in the 3D printing process. We found several ways the artefacts were worn throughout the conference, most commonly on conference badges, straps, jackets or shirts (see Fig.3).

Interestingly, a couple of participants altered their tweet behaviour to explore how this would effect their shape. One attendee who was not happy with his initial digital shape when it was previewed on-screen came back after having tweeted more to see if his shape expressed his engagement with the conference better before printing it out. Another attendee was very keen to have his shape printed but when generating a shape it visibly transpired that he hadn't tweeted about the conference which was a prerequisite for any shape to be created. He then went back to the conference, tweeted more, and returned to create his shape. In these cases the digitally printed artefact encouraged reflection and certain behavior changes.

Figure 3: Uses of tweet translations

Another attendee who received her shape later at the closing party was very excited about her artefact and tweeted: "3D printed Twitter badge selfie!! Thanks @bettinanissen #eyespoppingoutofheadwithexcitement" (Fig. 4a). Apart from the enthusiasm for the personalised shapes, we have hints that the artefacts might also have longer-term value. Receiving additional tweets after the event thanking us for the shapes and experience suggests the value of the personal artefact post-event, e.g. one example included a picture of the shape attached to the company's business logo (Fig. 4b): "Our awesome (and unique) 3d printed clip is now installed on our documentation. Thanks @bettinanissen".

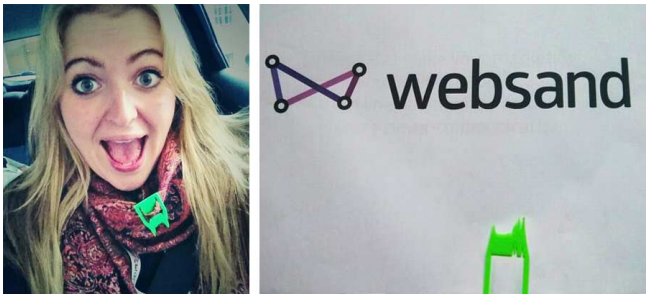

Figure 4: Translations (a) in a selfie and (b) on a business logo

Initiating Conversation

Throughout the later part of the conference and especially at the conference dinner we observed several people comparing their shapes with one another, for example while waiting for food or coffee. Such uses of the shape are many and varied. One attendee stated "I'm not very good at talking to people at conferences if I don't know anyone but this [shape] gave me something to talk to people about and start a conversation." Other conversations involve people comparing their shapes and reasoning about differences and, through this, potentially making new contacts.

When we asked two attendees who were comparing their shapes (Fig. 5a) what they were looking to discover, they humorously replied that they were trying to find out if they are "tweet soulmates" with their tweeting habits becoming aligned over the course of the conference.

Reflection and Imagination

Beyond the artefacts starting conversations amongst attendees, they also encouraged people to interpret their shape in their own way and reflect upon their activities at the conference and how they had been translated into physical form. One participant, when asked if people talked to him about his shape, replied that "everyone did and wanted to know what it is". He then went into a fairly detailed description of how he explained it to people interpreting the shape as his "embodied tweets about technology, innovation, beer and cake" while jokingly pointing at different spikes of his tweet translation with cake being the biggest spike "because he loves cake".

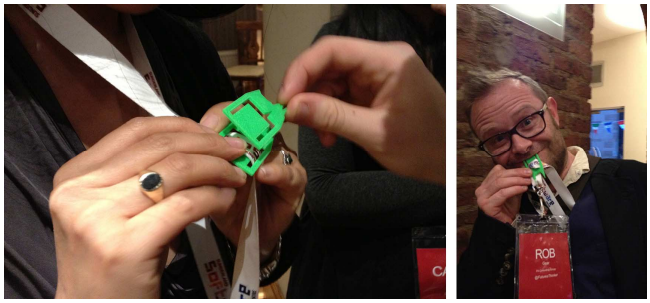

Figure 5 (a) Comparison of translations and (b) showing fangs

The shapes often elicited imaginative associations from participants, particularly when they first encountered them: for example "it looks like a cathedral" or it resembled teeth or fangs, which was acted out by the participant playfully (Fig. 5b). One participant described the artefact as "unique fingerprint" comparing it to personalised tangible encryption keys. In all these ways, the tweet translation was a resource for varied responses from reflection on people's behavior to imaginative responses to the shape and possibilities for its use. While the generated shapes needed initial explanation of their relation to tweet data, they allowed participants to tell their own stories to give them meaning. As one participant emphasised: "It's good that it's abstract so you can make up your own interpretation".

Limitations and Challenges

Although digital fabrication has been extensively explored in HCI research, several of the tech-savvy conference attendees had not seen a 3D printer in action. This made it difficult to differentiate participants' experiences of the data translation activity from the novelty effect of the technology. However, we believe both aspects add value to the overall making experience. This was confirmed by participants who were acquainted with digital fabrication technology and still interested in the personal tweet translations, the processes of making them as well as the artefacts themselves. For other participants, the broader implications of our work were a key to their appreciation. One attendee tweeted "Love crossover from virtual to craft." showing how seemingly separated digital content and physical making could be integrated through a participatory data translation activity in a craft-like way.

However, being situated within a fairly tightly scheduled conference program, the forms of participation we could develop were limited. Our algorithmic fabrication technique, while it still encouraged people to dwell and engage, was mindful of the need for rapid response during break times so that a number of people would get the chance to participate. This did not allow us to explore how people might engage with and invest meaning into digitally fabricated artefacts when their involvement with making is more prolonged. To discuss the relationship between data, physical artefact and fabrication in more depth, we initiated a much longer-term study..

CRAFT MOVEMENT TRANSLATIONS

Context and Study

For this study, we worked with a small group of 4-6 local crochet practitioners with varied skill levels (beginner, intermediate, professional) over a longer period of time. This gave us the opportunity to take a more iterative and dialogical approach to design exploration than in the previous case study. We could explore different ways of engaging the participants with their data and develop different data translations and activities.

Initial Workshop

In an initial workshop we encouraged the participants to discuss their experiences and thoughts about their practice while encouraging them to simply crochet the way they usually would during their weekly meet-ups (Fig. 6a). The main topics of the conversations were the importance of the crochet hook, its shape, size and the materials it is made of, the difficulty in understanding the 'flow' or tension of the wool and reasons for their preference of crochet over other crafts such as knitting, describing crochet as easy to learn, addictive, productive, meditative, colourful, creative, sculptural and giving a sense of achievement.

Figure 6: (a) The workshop setting and (b) the sensor hook

While the participants shared their experience and thoughts about their practice with us, we additionally captured some initial data from their movements through a sensor attached to the back of a crochet hook (Fig. 6b). To make this process as noninvasive as possible, we used a small wireless movement sensor, WAX9 (www.axivity.com), to record accelerometer and gyroscope data in real-time while the participants were crocheting. We initially asked them to each crochet a basic pattern in order to capture comparable data that we could then explore for potential data translations.

Data Translation Workshops

For the next workshop, we chose to translate the captured movements by combining the data into 3D coordinates to form path-like patterns. Again, generated by a custom Processing script, this translation showed each participant's unique crochet movements as an abstract form (Fig.7).

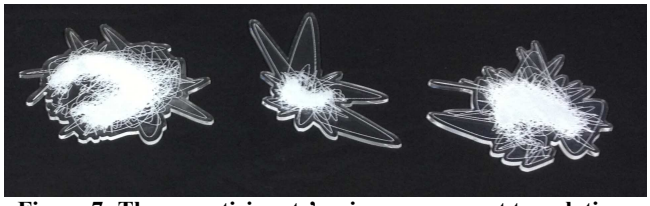

Figure 7: Three participants' unique movement translations

These digital translations were then translated again into physical forms by laser engraving and cutting a variety of materials. Additionally the digital patterns were translated into an extruded 3D model via a heatmap script and 3D printed. We used a range of materials: card, fabric, perspex and wood (Fig. 8). This was due to our growing awareness of the importance of the tactile experience of different materials to the crochet practitioners. Alongside the laser cut translations, we also added print outs of the same paths to see if this would elicit a different reaction. In the workshop we then presented these materials (Fig.9) without the crochet practitioners knowing how the shapes were generated and also unidentified so that they didn't know which shape was associated with which person. In this way, we sought to encourage discussion about the shapes, their techniques and the relations between them. We then revealed whose shape was whose and were more active in explaining and sharing the process with the participants, including showing them the sketch that generated the form amongst other graph-like representations of their data.

Figure 8: One participant's translations in different materials

For the next iteration, we took on board participants' feedback from the first workshop. In particular, there was a strong desire to see the shapes being generated live, to "see how it works". This was responded to by developing the initial path generation script further so as to be able to stream real-time data from the sensor on the crochet hook directly to a path being generated on screen. Other uncertainty that was expressed (such as "why doesn't it look more like crochet?") was responded to by developing a new translation design with the intention to show the data more recognisably as stitches or rhythm. For this purpose we translated the x, y and z components of the data into three separate, concentric radials (Fig. 10). For example, the left radial shape shows fairly steady movements of one participant with only minor outliers compared to the more varied movements of another participant on the right resulting in a more jagged shape.

Figure 9: (a) Different materials in the first workshop and (b) comparing translations in the second

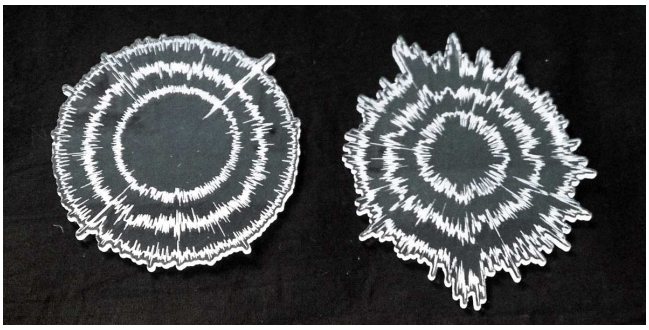

Figure 10: Radial translations for second workshop

During this workshop we started by discussing the old and new shapes that were made before introducing the interactive data path generator. Initially, we got them to crochet with the sensor-augmented hook blind (Fig.11a) so that only the other participants could see the shape being generated while the practitioner was focusing on their craft. We then let them go through the same process again but with the shape being generated visibly on screen. We then compared and discussed both shapes and encouraged them to choose a shape that we would laser cut together.

Figure 11: (a) The interactive shape generation system in action (b) a personalised laser cut shape

The second part of this workshop took place in our lab's machine room where we showed, explained and used the laser cutter (Fig.12) to cut the personalised shapes while

giving participants the possibility to make changes, add holes for potential use, or scale to a size they liked (Fig.11b). After all the shapes were cut, we closed the workshop with a discussion about the process of generating and fabricating their shapes. These workshops were all documented via audio and video recordings which were transcribed for analysis alongside the researchers' field notes and observations.

Figure 12: Laser cutting the shapes

Observations

Reflective Conversations

Throughout all the workshops with the crochet practitioners, we found that extensive discussions took place about different crochet techniques, encouraged by the shape of the artefacts and comparisons between them. For example, one of the participants observed: "I think this is mine because it is quite dense" describing her movements as quite jerky. Similarly one of the participants suggested, pointing at a more curved shape, "maybe this could be yours because you twist more". This reasoning, comparison and sharing of shapes was a common feature in both workshops and highlights how these shapes encouraged associations and reflection on their crochet techniques.

In other cases, the conversations about crochet techniques and how a person handles their crochet hook were taken as suggestive of the participant's personality. The attendees to one workshop reasoned that one shape must belong to a person who could not attend because her movements are more exaggerated and "that's the personality that she is". While in other conversations a participant said "I hope this is mine" because she liked the particular shape it made admiring its neat and symmetrical form.

Aided by the controlled workshop setting and the directly comparable multiple objects, this reasoning and comparison work was very noticeable with participants potentially seeing a close, valuable relationship between the data artefacts and themselves due to the embodied connection between the data and their craft practice. As one of the participants reflected on her shape after the first workshop: "Its form is very concentrated and made me think about how I perform craft activities. I have often thought that I am a bit clumsy and imprecise when I am working but that showed me that I can be quite meticulous and pay attention to detail". This shows how the artefact encouraged the craft practitioners to think about their craft practice in a different way. Another participant noted: "I was thinking about my crochet, I do keep my hands quite still and quite close and that's maybe why it [the shape] is kind of quite narrow". In all these ways, our data translations provided an occasion for the practitioners to reflect on and compare their different ways of doing their craft.

Making Meaning Through Association

Throughout the workshops numerous associations were made between the generated shapes and more familiar forms. For example, the radial shapes were associated with flowers or poppies, the live generated shapes were compared to airplanes, comets, fish, bees or a "cocoon made by a drunk caterpillar" (Fig.13b). It is important to note how such associations are used in conversations between our participants. The shape associations were related to the participants' craft practices in a number of interesting and consequential ways. For instance, a shape taken to look like a flower was considered as the basis for the design of a brooch. In other cases, these associations compactly summarised various features of the data, such as densities, repeated patterns, curves and outliers. For example the association to a bee has a clear distinction between a dense body and the less dense curved wings (Fig. 13a). One participant reflected on this process being interesting because "you could see which bits were the dense bits and which bits were the bits where you are moving around a bit more".

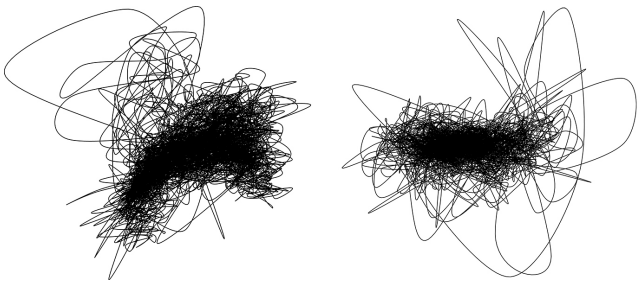

Figure 13: Shape associations (a) a "bee" and (b) "cocoon made by a drunk caterpillar"

Use, Value and Meaning

Our participants were not confined to these associations of generated shapes and familiar forms. For one of the crochet practitioners: "I like that it visualises a tradition". She characterised the artefact as being "written in secret crochet code" which, for her, signified her "struggling and (more or less) succeeding to learn a skill I'd always admired and associated with my granny and mum". In this way, the artefact enables her to link up a tradition, her own remembrance of her family, and her current struggles. She reported that she had taken one of the data translations and "placed [it] on my mantelpiece for me to feel proud of " (see Fig.14b), a site one can interpret as a special place in her home. Another participant placed her 3D print in her

studio after showing it to her family saying that she finds the print and the idea of 3D printing "inspirational".

Figure 14 (a) 'trying on' the shapes and (b) on the mantelpiece

This shows an interest in the shapes as themselves having a potential value *in and for her practice*, perhaps in terms of future developments of it. "I have my piece of 3D printing on the shelf in my studio. […] I got to show people at the studio especially during the Art Tour and people were interested in the idea of transferring movement into a sculpture." Different uses of the artefacts were explored, such as coasters, badges or hair clips. "They would look great on a jacket with the colour coming through." Others thought of ways to embellish their shape: "I like to put flowers on mine". The relative abstraction of the shapes, without any particular pre-determined use, enabled the participants to meaningfully appropriate their shapes and sparked their creativity. Taken together, these examples suggest an emerging recognition that *our craft* (data translation) might come to have a role in theirs (crochet and allied practices) either reminding participants of their proud embeddedness within a tradition or in terms of providing inspiration or actual materials which might be of practical use – a point we will shortly return to.

The (Dis)entanglement of Fabrication

In our later workshop, we involved our crochet practitioners end to end in the fabrication process from data capture through visualisations to the creation of laser cut shapes. One of the participants stated that they "liked having input into how they [the shapes] were made […] and seeing the different aspects of it". And when asked about how that compared to just receiving their shapes the previous time, a participant said it was good "going through the whole process of seeing it happening, seeing the difference, how it looked on screen, deciding and then printing [laser cutting]". With these comments the participants clearly stated the value of their involvement not only in the fabrication process but also in data capture and shape generation, "so it feels like it kind of has more meaning" than in the previous workshop where shapes were presented without the crochet practitioners being involved in their creation beyond being the source of the data. This shows that the more concerted involvement of participants with the capture of their own data and first hand acquaintance with the steps involved in digital fabrication not only encourages reflection and conversation but allows for meaningful engagement. One participant commented that through fabricating the shapes "it was more real for me" which other participants agreed to.

Extending the Craft and Reciprocity

Seeing the shape generated on screen while crocheting clearly influenced the participants' way of crocheting by either looking to see what the shape looked like or by slowing down to see what happens. One participant even stopped to just move the hook around to see how the shape responded to her movements. This showed that the participants were very keen to understand how the data and its translation related to their movements. Indeed, one participant wanted to try to perform what she called "interpretative crochet" in a joking reference to 'interpretative dance', where she influenced the generated shape by the way she crocheted rather than vice versa.

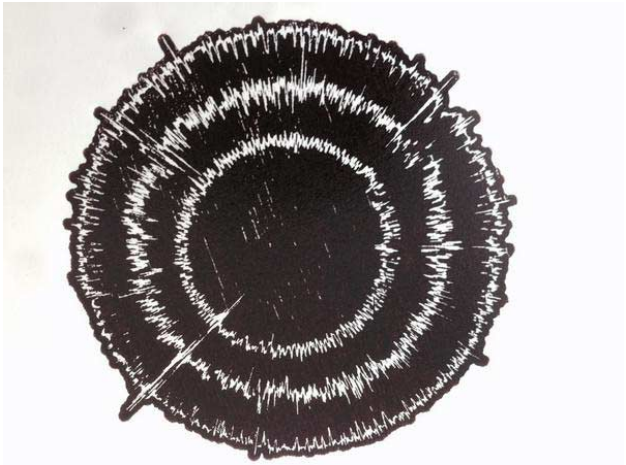

Figure 15: Woodcut printed shape

With these examples, we can already see how the practitioners were beginning to become more engaged in the overall activity of data capture, translation and fabrication, and started to explore possibilities in their own interpretative ways. While this was initially done to better understand how the data translation occurred, our practitioners' curiosity has developed further with one participant developing an idea during the second workshop to use one of the laser engraved shapes for woodcut printing in her artwork. As we didn't have enough time to laser cut a new personalised shape in this workshop, she took one of the pre-fabricated radial ones with her and posted a picture of the woodcut print on Twitter only a few hours later: "Print of a digital crochet engraving" (Fig. 15). As an artist she works with different printing techniques and had her own materials ready to hand to test this.

This example further emphasises a point suggested earlier. As our work with the crochet practitioners unfolded and they became progressively more aware of, and participated in, the making of their data translations, there is a shift from the researchers' interest in exploring the participants craft practice to, equally, the participants exploring the researchers' practice to use this as inspiration in their own work. This *mutual reciprocity of practices* was a surprising

development within the project and was in part enabled by the longer-term engagement we had with the participants. Importantly, it was also clear that, as design researchers, we were displaying aesthetic choices and creative judgments in our own work and the character of these and their rationale became, naturally, matters of curiosity for the participants. This relationship between craft and research practitioner developed through mutual interest in the other's practice and attests to the engaging aspects of the data translation activities we devised. It also shows an extensibility of craft practice in creative ways that has potential to combine new digital technologies with traditional art and craft practices.

DISCUSSION: JOINING THE THREADS

Working in two specific contexts we have explored new ways for situating digital fabrication within data translation activities to enrich reflection and interaction. Let us now draw on the findings of both projects and compare the two contexts and our experiences in them so as to formulate some design concepts which might help shape future research on situated participatory fabrication. It is in these concepts, exemplified by the work reported here, that we intend the main contributions of our research to reside.

Data Translation as Meaning Making

In both contexts, all participants showed curiosity to find out what their fabricated shape would look like and were eager to understand how the shape related to their actions. The process of engaging participants with their data, be it generated in real-time (crochet) or previously created (tweets), and involving them in the translation into fabricated forms has occasioned interpretative, sense making activities. These may concern the significance of a particular feature within the form (a spike or a repeating pattern), an association with a familiar shape, a connection with a particular event, or deliberations on personal history or the nature of craft practice. The tweet data was encountered, in a sense, 'ready made' rather than captured in an inspectable way during the fabrication sessions. This made it difficult, though not impossible, for participants to experimentally modify their behavior to see its consequences for data translation and fabrication. For the conference attendees, as a consequence, the shapes were less 'legible' or understandable and needed more explanation and description by the researcher. In the craft practice workshops in contrast, data was captured live from the embodied actions of participants and, accordingly, its significance could be interrogated concurrently. The more extensive engagement of crochet practitioners in data generation and translation, and indeed their participation in our whole research process, has helped them create an artefact that "feels like it kind of has more meaning".

With these differing ways of data engagement, we suggest that there is an important relationship between the kind of active involvement in the translation of data and the meaning invested in the tangible artefacts and the overall experience. We suggest that participation in data capture and translation enriches participants' opportunities for meaning making, as does taking part in the fabrication of the end-product. As Willis et al. have shown by turning 3D spatial drawings into laser cut objects: "There appears to be something inherently satisfying in the integral process of creating and realizing a design in physical form" [25, p.12]. Although we agree, their controlled setting differs from our 'in the wild' approach at the conference and our intensive exploratory sessions with the practitioners. This has enabled us to give more detail as to how such an 'inherent satisfaction' arises.

Situating Data in a Trajectory of Use

With the tweet translations, we had to obtain adequately meaningful data engagement while being mindful of the needs of the context. This required us to focus on the duration and simplicity of the activity rather than the depth of engagement with the data itself. Our later workshop with the craft practitioners also brought home to us how many steps there were in passing from their embodied practice, through data capture, selection, scaling, display and fabrication on machines which themselves need to be carefully configured with specially edited data files. As sociologists of science have repeatedly emphasised, these painstaking 're-representation paths' [10] are often abbreviated in published accounts with a consequent erasure of the craft skills of the researchers themselves. By conducting our fabrication sessions in the manner we did, where our own conduct became visible and accountable, we were reminded of how many steps to the process there were, how much aesthetic judgment is built in to the creation of shapes, and how skilled the operation of fabrication technology is.

Recapturing the steps suggests that it is appropriate to see data in a whole *trajectory of use*, where data might go through many translations, including those between different material forms. Indeed, our participants often considered extending these trajectories into future uses beyond the research encounter itself, whether these data were tweets or body movements and those future uses were as wearable clips or printing blocks.

If we see fabricated artefacts as situated within an extended trajectory of use, this can influence the forms data translation and fabrication can take. In both of our cases, the *relative abstractness and ambiguity* [4] of the shapes we made helped people appropriate them in a variety of ways. While the shapes could be related to tweet behavior and craft movements, respectively, they had a visual interest in their own right, enabling people to creatively entertain a variety of future uses. If we understand data translations within a trajectory of use, it seems that they should be done under an interesting dual auspice of *adequacy to the data* on the one hand and *requisite ambiguity with respect to future use* on the other.

From Data Materialisation to Data Translation

Throughout this paper, we have referred to our work as concerning 'data translation' rather than the more common

phrase of 'data materialisation'. This is worth commenting on. It is important to us that we refrain from a simplistic divide between the 'material' (e.g. crochet yarn) and 'immaterial' (e.g. digital data) though conflation of the digital (or the virtual) with the immaterial is often made unreflectively or even as a matter of philosophical commitment in some sources [1]. Similarly, the concept of 'data sculptures' [24] as fixed artefacts embodying data to convey meaning seems reductive for our purpose. We suggest (a) a more active role of the user in the creation of the artefact and its meaning, and (b) data being seen not as fixed but as a malleable medium open to interpretation and translation in multiple ways. We therefore refer to data translations to highlight that data is translated through different material media and that this can be a painstaking process involving careful data refinement, materials selection, aesthetic judgment, anticipations of future use. In all these respects, speaking of data materialisation encourages a simplification of the processes involved. To put the point as an aphorism: *there is more to 3D printing than just printing out*.

Data-Things and Social Objects

We have argued for situating digital fabrication within participatory data translation and making practices and have outlined some of the benefits of so doing. We feel that our approach takes a more fundamental approach than that of Ogawa et al [17], as we are not merely focusing on aspects of the fabrication process that "stimulates communication in society" but are exploring the impact of direct involvement in the fabrication process itself – in as extended a sense of that process as is practically possible. Our work has more in common with Nissen et al. [16] in seeing fabrication as a matter to embed within situated social practices – in that case, souvenir-making with visitors to an art exhibition. We extend this work in a number of ways. First, we have explored a variety of different settings and practical strategies for fabrication in a manner that is in sensitive response to an opportunity and its context. Second, we have been able to sustain a long-term relationship with a group of practitioners which has helped us to explore a more end-to-end participatory fabrication encounter. Third, we have focused on how personally-relevant data can be captured and deployed in fabrication, conceiving of data in an extended trajectory of use.

To express this compactly and to extend the use of Ingold [7] made by [16], *we conceive of our artefacts as 'data-things'* – highlighting that mere objects can become 'living things' for someone through their participation in the making process. In a similar fashion, Nina Simon [22] writes about a 'social object' "as one that connects the people who create, own, use, critique, or consume it. Social objects are transactional, facilitating exchanges among those who encounter them." We believe that the conference attendees and crochet practitioners we have worked with orient towards our artefacts as social objects, as data-things.

From Mutual Curiosity to Hybrid Research Practices

In both of our studies, the curiosity that participants had in our research was notable. Part of this is, naturally, to do with the relative novelty of the technologies we are using. But, above this, our work stimulated people's imaginations into suggesting extensions to our own research as well as future uses for fabrication technologies in general. The curiosity that participants have for the research process is a matter that is often ignored but can well shape the value that they perceive in designed artefacts [5].

This curiosity developed in an unexpected manner in the second study which is of particular interest to discuss here. As our relationship with the crochet practitioners deepened, we have noted that a reciprocal interest in each other's activities *as craft* emerged. This suggests that we can speculate on the possibility of *hybrid practices which combine craftwork with research* in novel ways. In existing work, Rosner has investigated how digital technology can mediate craft practice [20] and elicit reflection [21], while Zoran [27] has combined digitally fabricated elements with traditional craft techniques. The relevance and value of DIY making to HCI has been acknowledged with Lindtner et al. [11] recommending a collaborative approach for researchers to work more directly with makers and the maker community to develop innovative research initiatives. While our work is consistent with these approaches and recommendations, in our second study, we have tried to forge yet more intimate connections with craft practice, first, through exploring the potential of translating embodied craft movements into unique tangible artefacts and then by deepening the possibilities for reciprocal participation between craft and research worlds. Exploring what these hybrid craft-research practices might look like and what data-things they might make is our future work.

CONCLUDING REMARKS

Through two case studies, we have progressively explored an approach to working with fabrication technologies which emphasises participation in data translation and the creation of artefacts which are derived from personal experience (e.g. tweets) or skill (e.g. craft movements). We have demonstrated that direct involvement in digital fabrication can help people invest meaning into artefacts and facilitate reflection while encouraging practitioners, reciprocally, to incorporate new forms into their work. To close, we summarise some design concepts arising from our reflection on our work and the different contexts in which we have engaged. In condensed form:

- *Data translation is a matter of investing meaning.* As we translate data from one form to another and fabricate artefacts on that basis we are creating occasions for meaning making and reflection.
- *Understand data in a trajectory of use.* Data undergoes multiple translations and changes of significance, some predating our interventions, some which we effect

ourselves, some which are in the hands of others in the future. Accordingly, it is often right to

- *Create artefacts with a requisite ambiguity and abstraction* to enable varied appropriation in use.
- *Consider personally relevant data as a malleable material* and facilitate participation in its capture and translation so as to create
- *Living data-things* rather than ready-made objects. Through this, we can open out the possibility of
- *Hybrid research practices* where research and other crafts are intertwined.

While it is not always possible to explore all of these concepts simultaneously, and one of our studies shows the compromises that often have to be made, we hope we have outlined a novel image of how personal data can be worked with in participatory fabrication activities. In so doing, we hope we offer productive perspectives on digital fabrication beyond its use as a tool for manufacture, while furthering the cultural and research conversations around personal data and its use.

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