Crafting Interactive Decoration

STEVE BENFORD, University of Nottingham
BORIANA KOLEVA, University of Nottingham
ANTHONY QUINN, Central St Martins College of Art and Design
EMILY-CLARE THORN, University of Nottingham
KEVIN GLOVER, University of Nottingham
WILLIAM PRESTON, University of Nottingham
ADRIAN HAZZARD, University of Nottingham
STEFAN RENNICK-EGGLESTONE, University of Nottingham
CHRIS GREENHALGH, University of Nottingham
RICHARD MORTIER, University of Cambridge

We explore the crafting of interactive decoration for everyday artefacts. This involves adorning them with decorative patterns that enhance their beauty while triggering digital interactions when scanned with cameras. These are realised using an existing augmented reality technique that embeds computer readable codes into the topological structures of hand-drawn patterns. We describe a research through design process that engaged artisans to craft a portfolio of interactive artefacts including ceramic bowls, embroidered gift cards, fabric souvenirs and an acoustic guitar. We annotate this portfolio with reflections on the crafting process, revealing how artisans addressed pattern, materials, form and function and digital mappings throughout their craft process. Further reflection on our portfolio reveals how they bridged between human and system perceptions of visual patterns and engaged in a deep embedding of digital interactions into physical materials. Our findings demonstrate the potential for interactive decoration, distil craft knowledge involved in creating aesthetic and functional decoration, highlight the need for transparent computer vision technologies, and raise wider issues for HCI's growing engagement with craft.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**;

Additional Key Words and Phrases: Craft, hybrid-craft, tangible, embedded, material, maker, DIY, fabric, wood, lifespan, sustainability, obsolescence, augmented reality, tangible and embedded interfaces, computer vision, seamful design, ambiguity

ACM Reference format:
Steve Benford, Boriana Koleva, Anthony Quinn, Emily-Clare Thorn, Kevin Glover, William Preston, Adrian Hazzard, Stefan Rennick-Egglestone, Chris Greenhalgh, and Richard Mortier. 2017. Crafting Interactive Decoration. *ACM Trans. Comput.-Hum. Interact.* 24, 4, Article 39 (March 2017), 40 pages.
DOI: 0000001.0000001

Author's addresses: S. Benford, B. Koleva, E. Thorn, K. Glover, W. Preston, A. Hazzard, S. Rennick-Egglestone, C. Greenhalgh, School of Computer Science, University of Nottingham, Jubilee Campus, Wollaton Road, Nottingham, NG8 1BB, UK; emails: {steve.benford, b.koleva, emily.thorn, kevin.glover, william.preston, adrian.hazzard, stefan.egglestone, chris.greenhalgh} @nottingham.ac.uk; A. Quinn, Product, Ceramic, Industrial Design Program, Central Saint Martins, Granary Square, London, N1C 4AA; email: a.quinn@csm.arts.ac.uk; R. Mortier, University of Cambridge, Computer Laboratory, William Gates Building, 15 JJ Thomson Avenue, Cambridge, CB3 0FD, UK; email: richard.mortier@cl.cam.ac.uk.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than the author(s) must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.
© 2017 Copyright held by the owner/author(s). Publication rights licensed to ACM. 1073-0516/2017/3-ART39 $15.00
DOI: 0000001.0000001

1 INTRODUCTION

We are surrounded by beautiful decorative patterns. From motifs and borders, to swathes of colour and texture, almost every object that we value is embellished with a pattern that has been carefully designed to enhance its beauty and value. We apply decorative patterns to our homes, furnishings and possessions and even to our own bodies, expressing our personalities and tastes by mixing and matching the materials that surround and cover us. Decorative patterns are an essential and ubiquitous feature of everyday life — quite literally 'part of the furniture'.

We explore how to make such patterns interactive so as to enable decorated artefacts to become connected to digital media that enrich their utility or meaning, for example connecting them to records of their provenance, contextual instructions and added-value services, or to personal memories of ownership and use. Our particular focus is on how to empower skilled artisans to design beautiful and interactive patterns and then successfully apply them to material artefacts. This contributes to two overlapping threads within HCI: Augmented Reality (AR) which is concerned with scanning and recognising visual codes and Tangible and Embedded Interaction (TEI) which is concerned with embedding the digital into the material.

Considering AR, the notion of scanning visual codes in order to unlock digital interactions has been with us for more than sixty years since the barcode was patented in 1952 [Woodland and Bernard 1952]. Two-dimensional QR codes [ISO 2000] are now commonplace while fiducial markers support 3D tracking [e.g. Bencina et al. 2005; Fiala 2004]. These various visual codes are carefully engineered to be robust and scalable. They are also inherently recognizable for what they are – there is no mistaking a barcode or QR code once you have encountered one. While this enables users to readily identify them, it comes at the cost of a limited aesthetic [Costanza and Huang 2009]. In short, they are designed to be robust, not to look good. There have been attempts to redress this aesthetic. Companies such as Barcode Revolution [2013] and D-Barcode [2013] embellish barcodes to create playful personalised designs. Some AR systems employ image processing to recognise naturalistic markers, for example Google Goggles [Google 2013], Blippar [2013], String [Powered by String 2013], Embedded Media Markers [Liu et al. 2010], reacTIVision [Bencina et al. 2005], ARTag [Fiala 2004] and d-touch [Costanza and Robinson 2003]. Rather than focus on the underling technology, our interest lies in understanding how skilled artisans learn to embed such markers into wider decorative patterns.

In turn, TEI has a longstanding interest in embedding the digital into the physical, from early graspable interfaces [Fitzmaurice et al. 1995] and proposals for tangible bits [Ishii and Ullmer 1997] to recent notions of transmaterials [Brownell 2006], composite materials [Vallgårda and Redström 2007] and textures [Robles and Wiberg 2010]. This reflects a growing interest in making and crafting, including embedding digital technologies into traditional craft practices such as knitting [Rosner and Ryokai 2009] and bookbinding [Rosner and Taylor 2011] and discussions of the relationship between the material and digital [Gross et al. 2014; Rosner et al. 2012; Tsaknaki et al. 2014]. Our interest lies in revealing the craft practices of artisans as they learn to apply interactive decoration to material artefacts.

Our argument unfolds as follows. We begin by situating our research within the wider context of craft and its relationship to digital technologies in Section 2 before summarising our Research Through Design process in Section 3. We then present our portfolio of artefacts in Section 4 and annotations on design rationale and lessons learned in Section 5. Finally, Section 6 discusses wider implications for HCI in terms of bridging between human and system interpretation of images and accommodating the materials, form, structure and function of artefacts.

2 CRAFT AND DIGITAL TECHNOLOGIES

The nature of crafting has evolved over thousands of years through antiquity, medieval guilds and the industrial revolution to contemporary studio crafts. Unsurprisingly, the term 'craft' has acquired many commonplace meanings, from the relatively narrow sense of the practices of trained artisans working traditional materials, to a more everyday usage that encompasses nearly any practice that involves elements of skill and dedication. From an academic standpoint, the meaning and nature of craft is contested, not least in its relationship to its sibling disciplines of art and design, and especially its relationship to technology. We therefore take a little time to frame our own position.

While precise definitions differ, scholars broadly associate craft with a common set of features. Metcalfe, writing in Dormer [1997, p70], emphasizes the importance of craft objects as being substantially *made by hand*, a view emphasised by Ingold [2013]. There is a widespread sense of craft involving high-levels of *skill and craft knowledge*, acquired through *repetitive practice*. Dormer [1997, p14] identifies a core value as being the *freedom* that comes through possessing skill and control over process. In a more practical vein, one can catalogue examples of *studio craft* that involve working *traditional materials* such as textiles, clay and glass.

More problematic, is the relationship between craft and technology. While it is recognized that even ancient craft practices involved hand tools, the rise of mass production during the industrial revolution set craft on a collision course with technology. Reactions to the deskilling of artisans ranged from the machine-smashing Luddites to the 'arts and crafts' movement that celebrated a return to a preindustrial ideal of crafting, inspiring a golden age of the decorative arts in the early 20th century. By the middle of the century, however, the status of craft was in decline, as both art and design turned away from the material towards the conceptual. The latest technologies to challenge craft are digital, with the combination of Computer Aided Design and Computer Aided Manufacturing – CADCAM – speeding up mass production and raising questions whether computers may ultimately render computer-designed products indistinguishable from the handcrafted.

This brings us to HCI. Given its core concern with digital technologies, our field might possibly be seen as being part of this latest technological wave to threaten the values and practices of craft. However, the emergence of embedded electronics, tangible interactions and even augmented reality may in fact herald something of a return to the material. Consequently, there is also a growing interest within HCI in maker and hacker cultures and in revisiting handcrafting. Cheatle and Jackson [2015] consider the subtleties of how a highly skilled artisan employed CNC machinery in furniture making. Tsaknaki et al. [2014] report how digital technologies can be 'worked' into the traditional material of leather. Rosner and Taylor [2011] explore HCI in support of bookbinding, while Rosner and Ryokai [2009] consider knitting and Rosner et al. [2015] explore the application of conductive inks to ceramics. Finally, McCullough [1998], writing from outside of HCI, argues the case that the digital can itself be crafted.

Against this broad backdrop, we clarify our own interest. First, we are focused on digitally augmenting material artefacts that are substantially handmade from traditional materials. As noted above, we anticipate that connecting such artefacts to digital records and services might potentially enrich their provenance, utility and personal meaning. Second, rather than seeking to emulate or replace hand crafting with digital technologies, our goal is to better marry the digital – in our case AR and TEI – with traditional materials and practices by developing digital technologies that are open and malleable to artisans and that respect their craft values of skill, knowledge, hand-making and close control by humans. Ultimately, this may be one step on a longer journey towards a deeper merging of the physical and digital in craft, one in which the two are no longer seen as separate, or as representing opposing values of handcrafting versus mass-production, but rather jointly become new forms of 'transmaterials' [Brownell 2006] or 'composite materials' [Vallgårda and Redström 2007] as we discuss later.

3 FOLLOWING RESEARCH THROUGH DESIGN

We follow the approach of Research Through Design, relating the craft activities of artisans to generalizable principles and knowledge that constitute HCI theory. The essence of the approach lies in being practice-led, with designers creating specific artefacts that embody opportunities or problems. Beyond this, however, there is divergence within HCI as to precisely what constitutes research through design and especially how its outcome might best be evaluated.

Zimmerman et al. [2007] build on Frayling's notion of Research Through Design [Frayling 1993] to articulate a model of interaction design research for HCI. They exhort HCI researchers to adopt the approach as a powerful way of tackling "wicked problems" that, due to the conflicting views of diverse stakeholders, cannot easily be modelled or readily addressed using the "reductionist approaches of science and engineering". They stress the designer's role in "trying to make the right thing" and the importance of design artefacts as "concrete embodiments of theory and technical opportunities". Significantly, they also call for a greater clarity and consistency as to how HCI might recognise and evaluate the outcomes of research through design, offering the four criteria of: process, invention, relevance and extensibility.

Others have argued for a more relaxed and exploratory view. Gaver [2012] celebrates the diversity of approaches, arguing that this provides opportunities for creative and playful engagements with the world and advising the community to be "wary of impulses towards convergence and standardisation and instead, take pride in its aptitude for exploring and speculating". He argues that the kind of theory that emerges from research through design is inherently provisional, contingent and aspirational. He further proposes that the outcomes of research through design might usefully take the form of portfolios of artefacts and systems that are annotated with "topical, procedural, pragmatic or conceptual" insights, from reflections on use in the field to conceptual frameworks.

Our own interpretation leans towards the creative and exploratory. We are not so much concerned with tackling a known wicked problem as we are with supporting the creative craft practices of artisans. We therefore undertake and document an exploratory research process. While we recognise the importance of process, invention, relevance and extensibility and hope that they are to be found in our work, we find it especially useful to present our outcomes as a portfolio of artefacts that are annotated with design insights as Gaver suggests.

Practically speaking, we engaged professional artisans with skills in visual design and material craft, briefing them to create a portfolio of beautiful and reliably[1] scannable artefacts. A particular focus of this paper is on how our artisans tackled the visual and material aspects of crafting these artefacts.

Our artisans included ceramicists; the proprietor of a craft shop who created bespoke gift cards, textile designers working with a local lace museum to create souvenirs, and a professional luthier at a school of guitar making. We worked closely with them to create a diverse portfolio of artefacts including tableware, gifts and musical instruments from ceramics, paper, fabrics and wood. Along the way – a journey that took three years – we documented their practices as annotations to this portfolio. The resulting portfolio comprises four kinds of decorated artefact:

[1]By reliable we mean that the patterns should be readily scannable by a reasonably experienced user under typical lighting conditions. In practice, reliability was a matter for the professional judgement of the design team, especially the lead designer, who tested and signed- off the final artefacts.

Ceramics and tableware – we engaged five ceramicists to create a collection of interactive tableware for a restaurant. This comprised bowls, placemats and menus displaying decorative patterns that linked to interactive services to deliver an enhanced dining experience. The main focus here revolved around creation of an extended pattern book and the possibilities and challenges of applying these patterns to *ceramics*.

Mixed-media gift cards – we engaged a local craft shop to explore the possibilities of interactive gift cards, handmade from card and fabrics. Two artisans ran workshops to teach customers how to make their own gift cards, focusing on techniques for cutting, layering, stitching together and otherwise combining *card* and *embroidery* to create interactive decorative patterns.

Fabric souvenirs – we engaged textile designers and a historic lace archive to create an interactive souvenir for a museum shop. The focus here was on the application of interactive decoration to *textiles*, including the challenges of dealing with different finishes, stretch and drape.

A wooden acoustic guitar – we engaged a professional luthier and a graphic designer to create a hand-made acoustic guitar with interactive patterns inlaid into its wooden surfaces so that both players and audiences could scan it to learn about its history. The focus here was on inlaying interactive patterns into a complex *wooden* structure.

Before presenting our portfolio in detail, it is first necessary to introduce the underlying technology that was used to create interactive decorations. As noted earlier, various image recognition technologies might potentially be employed to recognize aesthetic decorations. We chose to build on the d-touch approach proposed by Costanza and Huang [2009] that recognizes topological structures in images. Key to d-touch is the idea that people who learn its relatively simple topological rules can draw their own scannable designs from scratch. We illustrate this idea by way of a simple example. Topologically speaking, Figure 1 (left) comprises five white regions that are joined up with black lines to form an overall connected shape. These regions then contain different numbers of solid blobs within them – one, one, one, one and two blobs respectively. Provided that the regions are all connected by an unbroken solid line and that the blobs themselves are solid, then this will be recognized as the code 1:1:1:1:2 (the ordering of the regions is not significant and by convention codes are presented in ascending order). In principle there might be far greater numbers of regions and blobs, opening up the potential for working with a very large code-space thought this will be subject to the practicalities of camera resolutions.

The d-touch algorithm does not consider the shapes or ordering of the regions and blobs as being significant. Consequently, Figure 1 (right) shows a second visual representation of the same code that adheres to the same topology of five connected regions containing the required numbers of solid blobs. While this ambiguous relationship between visual imagery and embedded codes may not be appropriate for all applications (those that require images to map to unique addresses), we were drawn to its creative potential, sensing the possibility that it might provide skilled visual designers which an expressive medium for creating interactive decorations.

We implemented the d-touch algorithm in a mobile app called Artcodes[2] that supports scanning interactive decorations and their mapping to digital content, releasing this on Google Play and iTunes so that other practitioners and researchers could also experiment with the approach. We iteratively refined the implementation of the algorithm and also extended the functionality of the

[2]A note on naming. Earlier versions of 'Artcodes' were named 'Aestheticodes'. The name was changed for reasons of memorability and ease of spelling. Artcodes implements the topological rules that were first proposed in the d-touch system. Throughout this paper we refer to the 'Artcodes app' as being our implementation of the 'd-touch rules' (with some extensions and additional features) and to 'Artcodes' as being visual markers that have been designed using this app and that are readable by it.

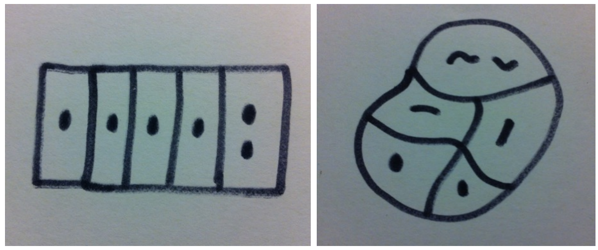

Fig. 1. Two representations of the d-touch code 1:1:1:1:2.

app as the project unfolded, resulting in the final version presented in Section 4.5 below as being a key part of our portfolio.

We have found it challenging to present the details of our annotated portfolio in the linear form of an academic paper. Our solution is to present it in two parts. In Section 4 we document the artefacts within the portfolio, summarising how and why they were made. In Section 5, we present key insights into the crafting process as annotations, grouped under the four themes of: pattern material, form and function, and process. Section 5.6 presents a visual summary of both artefacts and annotations in the style of Gaver [2012].

4 A PORTFOLIO OF INTERACTIVE DECORATED ARTEFACTS

We introduce our portfolio of artefects, sketching out the broad context of each artisan's work, the design process they followed and they artefacts they ultimately produced. However, we first offer a general account of how we set about recruiting them and the basis on which they worked with us. Overall, recruitment was an iterative process, following a snowballing approach that led to a total of eleven different visual designers becoming involved in various ways. We began by recruiting one initial artisan, a graduate in design with a particular expertise in ceramics. She engaged closely with the technology development process throughout, eventually assuming the mantle of lead-designer as a core part of the development team with responsibility for recruiting and training others and for feeding design insights back into technology development. She has since become a salaried researcher on the project and is an author of this paper.

Our first engagement was the ceramics and tableware example for which we recruited a further six graduate designers who were trained in drawing and using the Artcodes app during a day-long workshop. This training followed a studio-style approach that involved 'learning by drawing', beginning with copying simple designs similar to those in Figure 1 before moving on to create their own more complex designs. There was a particular emphasis on creating multiple visual representations of the same code as well as appreciating the "dos and don'ts" of how to draw valid markers (e.g., that the technology is very sensitive to lines properly joining up or to small white spaces appearing in otherwise solid blobs).

Five of our six workshop recruits then accepted a commission to produce an initial pattern book (Figure 2). This required roughly a week of effort from each of them to iteratively work up a series of five designs each. This involved frequent debugging conversations with our lead designer to make their designs fully functional and reliable (which inspired the introduction of debugging interfaces into the app that we discuss later). One of this team proved to especially skilled in the approach and went on to work on a series of further projects, including designing the Celtic patterns for the acoustic guitar.

The fabric souvenirs project involved recruiting and training two textile designers from the fashion and textiles department of a nearby University that hosted a local lace archive. The mixed media gift cards project was undertaken by two independent artisans who ran public craft sessions in a commercial craft shop and who had encountered the Artcodes app at a design fair.

In terms of the time required to learn the approach, our first training workshop was relatively long (a day) as it was also used to gather research data through a series of discussions. We have since refined the approach so that we can teach people the concept of how to draw a code in a few minutes, and routinely do so at craft fairs, tradeshows and even academic conferences (including ACM CHI), although as with any such craft skill, it then takes time and iterative attempts to master the detail, such as the intricacies of 'debugging' complex designs as we discuss later. Online tutorial material is also available at our community website (artcodes.co.uk).

Once trained, the designers tended to work independently in their own studios, though typically used email and occasional face-to-face meetings to resolve problems. With the three exceptions of our lead designer, the salaried researcher in the lace archive and craft the shop owner who each brought their own source of funding, we engaged our designers on a freelance basis, paying appropriate daily rates. They retained ownership of their copyright, with us having a license to use the designs for research and an agreement to negotiate future terms for any commercial use that might ensue.

In terms of the eventual fates of the artefacts, the pattern books and tableware sets, the lace sample sets were distributed for publicity, the gift cards were kept by their makers and the guitar was used as a travelling technology probe [Benford et al. 2016]. We also invited our artisans to take part in project feedback meetings and interviews at which we captured their accounts of the design process and opportunities and challenges that they had encountered when using the technology.

4.1 Ceramic tableware

Our first engagement involved designing and fabricating interactive tableware for the Busaba Eathai chain of Thai restaurants based around London in the UK. This is reported in detail in [Meese et al. 2013]. As noted above, following initial training, we commissioned five artisans to create a pattern book of designs. Each was asked to produce three thematically distinct designs for each of three codes. We assembled the resulting forty-five designs (five artisans x three themes per artisan x three codes per theme) into a pattern book. Figure 2 shows one representative example of each of the fifteen themes, grouped by artisan. This selection reveals how they were able to embrace the topological structure of the drawing rules to embed markers into a variety of patterns, ranging in style from ones based on figurative motifs involving plants and animals, to more abstract forms, to repeated patterns.

These designs also reveal how our artisans exploited the ambiguous nature of the mapping between visual patterns and embedded codes that is inherent in the topological approach. For example, Figure 3 shows three very different patterns all of which contain the Artcode 1:1:1:1:2. Conversely, Figure 4 shows three very similar visual designs for different underlying codes in which the artisan has deliberately varied the numbers of blobs in the penguins in order to change the code while also varying the number scattered around the penguins so as to distract the eye from this.

We conducted an ideation workshop with eleven Busaba staff to explore which restaurant artefacts might be decorated with patterns and what kinds of digital interactions might ensue. The consensus was to decorate various examples of 'tableware' including ceramic bowls, menus and disposable placemats and to associate scanning these with interactive services that would promote the Busaba culture and enhance their restaurant service. Specific ideas carried forward

Fig. 2. The fifteen themes in the Artcodes pattern book.

Fig. 3. Three distinct visual designs for the Artcode 1:1:1:1:2.

to prototyping included scanning menus to reveal information about the 'specials' of the day; scanning bowls to access recipe cards (with the idea that bowls might also taken home as souvenirs as part of the Busaba loyalty scheme); and scanning a paper placemat to trigger details of your individual order. We concluded by fabricating fifteen sets of tableware (one combination of bowl, placemat and menu for each of our fifteen themes) and demonstrating these at a Busaba restaurant during the 2012 London Design Week festival. Selected examples are shown in Figure 5.

4.2 Mixed-media gift cards

Our second engagement focused on the decoration of handmade gift cards. We engaged two artisans who sold handmade cards in a local gift shop, the first an expert in illustration and paper cutting and the second an expert in in embroidery and stitching. Once familiar with the Artcodes app, they designed and delivered a three-hour long crafting workshop at which customers learned to create

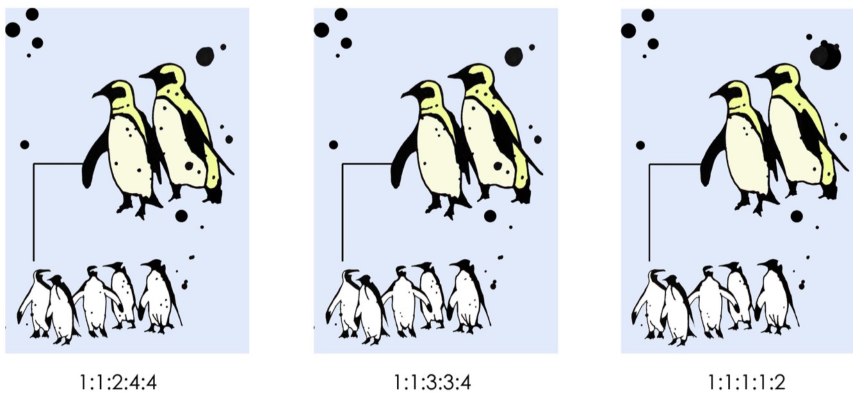

Fig. 4. Three similar looking designs for different codes.

Fig. 5. Artcode decorated place settings being demonstrated at Busaba.

interactive gift cards using card, thread, printed paper, pencil and ink paper and fabrics that were cut, layered and textured in various ways (running these kinds of craft workshops is part of the regular business of the shop). They were supported by the archivist of a local company who brought along a selection of art-deco patterns taken from historic packaging to serve as inspiration (Figure 6, top left). Our two artisans established a three-stage approach to crafting Artcode gift cards. First, they extracted geometric shapes from the art deco packaging material to serve as templates for Artcode regions (Figure 6, top right). Next, they invited customers to complete functioning

Artcodes by extending these templates with appropriate numbers of blobs that were stitched using multi-stranded embroidery thread (Figure 6, bottom left). Finally, they encouraged customers to distress their cards so as to add additional texture (Figure 6, bottom right) and to modify templates by cutting material out of them to make them appear more 'organic'. After learning this process, customers were given time to develop their own designs.

Fig. 6. Hand-crafted gift cards.

The workshop concluded with a discussion of potential applications of augmented gift cards focusing on how they might become associated with digital media. Three principle perspectives appealed to participants here. The first was as a gift for others – embedded Artcodes might link to digital media that augmented the meaning of the card as a gift, for example personal messages or photographs. The second was promoting the artisan – the pattern might link to promotional material highlighting the work of the craftsperson who had produced it. Last, was as a souvenir of the workshop – the card might link to further training material on how to craft cards and Artcodes.

4.3 Fabric souvenirs for a museum gift shop

Our third engagement focused on applying Artcodes to fabrics. For this we engaged a team of fashion and textile designers based at nearby Nottingham Trent University and curators from Newstead Abbey, a local museum that was exploring how to engage visitors with its historic lace collection. Early discussions raised he idea of creating souvenir packs of interactive lace samples for the museum shop based on historic designs from the collection. A team comprising two experienced fabric designers who specialized in lace, an experienced graphic designer who had previously worked with the Artcodes app, and the collections access officer from the museum then embarked six month exploration of applying Artcodes to fabrics, with a particular focus on designing and manufacturing scannable patterns inspired by traditional lace designs.

The team began by experimenting with applying existing Artcode designs from the pattern book described earlier to various fabrics. The chosen designs were digitised using the Wilcom EmbroideryStudio software and then automatically fabricated using a Barudan embroidery machine. The designers explored a variety of backing materials, stitch types (running stitch, satin stitch, blocks of stitches), stitch lengths, widths, densities and colours at this stage.

Following early explorations, the next step involved selecting examples from the historic lace archive and adopting them as inspirations for Artcode patterns. Figure 7 shows how this process unfolded. First, a historical design was chosen (top left). This was then adapted to fit the topological drawing rules, producing a drawn design that could be reliably scanned (top right). This new design was digitized using the Wilcom Software (bottom left). Finally, appropriate parameters were set and instructions sent to the Barudan embroidery machine to fabricate a sample (bottom right).

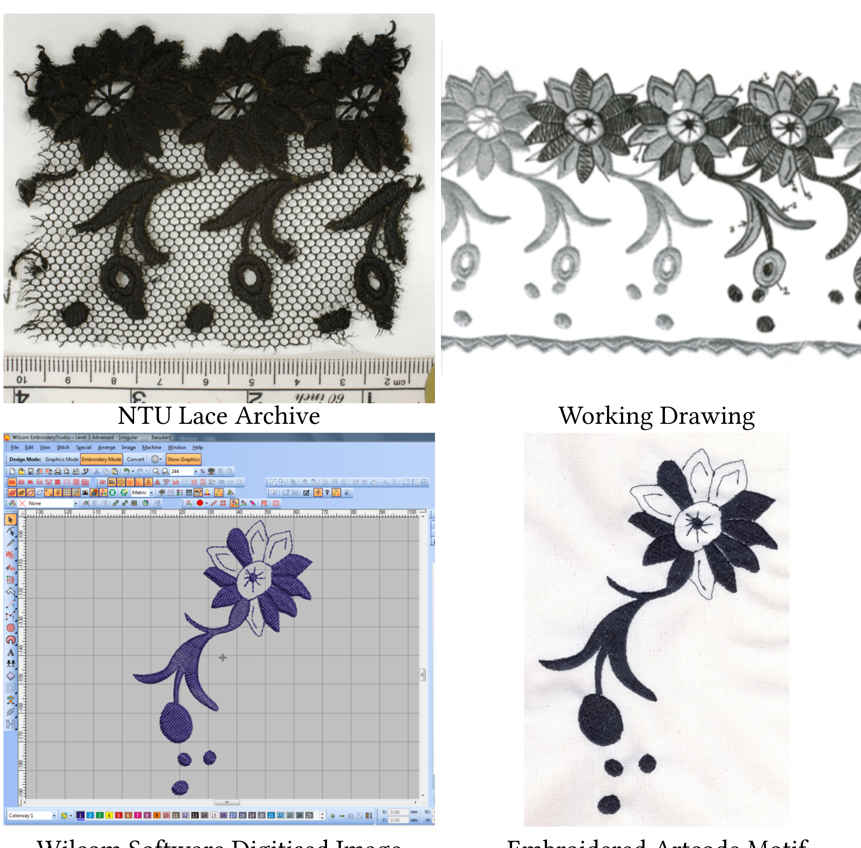

Fig. 7. Embroidered souvenir for a lace museum.

The final activity was to explore how visitors might engage with the historic lace collection by scanning the fabricated samples. Ultimately, the team chose to produce souvenir lace packs that visitors might acquire at the gift shop and take away with them, scan with their own devices and possibly show to others too as a way of advertising the collection by word of mouth. We fabricated souvenir gift packs each featuring an embroidered fabric sample, a second lace pattern on paper, and a set of instructions and pointer to the Artcodes app (Figure 8).

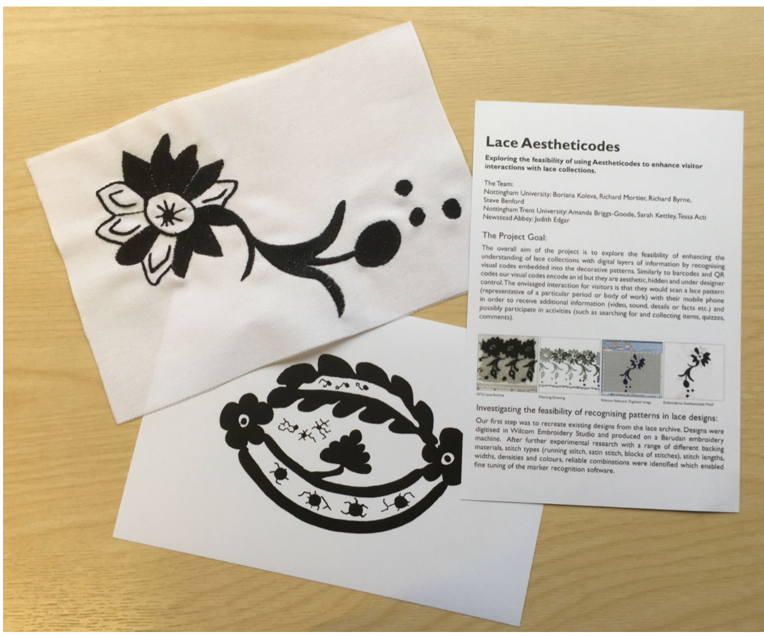

Fig. 8. Hand-crafted gift cards

4.4 A wooden acoustic guitar

Our final artefact is handmade acoustic guitar that was built as part of a project to create musical instruments that can be queried to reveal their life stories, from how they were made to who has played them. From the perspective of this paper, this unusual artefact offered an opportunity to explore the inlay of decorative visual codes into a complex wooden structure. The initial concept and design of the guitar was presented in [Benford et al. 2015]. The following briefly summarises the relevant aspects its design and construction for completeness.

We engaged a traditional luthier who was skilled in the craft of guitar making and a graphic designer who was skilled in the design of Artcodes in an iterative six month design process that spanned designing and building the guitar; designing and inlaying Artcode patterns; and prototyping mobile experiences to access its history by scanning its decoration. We adopted the roving Irish bard Turlough O'Carolan (1670-1738) as our muse for designing a storytelling instrument. In response, our graphic designer began to sketch out a series of the Celtic-knot designs (Figure 9, left) that were ultimately translated into scannable Artcodes in CorelDRAW (Figure 9, right).

These initial designs were adapted to fit different surfaces of the instrument. Ultimately, we chose to decorate six different surfaces of the guitar: the headstock (Figure 10, top middle) where the maker's label normally resides; the back (Figure 10, top right) which provided space for a large

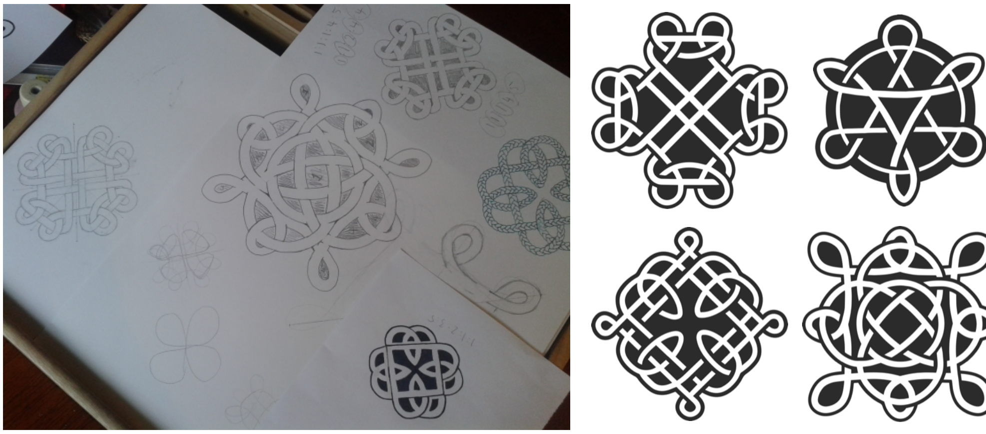

Fig. 9. Early Celtic knotwork sketches (left) and scannable designs (right).

pattern; a fret-marker at the twelfth fret (Figure 10, bottom right); the soundboard on the front of the guitar for which we designed an additional flowing knotwork pattern (Figure 10, top left); a removable soundhole on the top of the guitar that was introduced due to the unusual soundboard design (Figure 10, bottom left); and finally a small nook in the cutaway underneath the guitar (visible in Figure 10, top right).

The Artcode patterns were applied to the different surfaces of the guitar using a variety of techniques. Due to the unusually extensive amount of inlay on our design when compared to most contemporary guitars, this involved a combination of manual and mechanized craft techniques. The smaller pattern on the headstock was filled with a mixture of black dust and resin (Figure 11, top). Most other areas, especially the sound-board and back, were inlaid with darker woods that were laser cut (Figure 11, bottom left), glued in place and then finished with a matte varnish so as to minimize reflections that might interfere with scanning. This required fine manual work from the luthier to rout out the etched patterns on the body of the guitar, assemble the laser-etched inlay into this like a jigsaw, glue it in place and carefully sand down and finish the surface (Figure 11 bottom right).

Following its completion, Carolan was released 'into the wild' to visit different players. As documented in [Benford et al. 2016], over the course of a year it travelled to 6 homes, was played at 3 gigs and 2 recording sessions, visited 8 clubs or jam sessions, hosted an 'open mic' event, resided in a shop and undertook an international road-trip, during which more than 30 players contributed materials to its digital history. This experience shed light on the nature of the mappings between Carolan's six interactive surfaces and its growing digital record, revealing how three surfaces retained a more or less constant associations throughout (the headstock to the official maker's certificate, the sound hole with the user guide and the fretmarker with the technical specification) while the remaining three tended to be more freely appropriated, being mapped to different content (e.g., playlists, personal websites, video recordings) to suit each new player or context that the instrument visited.

4.5 The Artcodes app

We conclude this overview of our portfolio with a brief overview of the Artcodes app itself. The app evolved considerably as a result of crafting these artefacts and the following is a snapshot of its functionality as it stood at their completion.

Fig. 10. Photomontage of Carolan guitar.

The core function of the app is to support the scanning of markers as shown in Figure 12, (top centre). The user frames what they believe to be the relevant part of pattern in the video window, in this case the headstock of the Carolan guitar. On detecting a valid Artcode, the name of its associated content appears ("Carolan Guitar" in blue); the user then presses this in order to follow the link and view the content, which may be any web resource (webpage, web-hosted video, audio etc).

In order to support debugging and also make it easier for people to discover markers in unfamiliar and complex patterns, designers and/or end-users are also able to toggle on and off various modes that overlay the outlines and values of detected codes on the video view and/or show how colour thresholding works. These features are shown in Figure 20 below and discussed in Section 5.2.

A distinctive feature of the Artcodes app is the concept of experiences. The app allows the user to select a particular experience through which to view a marker. An experience is a particular mapping between a set of markers and some digital content. Selecting an experience defines both which codes are deemed to be valid at the present time and the content that they will lead to. By selecting among different experiences the user might therefore choose to interpret the same markers in different ways at different times. On opening the Artcodes app, the user is presented

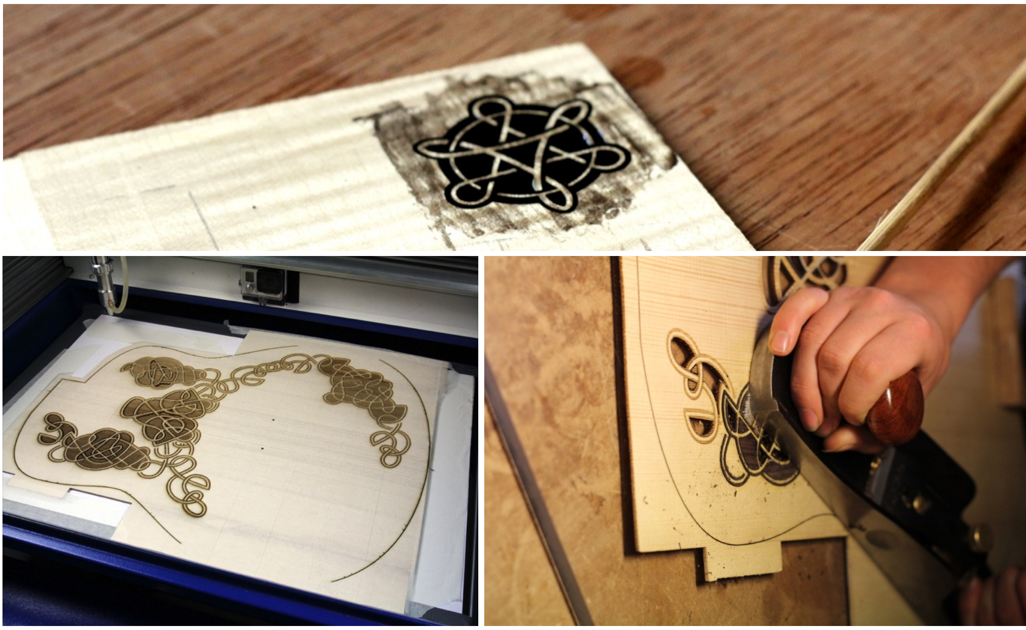

Fig. 11. Laser-etching the Artcode outlines into the soundboard (left) and manually fitting and finishing the darker inlay into this (right).

with a list of recommended experiences that have downloaded from a server (Figure 12, top left). Recommendation is done on the basis of featured, favourites, recently used, and valid at this location and time as specified by the experience creator. The label in Figure 12 (top centre) shows that the user is currently scanning the Carolan guitar using the "Carolan at IDC" experience that was created when the Carolan guitar was taken to the Interaction Design & Children conference.

Although the focus of this paper is on the drawing of markers and their application to various physical materials, we note that the app provides menus for authoring an experience from scratch, giving it a name, image, description, specifying a list of valid code values and associated URLs. The user can also copy and edit an existing experience, changing any of these properties. Figure 12 (top right) shows the "Carolan at IDC" experience opened up and ready for editing. On selecting the 'edit' option the user is presented with the list of currently valid codes for this mapping (Figure 12, bottom left). They can then select and edit specific code mappings (Figure 12, bottom middle) changing its URL and also adding more codes that will also trigger this URL. Finally, they can specify the valid time and map location for this experience as shown in Figure 12 (bottom right). Once edited and saved, they can share the new experience with other Artcodes users using the share button visible in Figure 12 (top right). In this way experiences can be edited and appropriated as described further in [Benford et al. 2016]. The remainder of this paper continues with our discussion of crafting the interactive patterns.

5 ANNOTATIONS ON THE NATURE OF THE CRAFT

Having introduced the artefacts in our portfolio, we now turn to the annotations. We reflect across the portfolio, delving more deeply into the examples so as to unpack the 'craft knowledge' involved in creating interactive decorative patterns that were both beautiful and reliable. We focus on five aspects of the craft:

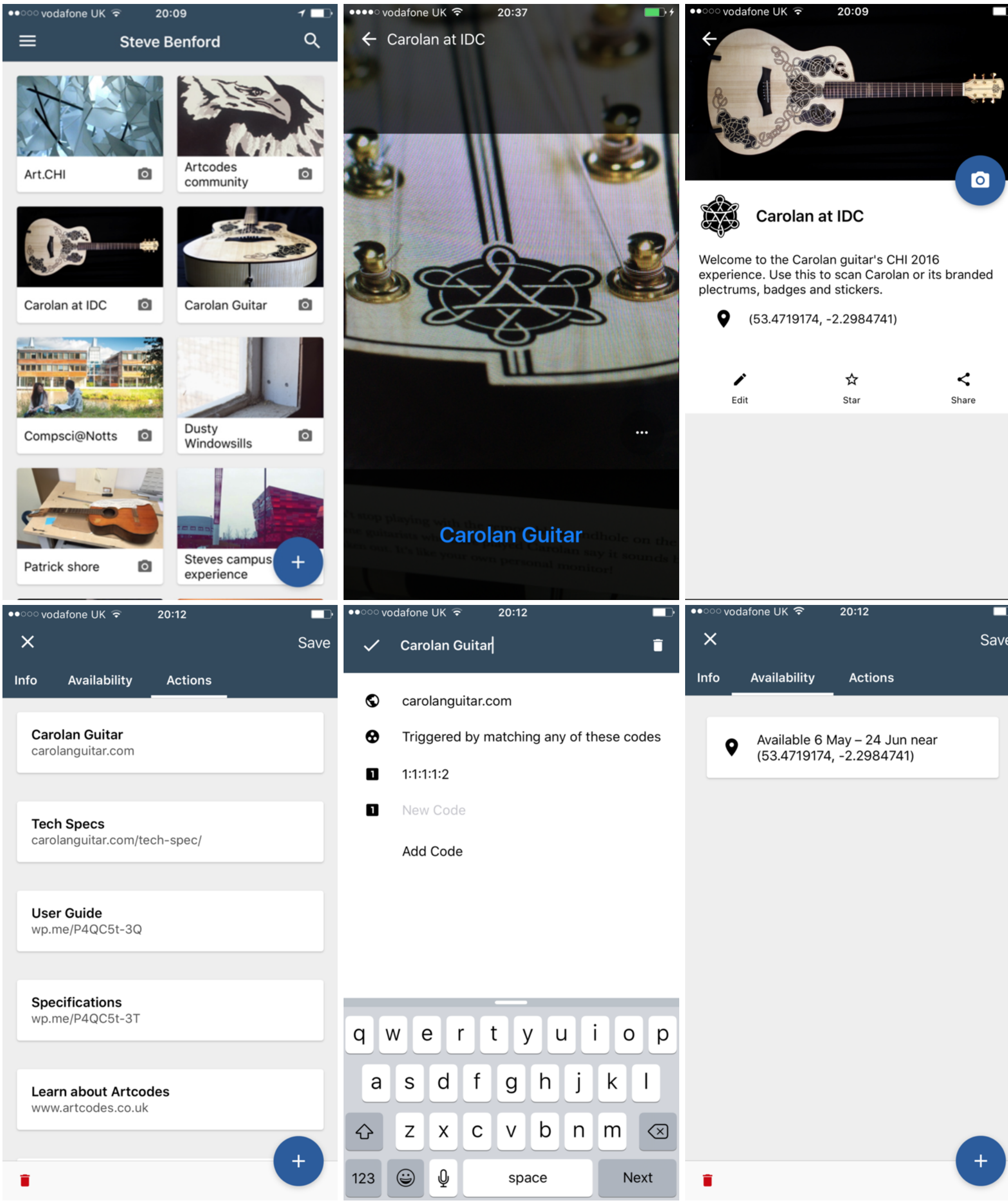

Fig. 12. A tour through the Artcodes app. Selecting an experience (top left). Scanning a marker through a selected experience (top middle). Opening an experience for editing (top right). The current list of valid codes for this experience (bottom left). Editing a specific code (bottom middle). The current availability of the experience (bottom right).

Pattern – how our artisans set about embedding recognisable visual codes within wider decorative patterns;

Materials – how they learned to accommodate the material qualities of the different surfaces to which patterns were applied;

Form and function – how their designs also responded to the form and function of artefacts;

Mappings and interaction – how an artefact becomes mapped to digital content and how users discover and interact with codes as part of an overall digital user experience;

Process – how our artisans draw on traditional craft processes and techniques but also integrated these with mechanised approaches.

5.1 Pattern

Naturally, a great deal of attention is paid to the appearance of the decorative patterns. This requires creating patterns that are aesthetically pleasing while adhering to the underlying d-touch rules. It often involves embedding one or more Artcodes as interactive hotspots within a wider decorative pattern, parts of which are not interactive. This is exemplified by many of the patterns in Figure 2 and also the flowing knotwork on the front of the guitar that contains a single code repeated three times. We observed several motivations for embedding Artcode hotspots into wider patterns:

- To decorate a large artefact that the user cannot easily scan in its entirety (think of upholstering a large piece of furniture or designing wallpaper);
- To deliver an experience in which the user needs to discover hidden codes by exploring the artefact;
- To create a narrative where the user successively scans codes within the pattern to reveal a story;
- To increase reliability through redundancy, ensuring a reasonable chance of scanning at least one code from several that are 'in shot' at a given time.

Our artisans found that the topological nature of the d-touch rules provided a powerful scaffold for creative visual design. Perhaps surprisingly, they were largely positive about the constrained nature of the rules. Not only were these evidently comprehensible, but the constraints appeared to provide a framework for playful creativity (*"I found though that the more you played with the codes the more versatile you realised the formula is – and really a huge scope of imagery can already be created within the existing structures"*). Other constraints however, were less appreciated such as requiring a necessary thickness of line or limitations on colours, both of which were seen to limit visual aesthetic.

By interviewing our artisans about their designs, we were able to uncover how they set about disguising codes within patterns. Their tactics are neatly illustrated by the single complex design shown in Figure 13 in which the same Artcode (1:1:2:2:6) is replicated three times within a single image.

Figure 14 highlights the locations of the Artcodes within this overall design and reveals five key techniques for disguising an Artcode within a pattern.

Disconnected elements – our artisans soon realised that they could add all manner of embellishments outside of d-touch regions without affecting the validity of the code (*"Like a Morrison picture but with loads of background detail ... so it was camouflaged ... I'd have loads of foliage or background imagery and then just have the code hidden inside"*). Visual elements that fall outside of the regions of an Artcode such as the black foliage above the purple bird are ignored by the scanning software, but may form a coherent part of an overall picture for the viewer. Such additional elements may also serve to make the image more complex and so discourage close inspection by the viewer to work out the locations of codes.

Extended and thickened lines – even where they form part of the Artcode, dark lines can be embellished in many ways, including being thickened into solid regions that may appear to be

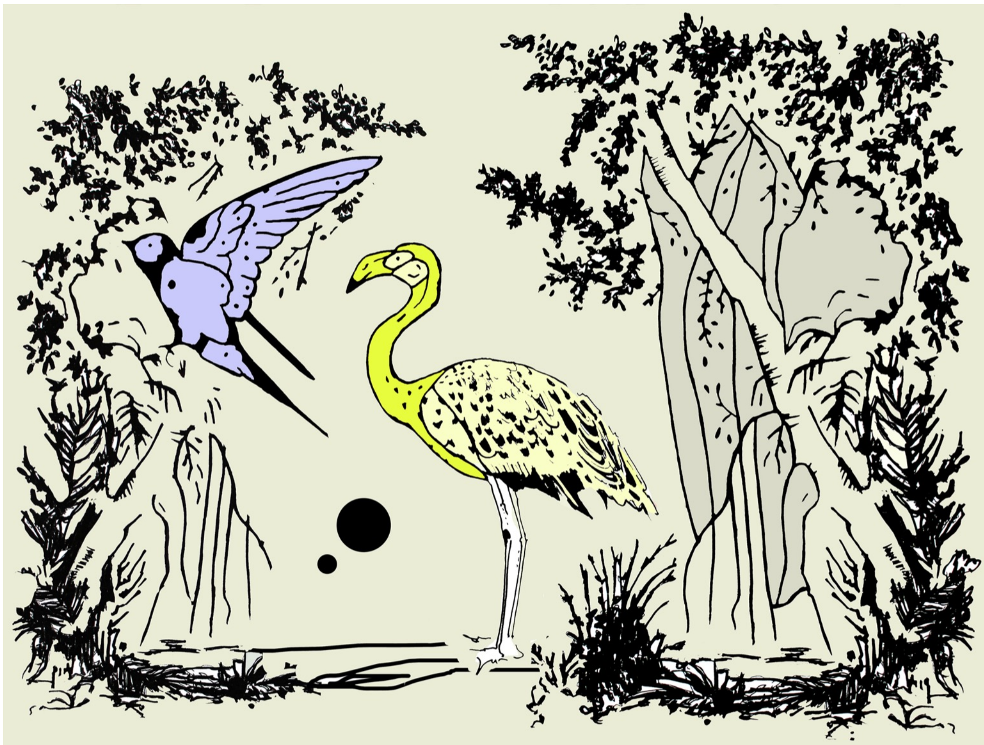

Fig. 13. A complex pattern containing three embossed Artcodes.

Fig. 14. Example of disguising codes in a wider pattern.

visually significant to the user (the neck, beak and wing of the purple bird). Equally lines can bend, curl and branch into very fine detail but provided that they remain joined up will be treated as equivalent to a simple line by the system: *"Initially you think 'I can only put one mark in that region' but then you realize you can put as many as you want as long as you connect them to the outside line."*

Hardly visible break and joins – small breaks in a line may be highly significant to the software but hardly visible to the user. Conversely, elements that are in fact thinly joined will be seen as such by the system, but might be treated as separate by the viewer, especially if they are strikingly similar in appearance to other nearby disconnected elements. The wing and leg of the central standing bird are not fully joined up into regions and so do not form part of the Artcode even though the viewer may perceive them as joined. Employing this technique led designers to constantly push the boundaries of recognizable 'line thickness', that is the minimum thickness of line that might be expected to be reliably readable by the app. In the early days, we established rules of thumb as to appropriate thicknesses and even suggested the use of thicker pens, both of which were unpopular with designers. Subsequently, improvements in camera resolution on mobile phones coupled with designers evolving 'feel' for the technique enabled them to become increasingly subtle in the breaking and joining of lines as a way of disguising codes.

Understanding thresholding – through a process of experimentation, our artisans discovered for themselves that our implementation of the d-touch rules ignored some colours as a result of thresholding the image to black and white before computing contours and topological structures. This allowed them to add colours to their designs that would be significant to humans while also being ignored (thresholded out) by the system, greatly enriching the aesthetics of their patterns. By way of example, Figure 15 shows how the image of the two birds appears to the system after thresholding has been applied.

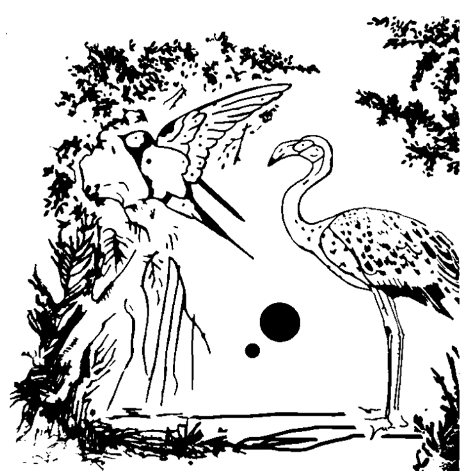

Fig. 15. The pattern after thresholding.

Our artisans also discovered that this thresholding was dynamic, being determined according to the range of colours visible in the image at any moment. On the one hand, this made it trickier to predict whether coloured codes would behave consistently as the camera panned across a complex pattern, leading to requests for greater feedback from the software as we discuss below. On the other, it opened up new creative possibilities including the idea of 'panning and zooming' patterns. As the camera pans and zooms across a large pattern so the range of colours its sees – and hence the greyscale threshold – dynamically changes. A skilful artisan can exploit this to create codes that appear or disappear according to whether other elements of the wider pattern are currently in view or not. Figure 16 shows an early example of a zoomable pattern in which the lighter codes are removed by thresholding when any of the darker lines are visible in the frame but become visible when they are not.

We emphasise that the artisans discovered this creative use of colour by themselves as we had initially considered it unnecessary to brief them about the internal details of how the Artcodes app processes images. As one suggested: *"At present the designs and patterns can only be read if they are produced in one solid strong colour. If it was possible that more colour variation and tonal difference could be read I think it would potentially add more depth to the designs"*.

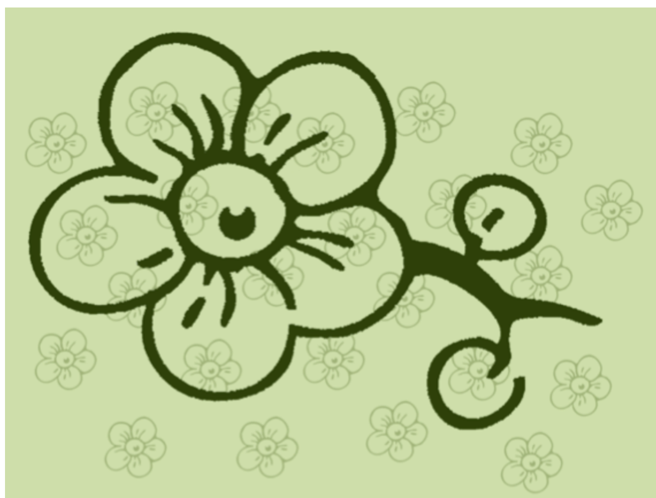

Fig. 16. An early zoomable pattern created by using colour.

Between them, these various techniques gave our artisans great latitude over the extent to which they chose to hide or reveal the presence of individual Artcodes within decorative patterns. This is neatly illustrated by the example of Figure 13, with the entirety of the purple bird on the left being an Artcode, explicitly framed for the viewer through the use of colour and surrounding whitespace in the image, while the same code is reproduced in only part of the second bird in the middle, and is then very heavily disguised in the foliage on the right.

5.2 Materials

It is one thing to design an effective decorative pattern. It turns out to be quite another to apply it to such varied materials as paper, card, fabrics, ceramics and wood. In this section, we reflect on the complex relationship between the visual design of interactive patterns and the materials to which they were applied. Our portfolio reveals a range of important material concerns as we now discuss.

Reflections and shadows – the reliability of computer vision may be greatly affected by lighting conditions. Specular reflections from shiny materials such as glazed ceramics (Figure 17) and satin fabrics 'whited out' specific parts of a pattern making that area unreadable. Shadows cast by external objects, ranging from eating implements, to users' hands and the mobile itself might confuse the thresholding mechanism with similar consequences (also visible in Figure 17). Given that such problems are often localised to part of a pattern at any given moment, the artisans' response was to exploit redundancy, replicating recognisable Artcodes multiple times within a pattern as noted earlier. This strategy makes good sense when one remembers that repeated motifs and repeatable patterns are commonplace in the decorative crafts (think of wall papers, and fabrics and the edges of bowls as common examples).

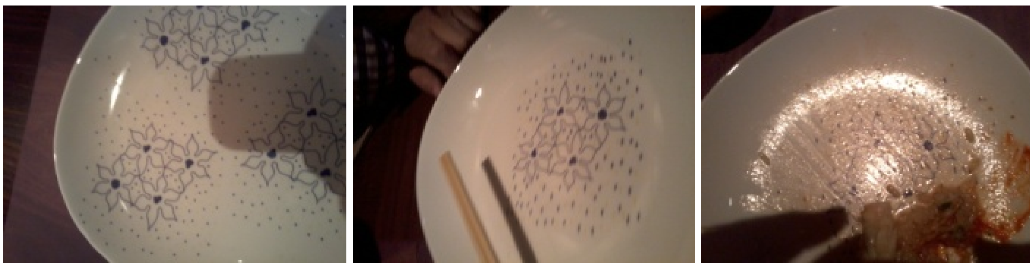

Fig. 17. Challenges of reflections, shadows and food.

Texture and translucency – the natural textures of many materials could also interfere with recognition. This was evident in the careful choice of guitar woods, most notably the flamed maple used for the back and sides (see the back of the guitar in Figure 10). Through a process of trial and error using small samples, the desire for aesthetically pleasing natural figuration in the grain was ultimately balanced against the possibility of accidentally introducing new visual artefacts into the design. A second important aspect of texture was the underlying coarseness of the material, for example the weave of a fabric, which in combination with choice of stitching would affect the resolution of an embroidered Artcode. Similarly the grain of wood in combination with the fineness of routing and cutting, would constrain the resolution of wooden inlay. Dense areas of embroidery standing proud of a base fabric would cause small but noticeable (to the system if not always to humans) shadows, while the depth of the soundboard on the guitar meant that the edges of the cut-out sound-holes appeared as dark shadows under some lighting conditions.

Texture however, is also an aesthetically desirable feature, and so effort was sometimes invested into adding texture, albeit without compromising scanning. This was particular evident in the design of the gift cards. Figure 18, shows how a texture composed of white embroidery thread was first sewn into a blank white card (left), a black template was attached over the top of it and blobs were then sewn on using a darker thread (right). The idea was that the white thread would add visual interest to the design without being visible to the Artcodes app's scanning software.

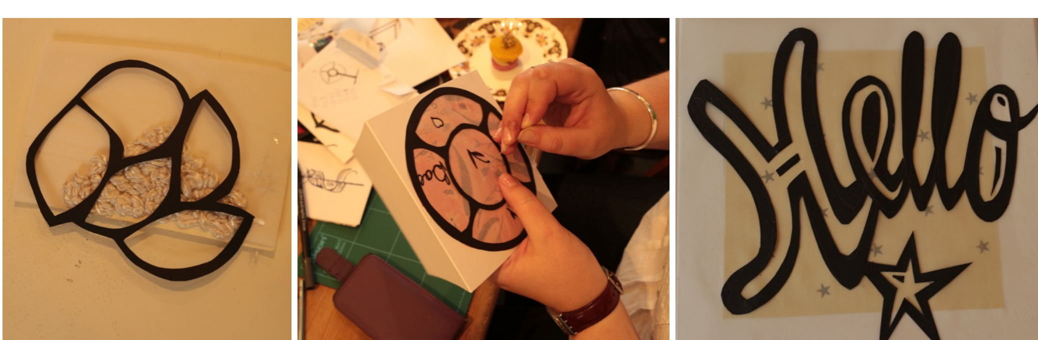

Fig. 18. Adding texture and translucent layers.

We observed the use of **layering** and **translucency** to create new aesthetic and interactive possibilities in which more or less transparent materials were overlaid on an Artcode design (Figure

18 middle and right). One creative possibility was to layer a translucent pattern over an Artcode to temporarily prevent scanning – for example a transparent window in the front of a card so that the Artcode inside can only be scanned once the card was opened.

Deformation – the stretching, bending, folding and draping of materials affected the readability of Artcodes. While the topological shape-independent approach of the rules naturally accommodates a degree of deformation in the image, stretching could open up gaps in rendered designs, for example as embroidered threads separated from one another. The wrinkles produced by backing materials such as silk and mesh (Figure 19) created further shadows, which could cause recognition problems. In contrast, Artcodes printed on lycra could be stretched far more and still remain scannable, with the topological approach of Artcodes proving resilient to spatial warping and distortions.

Fig. 19. Fine silk and a coarse lace mesh as backing material.

5.3 Form and function

The application of interactive decoration to an artefact involved looking beyond 'surface' concerns to also consider form and function. Our annotations here reveal how designers wrestled with dependencies between surface decoration and the deeper structure and the intended usage of artefacts.

Both the **external and internal structure** of artefacts as complex three-dimensional forms impacted on the design and application of interactive patterns. Externally, it was important to consider the various surfaces that an artefact might present for scanning. Cards have fronts and backs and insides and outsides; the Carolan guitar has a front back, sides, headstock, fretboard and cutaway; while garments and furnishings may have complex and even shifting surfaces due to fastening, draping and folding. The various surfaces of an artefact may offer different sized areas for decoration that in turn determines how intimate or public scanning needs to be. For example, the decoration of the Carolan guitar involved placing a large, relatively simple pattern on its back – the largest available surface – so that it might be scanned from several metres away. In contrast, the detailed code in the cutaway required careful scanning from just a few centimetres during close examination of the instrument.

Internal shadows arising from the 3D structure of the artefact could impact scanning. The fronts of gift cards might throw shadows onto the back, the sides of a deep dish might throw shadows onto the base of the dish, or the body of the guitar might throw shadows onto the cutaway and the small holes on its front could throw internal shadows. All of these effects could render Artcodes unreadable under certain lighting conditions and orientations. Beyond shadows, structures could occlude patterns in various ways, which sometimes raised design opportunities as well as presenting challenges. The most notable example of this is the fretboard inlay of the Carolan guitar that can only be read when the occluding strings are removed – an action indicating a particular relationship with the instrument.

Fabricating a solid object typically involves **joining separate parts** together and we saw how the inevitable presence of joins, seams and stitches needed to be taken into account. Embroidered fabrics and cards employed stitching and typically required the careful choice of threads that would remain invisible to the Artcodes software. As is typical of acoustic guitars, the back of Carolan was made from two 'book matched' pieces of wood that were carefully aligned and glued together to create a pleasing symmetrical visual texture from the natural flaming of the maple. Careful attention had to be paid to the finishing of this critical join so as to ensure that it would be invisible to the software.

The design of patterns also needed to respect the **structural integrity** of the artefact. Too much stitching and cutting of cards weakens them to the point that they cannot stand up while the soundboard of the guitar is an especially sensitive structure as we discuss below.

Our designers also needed to consider the intended **function** of an artefact. As well as offering different sized areas for decoration, the various surfaces of an artefact have different functional uses and associations. The top of a bowl is the main surface that is seen and used for eating while the bottom is typically reserved for a maker's-mark and other provenance information. The front of a card presents its public visible message, the inside provides space for the addition of a personal message, and the back again provides space for provenance information. Clothes have different decoration and more or less publicly visible labels on fronts, backs, insides and outsides. The guitar has a headstock where the maker's logo appears, a public front and various other features. Scanning these surfaces may potentially connect to different kinds of information which might in turn be reflected in the designs of the patterns; some might look more like formal logos (the pattern on the headstock of the Carolan guitar) while others might offer more hidden opportunities for interaction.

Finally, we saw how the design of interactive patterns needs to accommodate the dynamic aspects of how an artefact will be held and used, including recognizing the presence of external objects; we saw how chopsticks and cutlery threw shadows onto ceramic bowls in case of Busaba.

5.4 Mappings and interaction

We now turn to the digital experience of interacting with decorated artefacts. Our artefacts served as technology probes to engage various stakeholders in conversations about potential **content and applications**. The Busaba restaurant suggested services from ordering specials and tracking one's order to accessing menu cards (Section 4.1). The gift shop owner suggested attaching personal messages and craft lessons to gift cards (Section 4.2). The lace museum suggested attaching information about traditional designs to the lace souvenirs (Section 4.3). The Carolan guitar was associated with a wide variety of information from a thorough documentation of its making, to a detailed user guide including recommendations for studio recording equipment and settings, to recordings of gigs, new songs, personal repertoires and guitar stories (Section 4.4). Referring back to [Benford et al. 2016], we group these into three broad classes of content: information that enhances *provenance* (e.g., Carolan's history); information that enhances *utility* (e.g., restaurant ordering services); and information that enhances *personal meaning* (e.g., personal messages on gift cards).

A key design challenge involves **mapping** between the physical artefact and digital content. Our portfolio reveals various ways in which a single artefact can employ multiple Artcodes to link to content that addresses different stakeholders. The front of a gift card, for example, might link to a digital gift (perhaps a music track), the inside to a personal message created by the customer who purchases it, and the back to information about the design and other products provided by the maker or retailer. Carolan provides six points of linkage that were used for different purposes – the headstock pointing to the maker's certificate, the sound-hole to the user guide and other surfaces being more freely appropriated by current players [Benford et al. 2015]. Collectively, as a family or artefacts, the Busaba tableware provided multiple links to restaurant services. In response, we extended the Artcodes app to allow the creation, editing and sharing of mappings comprising multiple links as described in section 4.5.

A further concern is how users **discover codes**, especially when they are deliberately disguised within wider patterns. Our portfolio demonstrates that there is no universal approach to this. Some situations require codes to be immediately obvious (scanning a menu to learn about today's 'specials') while others may allow time to become intimate with an artefact (gradually discovering Carolan's more hidden codes). One can also envisage applications that feature the playful discovery of hidden codes such as a children's treasure hunt around a museum. Our portfolio reflects Meese et al. [2013] various strategies for dealing with this challenge of discovery. First, the codes themselves may be made more or less visually obvious, as illustrated by Figure 13 in which three versions of the same code vary from being visually distinct (the purple bird) to disguised (the foliage). Second, additional cues and instructions may be provided on first encountering an artefact, including physical instructions (included with the lace souvenir) or digital ones delivered via the app (each experience in Artcodes comes with a description that may cue the user, more or less overtly, as to what to scan). In these ways, designers can configure the level of support that is provided for discovering the interactive parts of patterns.

Finally, we note split opinions among designers and users as to the appropriateness of using commodity mobile phones and tablets to scan beautiful and bespoke hand-crafted artefacts. In some contexts where we expected this to be problematic, the Busaba restaurant for example, it transpired to be acceptable, with customers routinely using phones in the restaurant, including to take and share photos of the food. In others it proved more controversial. Some, though by no means all, users of Carolan observed that it felt somewhat disjointed to scan a traditional guitar with a mobile phone. Some suggested that it might be more appropriate to query the instrument by playing it which inspired us to create a first prototype musical equivalent of Artcodes, called Muzicodes, in which musicians can specify short musical codes as sequences of pitches and rhythms that can be recognized by a computer and then performed so as to trigger digital media and effects [Greenhalgh et al. 2016]. Another possibility to be explored in future work is to design more aesthetically appropriate forms of camera. Might digital cameras be embedded into companion products that do the scanning, or more simply, might phone cases might be decorated with matching patterns so that they become a more harmonious part of the overall experience?

5.5 Process

We can offer some insight into the process of creating interactive decorative patterns, both how designers approached the challenge of crafting their visual appearance, but also how the use of Artcodes became integrated with and sometimes even pushed back at traditional craft practices.

In terms of **creating visual designs**, the approach tended to be highly iterative, often progressing from hand sketching to the subsequent use of software packages such as Illustrator as the designs firmed up. Some asked whether there could be additional support for creating Artcodes within such tools, especially whether there might be support for the rapid creation of large numbers of distinct codes around a common design by quickly (maybe even automatically) introducing subtle variations.

We observed two broad strategies for creating visual designs. Most designers began by first creating a workable outline structure of regions and blobs (*"I find it easier to start developing an idea based on I know how many regions and I know how many blobs ..."*) and then gradually embellishing this to introduce more and more visual subtlety (*"... so adding these little bits it becomes more of a pattern"*). A second strategy involved sketching an overall pattern in a drawing style that involved many separated marks on the page before then working out which of these could be joined up to create the required numbers of regions and blobs: *"Actually I just start drawing it out how I naturally just draw like this with lots of little lines. So I just started drawing it out and then started kinda thinking which bits should I join so as to make them into regions"*.

However, our artisans rarely began with a blank page, but instead turned to existing designs for inspiration. Several designers working on the pattern book noted how they drew inspiration from existing designs ranging from *"traditional patterns on plates like fleur-de-lis"*, to the works of the famous arts and crafts designer William Morris, to *"very simplified Japanese drawings which is a good resource to work from because they work from those outlines"*. Exiting designs could provide more than inspiration however, and in several cases, were used as a source of template shapes for Artcode designs, an approach clearly demonstrated in the use of art deco designs in the gift cards and historic lace designs in the museum souvenir.

Working with diverse materials and physical forms brought Artcodes into contact with a variety of traditional craft techniques including cutting, routing, embroidering, stitching, dyeing, glazing, inlaying, varnishing, layering, book matching, distressing and others. While applying these techniques often involved handcrafting using traditional tools, we also saw the extensive use of machinery including for example the Barudan embroidery machine and a laser cutter, requiring Artcode designs to be imported into their control software, often a fiddly process.

A particular challenge lay in debugging designs. In general, debugging – meaning figuring out and removing the errors in the design of an Artcode or in its application to a specific material – was a complex business. Bugs could arise from various sources. First, a designer might misunderstand the topological drawing rules, a problem that tended to be encountered and usually rectified during the early stages of training. Second, the execution of a drawing might contain defects such as a fine lines that didn't quite connect or small white regions appearing in an area that was not properly filled in. Such problems could be more difficult to spot, especially in complex patterns. Trickier challenges arose from the application of designs to specific materials when reflections, shadows, textures and deformations could cause problems with scanning as described earlier in this section. Finally, bugs could arise from misunderstandings about the operation of cameras, especially about differences in resolution and sensitivity to lighting between different models. One particularly counterintuitive problem could arise from upgrading mobile phones, as higher resolution (i.e., better) cameras might 'see' breaks in lines and gaps in regions that had not been visible to lower resolution (i.e., worse) cameras. Upgrading a camera might therefore potentially cause an existing pattern to cease working. This might lead to backward incompatibilities and led to the idea of including 'camera profiles' with in experiences so that the app could be set to an appropriate camera resolution in software.

Debugging a code required revisiting the drawing, material and cameras in combination. This typically involved iterative applications of a design to a chosen material and testing with a selection of cameras. Debugging also relied on discussions with other experienced designers, supported with the exchange of images when working at a distance so as to share and build up craft knowledge.

Especially tricky cases would also be referred to the software design team for further investigation. An especially difficult challenge for debugging involved 'seeing as the camera sees', meaning being able to understand how the image would appear after key stages in the image processing pipeline, especially colour thresholding. In order to support this, we extended the app with several optional debugging modes that can be toggled on or off, including various combinations of revealing the outlines of detected codes (Figure 20, left) and showing the image after colour thresholding (Figure 20, right).

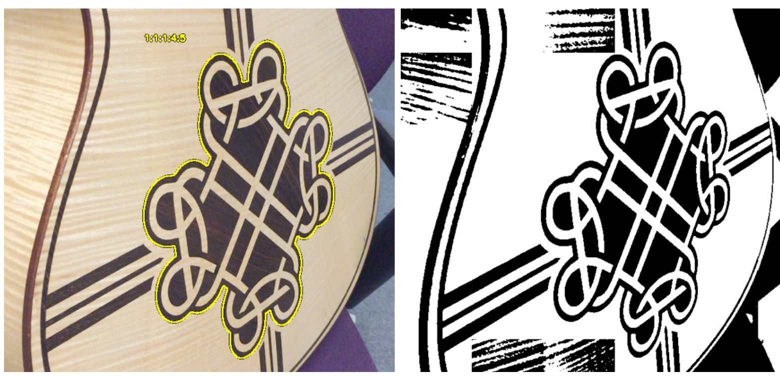

Fig. 20. Two debug modes in the Artcodes app: showing the outlines of detected codes (left) and showing the image after thresholding (right).

5.6 Carolan's soundboard as an integrating example

We now delve into one detailed example to illustrate how these various factors – pattern, material, form, function and process – impacted on one another and needed to be addressed in a holistic manner. Our chosen example is Carolan's soundboard, a delicate, complex and visually and functionally important surface of the guitar whose design involved an extensive dialogue between graphic designer and luthier.

The soundboard is the most sensitive part of an acoustic guitar, being highly influential in shaping its voice. Ideally, it is fashioned from an expensive tonewood (Spruce in Carolan's case), fashioned to be as thin as possible, placed under great tension so as to vibrate in response to the striking of the strings, and consequently supported by bracing from underneath so as to prevent its collapse. Its lower fatter bout (the wider part of the body) is especially sensitive and should not be cut through or heavily inlayed. The central and upper areas are more workable and typically feature one or more sound-holes (traditionally one in the middle) with an area sufficient to project the voice of the instrument.

The decoration of the soundboard brought together all of the techniques that we had developed elsewhere on the guitar. Our designer created a flowing Celtic knot design containing several repetitions of an Artcode in order to increase reliability through redundancy. The dark areas of this Artcode were formed from a combination of wooden inlay and mini-sound-holes that were cut through the soundboard, an innovation proposed by the luthier on seeing early designs. Realizing this design proved to be an especially complex task in which aesthetics (the flow of the design around the guitar) needed to be balanced against musical function (the need for a sufficient total area of sound-holes) and structure (avoiding cutting into the bracing or working too much on the lower bout).

Enabling the reliable scanning of this pattern entailed further challenges. First, we had to ensure that it would be scannable against the textured grain of the spruce as noted above. Second, we realized that the sound-holes allow light to enter the body of the guitar so that they may not show as totally black. We debated staining the inside of the guitar black to mitigate this problem but ultimately elected to leave it in a natural finish and rely on the user to get the feel of how to position the guitar in the light to read this particular pattern for aesthetic reasons.

Thus, the production of the soundboard became the critical point to which graphic design, woodcraft, structure, form and interaction were all brought together in a single moment of design. Balancing these various factors involved an extensive dialogue between the luthier and graphic designer during which they exchanged CAD images such as the one shown in Figure 21 in which the cut out areas of the patterns are coloured in red and are carefully positioned to avoid the underlying bracing (dashed lines).

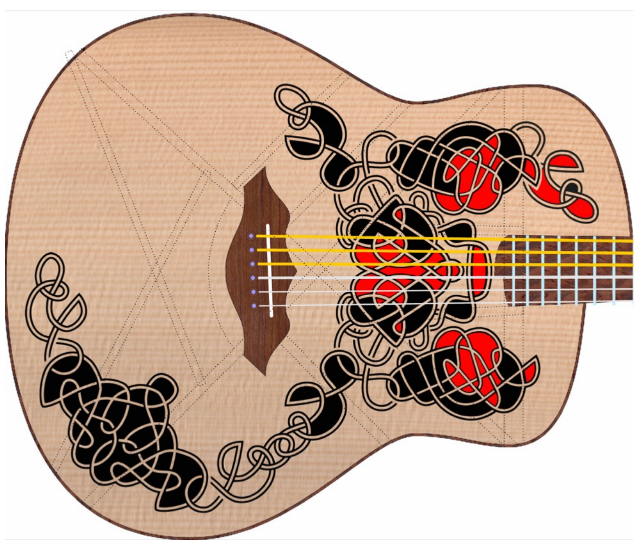

Fig. 21. Design of the Spruce soundboard. Black areas were to be inlaid with darker Mahogany while the red areas were to be cut through to form mini-soundholes.

Finally, we note how the design of the soundboard had profound implications on the wider structure and making of the instrument. The presence of many small sound-holes makes it impossible to 'get inside' the guitar to carry out routine maintenance, a problem that was resolved by a further innovation of creating the removable sound-hole on the top-side, held in place using magnets. Moreover, not only did the design push back at the form of the instrument, but it also altered the luthier's traditional craft practice through the extensive use of laser cutting that was then combined with hand inlay and finishing techniques to render the final surface. Thus, what was initially seen as an opportunity to decorate the surface of a traditional guitar with interactive codes ultimately drove deeper innovation in the structural design of the artefact.

5.7 Summary of artefacts and annotations

We conclude this section with a visual summary of our annotated portfolio, building directly on the stylistic conventions of the example presented in [Gaver 2012] in which artefacts are labelled with key design lessons – annotations – that are colour coded according to theme. Although Gaver explicitly notes "that annotated portfolios are not defined by their graphic presentation", i.e., this is just one possible representation of an annotated portfolio, we found it to be a particularly good fit for our portfolio and a powerful way of drawing together the key contents of Sections 4 and 5 into a single visual summary. In our case, there are four example artefacts: *ceramic tableware*, mixed media *gift cards*, *fabric souvenirs* and the *Carolan guitar*, each of which is annotated under the four themes of hiding codes in *patterns*, accommodating *material* properties, fit to *form and function*, *mapping* patterns to digital content, and integration with tools and *process*.

Fig. 22. Visual summary of our annotated portfolio in the style of Gaver [2012].

6 DISCUSSION

We now step back from the details of our annotated portfolio to consider the wider ramifications for HCI. Overall, we have revealed a deep process of crafting that involves the creation of rich visual designs that are then embedded into particular materials and artefacts. The following discussion considers these two key aspects of the craft in turn, relating each to the wider HCI literature. The first part focuses on the visual aspects of design, considering how our artisans came to understand the differences between human and system perception of visual patterns. Here we extend previous discussions in HCI of interacting with invisible sensing systems, openness and seams discuss by showing how they were able to bridge between these two very different perspectives to resolve issues with the reliability of scanning and inspire new creative opportunities. The second part focuses on how our artisans engaged with the material aspects of embedding interactive surface decorations into physical artefacts. Here we extend HCI's recent discussions of materiality with new insights into material properties; the structure, form and function of artefacts; and craft techniques and processes.

6.1 Bridging between human and system interpretation of visual patterns

There is a longstanding understanding in HCI that interacting with invisible sensing systems – including the kinds of vision-based augmented reality that we are dealing with here – can be challenging. As far back as 2002, Bellotti et al. [2002] articulated five key questions for the designers of invisible sensing systems:

(1) *When I address a system, how does it know I am addressing it?*
(2) *When I ask a system to do something, how do I know it is attending?*
(3) *When I issue a command, how does the system know what it relates to?*
(4) *How do I know the system understands my command and is correctly executing my intended action?*
(5) *How do I recover from mistakes?*

At first glance, the answers to these questions would appear to concern the design of the interface to the Artcodes app. Considering questions 1 and 2, the user addresses the system by pointing the sensor – camera – at an artefact (or part of an artefact) that they believe may contain a scannable code. They are guided in this by a live camera feed and a message that confirms that the system is currently in the mode of 'detecting' codes. Questions 3 and 4 are addressed by popping up a button labelled with the linked content whenever a valid code is detected. Question 5 is dealt with by having back buttons that allow the user to cancel the button and return to the scanning state. However, while the operation of the scanning interface should be clear and transparent, the same need not be true of the patterns themselves. As noted in section 5.4, the legibility or otherwise of a given design, by which we mean the immediately visibility of its embedded codes compared to any surrounding non-interactive elements, is a conscious design choice.

Determining whether and how to make a given pattern immediately legible or more playfully exploratory, while still maintaining an appropriate aesthetic, required our artisans to bridge between two quite different views of the world – the human view and the system view. While computer vision systems, as their name implies, in some sense 'see' images through cameras, they do not see them in the same way that humans do. Cameras have their own fields of view, colour images may be reduced to greyscale and then thresholded, contours are detected and matched to topologies and so forth. The challenges of enabling users to see as the computer sees have been previously reported by Morrison et al. [2014] following a study of using Kinect depth-sensing cameras to help perform clinical assessment of the movements of patients with Multiple Sclerosis. Our portfolio also reveals how humans – in our case the designers of interactive patterns – need to be able to see as the computer sees.

As obvious starting point was to understand how the Artcodes app interprets images through its implementation of the d-touch topological rules. It 'sees' nothing other than these structures and looks for them everywhere. An interesting feature of the app is that these drawing rules are open and comprehensible to designers. Other aspects of how the system sees, however, only came to be appreciated through experience. Appreciating the relationship between camera resolution, fineness of line, and likely viewing distance was important to balancing aesthetics and reliability and tended to emerge through experience. We reported above how artisans discovered the effects of thresholding for themselves and how ultimately this led to additional feedback being implemented in the app. Finally, artisans learned the particular sensitivities of the technology to reflections and shadows. In short, in order to successfully create interactive patterns artisans needed to understand much of the 'vision pipeline' through which the system captures and processes images.

In turn, our findings reveal how our artisans also understood how humans interpret visual imagery. A fundamental aspect of visual design concerns separating 'figure' from 'ground', meaning understanding how a viewer is likely to interpret an image as being something meaningful. This idea is taught as a fundamental aspect of graphic design [Zakia 2002] and in turn, relies on a series of principles explained through Gestalt psychology. When interpreting images, humans appear to employ principles such as similarity, proximity, grouping, alignment and closure to help separate figure from ground. Our examples of how designers disguise codes within wider patterns reveal how they relied on these same principles. Closure, for example, might lead a human to join up the gaps to form a region where the system would see none (the wing of the middle bird in Figure 13). Similarity and symmetry might lead them to connect up disjoint parts of the image to form a larger whole (e.g., the grey cliff behind the tree on the right of Figure 13) and proximity might lead them to associate disconnected embellishments with a significant structure (e.g., the foliage).

These examples reveal that, not only do designers appreciate how humans and the system interpret images, but that they also learn to manage and even exploit the differences between these two perspectives. On the one hand, these differences can be a source of problems that need to be solved. While the system may be highly sensitive to specular reflections and shadows, humans may be less so, learning to 'see through' them to the image beneath (just because part of the image is temporarily obscured by a reflection, we still remember that it is a bird and can fill in the gap). These differences in visual interpretation may make it difficult for untrained people to comprehend why the system appears to fail requiring designers to learn to become more sensitive to them – to see more like the system sees. On the other hand, these differences can be a source of creativity, enabling designers to 'trick' humans and disguise codes within patterns.

This line of argument builds on previous work in HCI into interactions with invisible sensing systems in the form of the *Expected, Sensed & Desired* (ESD) design framework [Benford et al. 2005]. This encouraged the designers of sensing-based applications to compare and contrast three distinct perspectives on interaction:

- *Expected interactions* – movements of an interface that users might naturally be expected to perform compared to those that might be possible but unusual versus those that are impossible.
- *Sensed interactions* – movements that can be sensed by the system versus those that cannot.
- *Desired interactions* – movements that are desired for a given application versus those that are not.

The framework invites designers to explore the partial overlaps between these categories so as to reveal potential problems (e.g., naturally expected and desirable interactions that cannot be sensed, or naturally expected interactions that can be sensed but are not desirable) as well as new opportunities (unusual interactions that can be sensed and might lead to surprising though desirable interactions).

We can adopt and extend this approach to help explain our findings here. We have argued that designers need to adopt the perspective of the human. While the original ESD framework focused on considering more or less expected *movements*, our focus here is more on reasoning about human *perception*, i.e. how humans interpret visual patterns. In turn, adopting the system perspective involves reasoning about the system's *sensed perceptions*. Thus, rather than reasoning about the range and nature of movements of an interface, the focus for analysing Artcodes is on perceiving the features of an image.

We therefore propose expanding original ESD framework as follows. Expected Interactions are expanded to become Human Interactions, a holistic view of how humans might perceive and act in relation to a sensing system and any artefacts of mutual interest. In turn, Sensed Interactions are expanded to System Interactions, encompassing how the system both perceives and acts in relation to the human and any artefacts of common interest. A systematic analysis and comparison of the two then informs Desired Interactions, either revealing problems that need to be resolved or suggesting new design opportunities. Figure 23 shows the resulting revised framework – with the revised name *Human-System-Desired* (HSD). The top part of the figure summarises the overall approach of systematically analysing and comparing human perception and action with system perception and action in order to reveal both design challenges and opportunities. The bottom-left draws on our findings to illustrate an example of applying the framework to identify an interactional problem while the bottom-right illustrates an example of a identifying a creative opportunity.

We propose that the capability to compare human and system perspectives and so shape desired interactions is facilitated by the rules and operation of the Artcodes app being relatively open to artisans. This brings us to another relevant area of HCI theory, the notion of *seamful design* that argues for the benefits of revealing and even exploiting the seams (gaps and imperfect joins) in invisible sensing and communications systems. Seamful design originated from experience with sensing systems such as GPS and WiFi, leading to examples of mobile games that employed limited coverage as a resource rather than a problem [Barkhuus et al. 2005; Chalmers and Galani 2004]. Our findings here reinforce the notion of exposing seams in vision systems, for example the effects of lighting and shadows on vision system (which effectively cause gaps in coverage analogous to GPS canyons) and in places quite literally relates them to the seams in underlying materials such as the stitching in textiles and joins in woods. While the examples above treat these as problems to be solved, the principle of seamful design suggests that we might adopt them as opportunities to be exploited. Might we design interactive patterns that rely on casting shadows in a particular way (like a sundial) or only become interactive under certain lighting conditions?

We saw earlier how our artisans appeared to appreciate the constrained nature of the topological rules, citing this as an inspiration for creativity. This mirrors findings from other creative fields such as music where the imposition of constraints has been seen as a spur to creativity rather than a hindrance. Boden [1990] argues that constraints are a vital source of creativity: "Far from being the antithesis of creativity, constraints on thinking are what make it possible. ... Constraints map out a territory of structural possibilities which can then be explored, and perhaps transformed to give another one". Building on Boden's arguments, Magnusson [2010] notes the common strategy of designing constraints into instruments so as to avoid creative paralysis arising from the "practically infinite expressive scope of the environment" while Gurevich et al. [2012] demonstrated how the construction of a highly constrained simple electronic instrument with apparently minimal capabilities led to musicians exploring diverse performance techniques and styles in practice. In a similar vein, we suggest that the' highly constrained d-touch rules underpinning Artcodes may be an important factor in stimulating creativity and inspiring the wide range of designs and styles are evident in our portfolio.

Not only are these rules constrained, but they also open up a degree of ambiguity in terms of the relationship between visual patterns and underlying topological structures. Our designers positively celebrated the ability to create different designs for the same underlying code, or alternatively to make very similar looking designs map to quite different codes. This mirrors a longstanding discussion in HCI of the role of *ambiguity* in interaction design, specifically how ambiguity of information, context or relationship can provoke interpretation during interaction [Gaver et al. 2003]. Here we report a new form of ambiguous information, an ambiguous relationship between

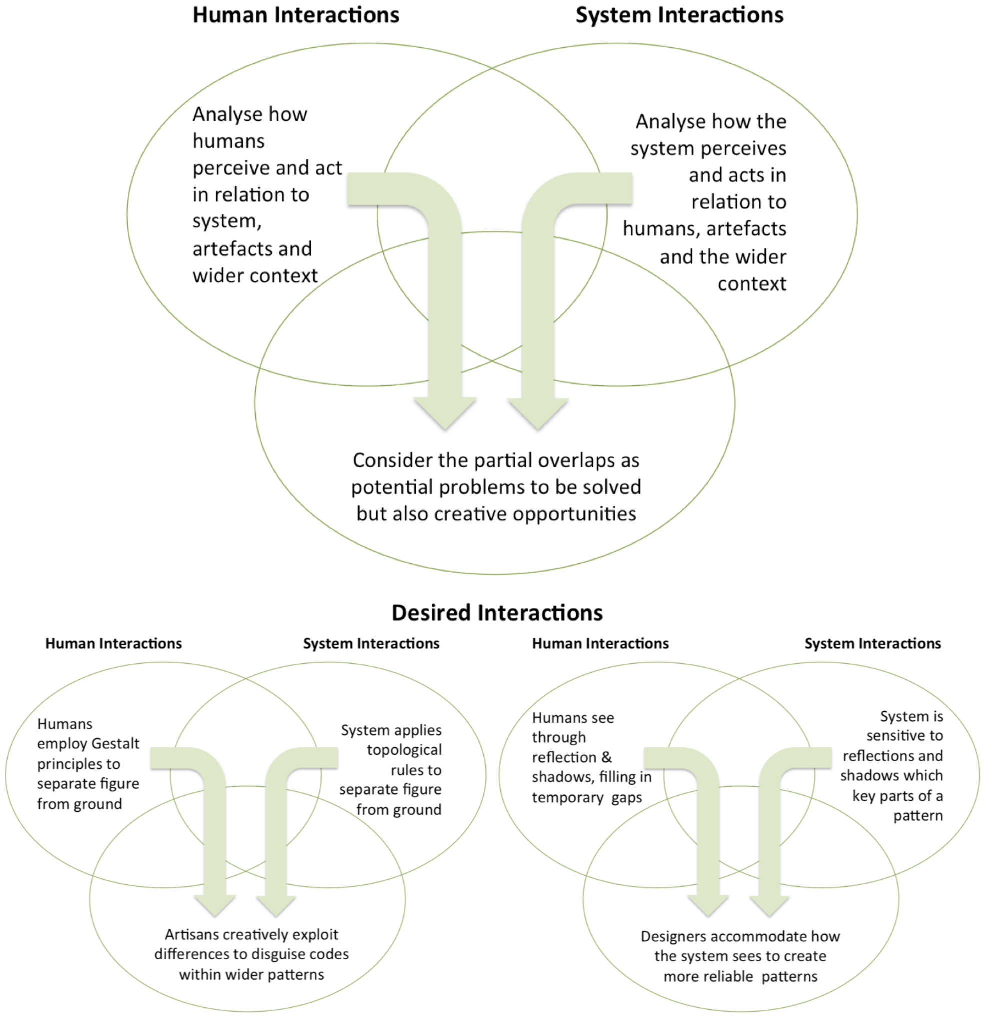

Fig. 23. The Human-System-Desired Interactions framework.

the appearance of an image and underlying codes that are embedded within it, that allow designers to create a range of interpretations.

6.2 Deep embedding, materiality and craft

Our findings extend beyond surface concerns with appearance and visual interpretation to also encompass the material properties of the artefacts. Consequently, they speak on-going discussions about the relationships between digital technologies, materiality and craft within HCI (and beyond) that we reviewed back in Section 2. Building on the results of a workshop at CHI 2012 [Rosner et al. 2012], Gross et al. [2014] articulated three major strands to this discussion – Tangible User Interfaces, composite- and trans- materials, and a growing engagement with craft – providing a broad framing for our discussion.

Early research in Tangible User Interfaces focused on the functional affordances of graspable interfaces [Fitzmaurice et al. 1995] but was soon extended by Ishii and Ullmer [1997] to incorporate an aesthetic perspective drawing on works such as Durrel and Bishop's Marble Answering Machine [Poynor 1995]. Their framing of 'bits as atoms' suggested looking beyond the surface to consider a more fundamental relationship between the physical and digital, an idea reflected in subsequent proposals for 'transmaterials' [Brownell 2006], 'composite materials' [Vallgårda and Redström 2007] and the notion that physical and digital materials combine to achieve different 'textures' [Robles and Wiberg 2010]. In reflecting on their experience with 'material probes' in which digital devices are decorated with various unconventional materials, Jung and Stolterman [2011] report how such materials shape both the aesthetic and functional qualities of an artefact and how their material characteristics need to be considered at the early stages of design.

While it may be a stretch to describe the artefacts in our portfolio as radical new kinds of composites or transmaterials, our findings reveal how interactive decoration is more than skin deep. Rather than simply 'slapping on' patterns, our designers needed to be intimately familiar with the physical characteristics of ceramics, fabrics and woods in order to deliver new physical-digital textures. Our findings reinforce Jung and Stolterman's view that such material properties need to be considered at the early stages of design, for example alongside graphic design so that the resulting decorative patterns are appropriate to the specific materials to which they are applied. They reveal that this involves many mundane – but important – practical concerns (as well as wider aesthetic ones) that affect the reliable operation of the patterns, for example adapting designs to accommodate the reflectivity of glazed ceramics, the stretchiness of embroidery or the texture of wood grain. This mirrors previous research by Rosner et al. [2015] who, through applying conductive inks to ceramics to craft interactive craft artefacts, noted how the painting of interactivity onto a ceramic surface needed to accommodate (and could ultimately exploit) material properties such as roughness, cracking and even breaking into fragments.

This balancing of aesthetic and practical concerns naturally leads us our third thread of discussion, a consideration of the nature of craft. There is a growing interest in HCI on how digital technologies may enhance traditional craft practices, for example integrating electronics into traditional practices such as knitting [Rosner and Ryokai 2009] and bookbinding [Rosner and Taylor 2011]. Our findings provide further examples of the integration of the digital with traditional craft practices, from embroidery to luthiery. They emphasise the handmade nature of crafting that involves the skilled manipulation of physical materials [Rosner and Ryokai 2009] and in which artisans acquire extensive craft knowledge of the techniques, tools and processes involved in working specific materials.

Of particular relevance is Tsaknaki et al. [2014] account of crafting digital interactions using the specific traditional material of leather. Through a series of design workshops involving skilled artisans, they revealed important craft knowledge concerning the use of leather as part of interactive artefacts: material properties of *softness* and *thickness* enabled the crafting of textured buttons on artefacts; the technique for *inlaying* enabled leather buttons to be inset into wooden recesses; the accounting for the natural *weight* of leather when overlaying it on pressure sensors; and the skilled technique of *stitching* to create three-dimensional structures from several two-dimensional pieces of material. They also revealed how the traditional tools and techniques of hand-making were supplemented with more *automated approaches*, specifically the use of a laser cutter to work thick leather and reduce fabrication time, although they also noted how this required integration with specialized software and required more planning and less ongoing adjustment during making.

Our findings, derived from experience with a range of further traditional craft materials, reinforce theirs. We have also seen the importance of accounting for softness, thickness and weight when working with a variety of materials from card and textiles to wood. We have noted key techniques such inlaying and stitching as well as new ones such as distressing. Like them, we have also noted the integration of handcrafting with various kinds of machinery. Thus we concur with Vasiliki et al's emphasis on the importance of specific material properties and techniques in crafting, and extend their account of leatherworking with further craft knowledge derived from working with other materials.

In addition, we have revealed details of how decorative patterns become even more deeply ingrained into artefacts, beyond the properties of the materials from which they are made. From gift cards to guitars, we saw how interactive patterns need to take account of the form and internal structures of artefacts, exploiting them to create new interactive possibilities while also avoiding compromising structural integrity. We also saw how the designs of patterns accounted for the function and meaning of the different surfaces of an artefact (most notably with the guitar) and suggested relationships with different kinds of people (e.g., players, audiences and 'maintainers'). Finally, our portfolio reveals how the application of interactive patterns ultimately pushes back at form, structure, function and meaning, driving innovations in the artefact itself.

Our focus here has been on the fine detail of how the digital becomes enmeshed with the material. We maintain that this is an appropriate level of discussion as craft is inherently about mastering the detail and building a body of craft knowledge. This said, we finish this theme by briefly reflecting on the wider relationship between craft and digital technology that we reviewed Section 2. In contrast to the technologies of CADCAM that are typically concerned with supporting production at scale, our development of Artcodes offers another route to developing digital technologies to support material practices, one that is about deep control by a skilled human over all aspects of the process, from visual design to material application. What is vitally important here is that the technologies are open to artisans at multiple levels and, ideally, are developed in response to their ideas – for example the introduction of controllable colour thresholding in the Artcodes app.

7 CONCLUSIONS

In this paper we have explored the challenge of how to decorate everyday artefacts with interactive patterns. Our long-term goal is to enable skilled artisans to create and apply patterns that are both aesthetically pleasing while also being reliably scanned. Our approach has been one of research through design, working with a pool of artisans to create a portfolio of artefacts before reflecting to draw out general design knowledge while also relating this to on-going research within HCI. We conclude our paper by emphasising three key contributions.

Contribution 1: Recognising the scope interactive surface decoration

Our first contribution is to foreground the importance and potential scope of interactive surface decoration. While visual decoration is an essential aspect of designing all manner of everyday artefacts, it has not been widely recognised as such within HCI. Although both augmented reality and tangible and embedded interfaces have of course considered how to attach recognizable visual codes to artefacts, including how to make these aesthetically pleasing, what we are arguing for here is a far wider perspective in which interactive decoration is routinely and widely applied to all manner of surfaces and artefacts. In this context, our approach of embedding, and especially of disguising, interactive codes within wider patterns challenges the conventional focus of AR. In parallel, HCI's growing discussions of crafting digital interactivity into material artefacts has tended to focus on embedded electronics rather than surface decoration. Our findings suggest complementing on-going research into embedded electronics and new materials with equal attention to their visual decoration. No matter what materials future artefacts may be made of, visual decoration will remain a vital aspect of their design.

In practical terms, we have demonstrated the potential scope of interactive surface decoration through the breadth of a portfolio that spans various artefacts (from bowls, to gift cards to guitars) fashioned from diverse materials (ceramics, card, textiles and wood) using a variety of traditional hand-crafting and modern mechanised techniques. Taken as a whole, our portfolio shows that artisans are able to design and apply interactive decoration to make a range of beautiful and functional everyday artefacts.

Contribution 2: Distilling craft knowledge for making interactive surface decoration

Our second contribution has been to reveal *how* artisans set about creating interactive surface decoration. We have documented detailed craft knowledge concerning how to design and apply interactive surface decoration, presenting fine details of how artisans manage to create aesthetic, functional and appropriate artefacts. Notable here is the level of creativity that they were able to bring to the Artcodes technology in terms of skilfully creating a wide variety of patterns containing disguised visual codes. We have revealed how this is a deep process that spans visual design (techniques for disguising interactive codes within wider patterns) and material craft (techniques for working specific materials and assembling them into complex artefacts). We also saw how the application of interactive surface decoration pushed back at the underlying characteristics of artefacts, ultimately reshaping their deeper structures. Crafting interactive decoration also requires balancing aesthetic and functional concerns. Aesthetics are clearly crucial and may even be the primary concern in many cases. And yet artisans must negotiate difficult trade-offs in working out how to embed moments of interactivity into particular surfaces and how to make this reliable on varied materials under real world conditions. Being able to successfully balance these various concerns involves a 'deep embedding' of the digital into the material, one that extends far beyond surface matters top also address materials, form, structure, function, meaning, processes and tools.

Again, in practical terms, we have documented detailed craft knowledge that describes how this deep embedding was achieved in a number of specific cases. We generalise this into three general design principles.

(1) **Embed interactive visual codes within wider aesthetic patterns.** The principle concerns the visual design of interactive patterns. The first question is to consider to what extent the interactive parts of the pattern need to be differentiated from their surroundings. Will unfamiliar users need to understand exactly how to interact with the pattern from the start or might is an element of playful discovery or acquired familiarity important to the experience. The second is then to consider specific techniques for disguising or revealing the interactive parts, especially drawing on knowledge of how humans are likely to perceive patterns (e.g., Gestalt principles that explain how people separate figure from ground) compared to system (e.g., knowledge of the computer vision pipeline).

(2) **Select the surfaces of an artefact to decorate with interactivity.** We have seen how choosing which surfaces to decorate involves balancing multiple concerns. Of course, it is important to understand what interactions are desired in the first place. Then it is necessary to carefully explore the range of surfaces that the artefact makes available for potential decoration. How are these employed in normal use? For example, are they routinely held, touched or obscured or will other materials be placed upon them? Selection might also consider logical or cultural associations including whether different surfaces speak to different audiences? Are some more public, perhaps as a result of having large and exposed areas, while others are more hidden? Can others only be accessed by particular people under special circumstances?

(3) **Accommodate material properties.** The crafting process also needs to address how material properties such as reflectance, texture, stretchiness and so forth potentially affect interactivity and whether they even suggest new creative possibilities for shaping interactive patterns such as accommodating natural grain and patterning. Materiality also extends to the underlying structure of the artefact, especially to maintaining its structural integrity. Finally, it is important to consider the techniques and tools required to work the chosen materials. Might the presence of extensive decoration benefit from or require rapid manufacturing technologies such as ever more readily available laser cutters, 3D printers and so forth and what level of integration is required with supporting design software.

Collectively, these questions constitute a high-level checklist to be considered when embarking on a process of interactive decoration, to be used in conjunction with human-, system- and desired- interactions framework presented in Figure 23 in order to systematically step through the complexities of deeply embedding interactive decoration into a specific artefact.

Contribution 3: Opening up computer vision technologies

Our final contribution is to argue more generally for the importance opening up the operation of computer vision systems to designers and potentially to end-users too. Computer vision is an especially flexible sensing modality that is becoming increasingly widespread in everyday life due to the ubiquity of cameras in mobile devices and the emergence of specialist depth-sensing cameras for computer games. However, computer vision is also a complex modality involving a various algorithms being configured and applied at different stages along a pipeline. Moreover, humans are equipped with their own sense of vision and natural understanding of how this operates. As a result, it is easy for people to become confused about how computer vision systems 'see' the world leading to interactional difficulties. This of course, is exactly the challenge that Bellotti et al. [2002] were referring to in their general discussion of invisible sensing systems that we discussed earlier on. Our contribution here is to shed light on specific nature of these issues with respect to computer vision.

We have revealed the key role of the artisan, especially the graphic designer, as the bridge between the worlds of human and computer visual perception. It is the artisan who comes to understand the different ways in which people and the system interpret visual images, trading these off to anticipate and resolve potential problems or inspire creative opportunities. We suggest that the open and ambiguous nature of the topological rules plays an important role here. With Artcodes, artisans can easily learn to understand how the technology interprets images, both in terms of the topological features that it exclusively 'sees' but also in terms of how images are processed (e.g., thresholded), especially in relation to different surfaces materials, as revealed by additional feedback in the app.

The question then becomes whether this principle generalises to other computer vision technologies? Could our artisans have created both aesthetic and functional interactive patterns using less open augmented reality technologies where the recognition rules and internal processing of the system are not revealed in advance. There are certainly many powerful AR technologies available as we noted earlier and no doubt that they can continue to be developed to accommodate the challenges of reliable operation on diverse material under real world conditions. And yet in the work reported here opening up the technology to artisans does appear to have enabled them to harness their creative abilities and design and craft knowledge. It is an open question for further research as to whether artisans would achieve equally compelling results using more closed vision technologies in which they are able to create any pattern they wish without as many evident constraints and with the system attempting to recognise it reliably. We have certainly seen that artisans can create interactive artefacts using Artcodes. It remains to be seen whether Artcodes' distinctively open and ambiguous approach is an inherent boon to creativity from which other approaches might benefit. Our intuition is that it may well be.

ACKNOWLEDGMENTS

This research has been supported by the Living with Interactive Decorative Patterns project (EPSRC Grant No. EP/L023717/1), by the Horizon Digital Economy Research Institute (EPSRC Grant No. EP/G065802/1 and EP/M02315X/1) and by the Fusing Semantic and Audio Technologies for Intelligent Music Production and Consumption – FAST – project (EPSRC Grant No. EP/L019981/1) project. We are extremely grateful to all of the artisans who have worked with us to create the portfolio of decorated artefacts.

REFERENCES

Barcode Revolution. 2013. Barcode Revolution website. (Jan. 2013). Retrieved January 1, 2013 from http://www.barcoderevolution.com/

Louise Barkhuus, Matthew Chalmers, Paul Tennent, Malcolm Hall, Marek Bell, Scott Sherwood, and Barry Brown. 2005. *Picking Pockets on the Lawn: The Development of Tactics and Strategies in a Mobile Game.* Springer Berlin Heidelberg, Berlin, Heidelberg, 358–374. DOI: http://dx.doi.org/10.1007/11551201_21

Victoria Bellotti, Maribeth Back, W. Keith Edwards, Rebecca E. Grinter, Austin Henderson, and Cristina Lopes. 2002. Making Sense of Sensing Systems: Five Questions for Designers and Researchers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02).* ACM, New York, NY, USA, 415–422. DOI: http://dx.doi.org/10.1145/503376.503450

Ross Bencina, Martin Kaltenbrunner, and Sergi Jorda. 2005. Improved Topological Fiducial Tracking in the reacTIVision System. In *Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05) - Workshops - Volume 03 (CVPR '05).* IEEE Computer Society, Washington, DC, USA, 99–. DOI: http://dx.doi.org/10.1109/CVPR.2005.475

Steve Benford, Adrian Hazzard, Alan Chamberlain, Kevin Glover, Chris Greenhalgh, Liming Xu, Michaela Hoare, and Dimitrios Darzentas. 2016. Accountable Artefacts: The Case of the Carolan Guitar. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16).* ACM, New York, NY, USA, 1163–1175. DOI: http://dx.doi.org/10.1145/2858036.2858306

Steve Benford, Adrian Hazzard, Alan Chamberlain, and Liming Xu. 2015. Augmenting a Guitar with Its Digital Footprint. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME 2015).* The School of Music and the Center for Computation and Technology (CCT), Louisiana State University, Baton Rouge, Louisiana, USA, 303–306. http://dl.acm.org/citation.cfm?id=2993778.2993853

Steve Benford, Holger Schnädelbach, Boriana Koleva, Rob Anastasi, Chris Greenhalgh, Tom Rodden, Jonathan Green, Ahmed Ghali, Tony Pridmore, Bill Gaver, Andy Boucher, Brendan Walker, Sarah Pennington, Albrecht Schmidt, Hans Gellersen, and Anthony Steed. 2005. Expected, Sensed, and Desired: A Framework for Designing Sensing-based Interaction. *ACM Trans. Comput.-Hum. Interact.* 12, 1 (March 2005), 3–30. DOI: http://dx.doi.org/10.1145/1057237.1057239

Blippar. 2013. Blippar website. (Jan. 2013). Retrieved January 1, 2013 from http://blippar.com/

Margaret A. Boden. 1990. *The Creative Mind: Myths and Mechanisms.* George Weidenfeld and Nicolson Ltd.

Blaine Erickson Brownell. 2006. *Transmaterial: A Catalog of Materials That Redefine Our Physical Environment.* Number bk. 1 in Transmaterial: A Catalog of Materials that Redefine Our Physical Environment. Princeton Architectural Press.

Matthew Chalmers and Areti Galani. 2004. Seamful Interweaving: Heterogeneity in the Theory and Design of Interactive Systems. In *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (DIS '04).* ACM, New York, NY, USA, 243–252. DOI: http://dx.doi.org/10.1145/1013115.1013149

Amy Cheatle and Steven J. Jackson. 2015. Digital Entanglements: Craft, Computation and Collaboration in Fine Art Furniture Production. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing (CSCW '15).* ACM, New York, NY, USA, 958–968. DOI: http://dx.doi.org/10.1145/2675133.2675291

Enrico Costanza and Jeffrey Huang. 2009. Designable Visual Markers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09).* ACM, New York, NY, USA, 1879–1888. DOI: http://dx.doi.org/10.1145/1518701.1518990

Enrico Costanza and John Robinson. 2003. A Region Adjacency Tree Approach to the Detection and Design of Fiducials. In *Proc. VVG.* 63–69.

D-Barcode. 2013. D-Barcode website. (Jan. 2013). Retrieved January 1, 2013 from http://www.d-barcode.com/

Peter Dormer. 1997. *The Culture of Craft.* Manchester University Press.

Mark Fiala. 2004. Artag revision 1, a fiducial marker system using digital techniques. *National Research Council Publication* 47419 (2004), 1–47.

George W. Fitzmaurice, Hiroshi Ishii, and William A. S. Buxton. 1995. Bricks: Laying the Foundations for Graspable User Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '95)*. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 442–449. DOI: http://dx.doi.org/10.1145/223904.223964

Christopher Frayling. 1993. Research in art and design. (1993).

William Gaver. 2012. What Should We Expect from Research Through Design?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 937–946. DOI: http://dx.doi.org/10.1145/2207676.2208538

William W. Gaver, Jacob Beaver, and Steve Benford. 2003. Ambiguity As a Resource for Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*. ACM, New York, NY, USA, 233–240. DOI: http://dx.doi.org/10.1145/642611.642653

Google. 2013. Goggles website. (Jan. 2013). Retrieved January 1, 2013 from http://www.google.co.uk/mobile/goggles/

Chris Greenhalgh, Steve Benford, and Adrian Hazzard. 2016. ˆmuzicode$: composing and performing musical codes. In *Audio Mostly 2016*. 1–8. http://eprints.nottingham.ac.uk/37081/ ACM 978-1-4503-4822-5. doi:10.1145/2986444.

Shad Gross, Jeffrey Bardzell, and Shaowen Bardzell. 2014. Structures, forms, and stuff: the materiality and medium of interaction. *Personal and Ubiquitous Computing* 18, 3 (2014), 637–649. DOI: http://dx.doi.org/10.1007/s00779-013-0689-4

Michael Gurevich, Adnan Marquez-Borbon, and Paul Stapleton. 2012. Playing with Constraints: Stylistic Variation with a Simple Electronic Instrument. *Computer Music Journal* 36, 1 (March 2012), 23–41. DOI: http://dx.doi.org/10.1162/COMJ_a_00103

Tim Ingold. 2013. *Making: Anthropology, Archaeology, Art and Architecture.* Taylor & Francis.

Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97)*. ACM, New York, NY, USA, 234–241. DOI: http://dx.doi.org/10.1145/258549.258715

ISO. 2000. *ISO/IEC 18004:2000 Information technology – Automatic identification and data capture techniques – Bar code symbology – QR Code.* Standard. International Organization for Standardization, Geneva, CH.

Heekyoung Jung and Erik Stolterman. 2011. Material Probe: Exploring Materiality of Digital Artifacts. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 153–156. DOI: http://dx.doi.org/10.1145/1935701.1935731

Qiong Liu, Chunyuan Liao, Lynn Wilcox, Anthony Dunnigan, and Bee Liew. 2010. Embedded Media Markers: Marks on Paper That Signify Associated Media. In *Proceedings of the 15th International Conference on Intelligent User Interfaces (IUI '10)*. ACM, New York, NY, USA, 149–158. DOI: http://dx.doi.org/10.1145/1719970.1719992

Thor Magnusson. 2010. Designing Constraints: Composing and Performing with Digital Musical Systems. *Comput. Music J.* 34, 4 (Dec. 2010), 62–73. DOI: http://dx.doi.org/10.1162/COMJ_a_00026

Malcolm McCullough. 1998. *Abstracting Craft: The Practiced Digital Hand.* MIT Press.

Rupert Meese, Shakir Ali, Emily-Clare Thorne, Steve D. Benford, Anthony Quinn, Richard Mortier, Boriana N. Koleva, Tony Pridmore, and Sharon L. Baurley. 2013. From Codes to Patterns: Designing Interactive Decoration for Tableware. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 931–940. DOI: http://dx.doi.org/10.1145/2470654.2466119

Cecily Morrison, Neil Smyth, Robert Corish, Kenton O'Hara, and Abigail Sellen. 2014. Collaborating with Computer Vision Systems: An Exploration of Audio Feedback. In *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. ACM, New York, NY, USA, 229–238. DOI: http://dx.doi.org/10.1145/2598510.2598519

Powered by String. 2013. Powered by String website. (Jan. 2013). Retrieved January 1, 2013 from http://poweredbystring.com

Rick Poynor. 1995. The hand that rocks the cradle. *ID Magazine* May/June (1995), 60–65. Also known as C.G. Smith 1995 The marble answering machine.

Erica Robles and Mikael Wiberg. 2010. Texturing the "Material Turn" in Interaction Design. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 137–144. DOI: http://dx.doi.org/10.1145/1709886.1709911

Daniela Rosner, Jean-François Blanchette, Leah Buechley, Paul Dourish, and Melissa Mazmanian. 2012. From Materials to Materiality: Connecting Practice and Theory in Hc. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems (CHI EA '12)*. ACM, New York, NY, USA, 2787–2790. DOI: http://dx.doi.org/10.1145/2212776.2212721

Daniela K. Rosner, Miwa Ikemiya, and Tim Regan. 2015. Resisting Alignment: Code and Clay. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. ACM, New York, NY, USA, 181–188. DOI: http://dx.doi.org/10.1145/2677199.2680587

Daniela K. Rosner and Kimiko Ryokai. 2009. Reflections on Craft: Probing the Creative Process of Everyday Knitters. In *Proceedings of the Seventh ACM Conference on Creativity and Cognition (C&C '09)*. ACM, New York, NY, USA, 195–204.

DOI: http://dx.doi.org/10.1145/1640233.1640264

Daniela K. Rosner and Alex S. Taylor. 2011. Antiquarian Answers: Book Restoration As a Resource for Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2665–2668. DOI: http://dx.doi.org/10.1145/1978942.1979332

Vasiliki Tsaknaki, Ylva Fernaeus, and Mischa Schaub. 2014. Leather As a Material for Crafting Interactive and Physical Artifacts. In *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. ACM, New York, NY, USA, 5–14. DOI: http://dx.doi.org/10.1145/2598510.2598574

Anna Vallgårda and Johan Redström. 2007. Computational Composites. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 513–522. DOI: http://dx.doi.org/10.1145/1240624.1240706

Norman J Woodland and Silver Bernard. 1952. Classifying apparatus and method. (Oct. 7 1952). US Patent 2,612,994.

Richard D. Zakia. 2002. *Perception and Imaging* (2 ed.). Focal Press.

John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research Through Design As a Method for Interaction Design Research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 493–502. DOI: http://dx.doi.org/10.1145/1240624.1240704

AUTHOR STATEMENT

This paper builds on and greatly extends a thread of research into interactive decoration that begun with the following CHI 2013 paper:

> Rupert Meese, Shakir Ali, Emily-Clare Thorne, Steve D. Benford, Anthony Quinn, Richard Mortier, Boriana N. Koleva, Tony Pridmore, and Sharon L. Baurley. 2013. From Codes to Patterns: Designing Interactive Decoration for Tableware. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13). ACM, New York, NY, USA, 931–940. DOI: http://dx.doi.org/10.1145/2470654.2466119

This earlier CHI 2013 paper reported the Ceramic Tableware example that we summarise here in 4.1 but did not cover any of the other examples. Some of its discussion of how designers came to understand how the system 'sees' patterns provided the seed for part of our discussion here.

The current submission then goes on to introduce three further examples of interactive decoration in Sections 4.2, 4.3 and 4.4. Two of these are entirely unpublished. The third, the acoustic guitar summarised in Section 4.4, has been the subject of two other papers. This following short paper at NIME 2015 introduced the concept and summarised the initial build of the instrument:

> Steve Benford, Adrian Hazzard, Alan Chamberlain, and Liming Xu. 2015. Augmenting a Guitar with Its Digital Footprint. In Proceedings of the International Conference on New Interfaces for Musical Expression (NIME 2015). The School of Music and the Center for Computation and Technology (CCT), Louisiana State University, Baton Rouge, Louisiana, USA, 303–306. http://dl.acm.org/citation.cfm?id=2993778.2993853

The following paper which has been accepted for publication at CHI 2016 presents a study of how players experienced the guitar and mapped it to its evolving digital record which is not the at all focus of the present submission:

> Steve Benford, Adrian Hazzard, Alan Chamberlain, Kevin Glover, Chris Greenhalgh, Liming Xu, Michaela Hoare, and Dimitrios Darzentas. 2016. Accountable Artefacts: The Case of the Carolan Guitar. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). ACM, New York, NY, USA, 1163–1175. DOI: http://dx.doi.org/10.1145/2858036.2858306

The discussion of human versus system perception in Section 6 explicitly revisits and extends a framework that we previously presented in a TOCHI paper ten years ago as one part of our overall discussion:

Steve Benford, Holger Schnädelbach, Boriana Koleva, Rob Anastasi, Chris Greenhalgh, Tom Rodden, Jonathan Green, Ahmed Ghali, Tony Pridmore, Bill Gaver, Andy Boucher, Brendan Walker, Sarah Pennington, Albrecht Schmidt, Hans Gellersen, and Anthony Steed. 2005. Expected, Sensed, and Desired: A Framework for Designing Sensing-based Interaction. ACM Trans. Comput.-Hum. Interact. 12, 1 (March 2005), 3–30. DOI: http://dx.doi.org/10.1145/1057237.1057239

Finally, our discussion of crafting has built on a submission to CHI 2013 that was rejected. The reviewers were enthusiastic about the direction of the work but felt it required further development. The material on crafting in this paper represents that further development and has not been published anywhere else.

Received February 2007; revised March 2009; accepted February 2017