Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation

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ABSTRACT

Traditional crafting methods such as stitching, embroidering, dyeing and machine sewing can be enhanced to create novel techniques for embedding shape-changing and colour-changing actuation into soft fabrics. In this paper, we show how embedding Shape-Memory Alloy (SMA) wire, copper wire and thermochromic thread into needles and bobbins, we were able to successfully machine sew interactive morphological capabilities into textiles. We describe the results of extensive design experiments, which detail how differing actuations can be achieved through a matrix of parameters that directly influence a fabric's deformational behaviours. To demonstrate the usefulness of our 10 techniques, we then introduce and discuss an interactive artefact we produced, using a subset of these techniques. We contribute such new techniques for creating soft-interfaces, imbued with actuation through tactile and self-morphing capabilities without motors or LEDs. We draw insights from this on the potential of the proposed techniques for crafting interactive artefacts.

Author Keywords

Shape-change; colour-change; actuation; soft-sensing; sew; fabric; dye; bacteria; research-through-design.

INTRODUCTION

Embedding sensing and actuation in everyday materials has inspired recent research in areas such as tangible, organic and soft user interfaces [18, 49, 44]. Some take the approach of innovating new materials that have computational properties [24, 16, 30, 55], while others fix electronic sensors, pneumatic or motor actuators into existing materials, such as paper, fabrics, wood, etc [56, 43, 19, 26]. In this paper, we explore an alternative approach to creating soft interfaces, which is to incorporate smart materials directly into the crafting and making stages of the sewn fabrics. Smart materials that have morphological (shape and colour-changing) capabilities such as thermochromic inks and shape-memory wires can be literally stitched, knitted and weaved into different textiles. Our research aims to explore the different emergent materialities [35] of fabrics crafted from such smart materials. To achieve this, we have adopted a 'Research through Design' [13] approach, which we refer to as 'co-designing with our materials'. We draw on the insights of Gaver [15], who frames the production of annotated portfolios as a rigorous theory and a developing form of research-through-design, to underpin our presentation of a series of laboratory experiments. This portfolio of design explorations, from our own creative practice, offers novel insight into the interactive potentials of the techniques we have exploited.

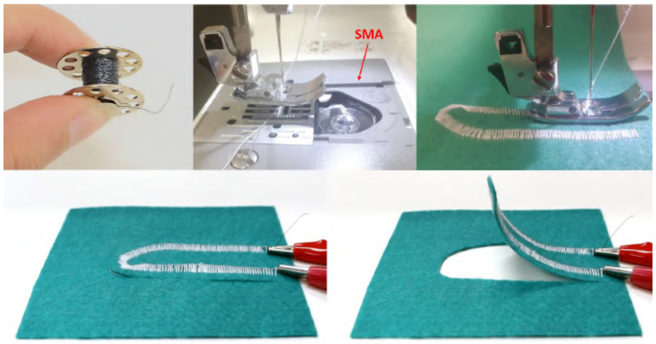

Figure 1. Technique 3: Machine-sewing SMA wire to fabric.

In this paper, we bring material science innovation of actuating *wires* to a new context and appropriated practices, as *threads*. This bridging between technology and crafting enables 'smart' materials to have new encounters with other materials (such as fabrics and textiles), other tools (such as needles and bobbins) and other machines (such as sewing machines or embroidery machines), see Figure 1. This approach broadens the accessibility of technology prototyping and has the potential to enable new previously unrealizable possibilities. For example, it allows any person to sew for themselves a shape-changing garment or make a colour-changing cushion gift without much of the common paraphernalia of digital technology development. Recent research in interactive e-textiles using servomotors and LEDs [22, 25] sits in opposition to notions of 'ubiquitous', 'seamless' and 'everyday use'. However, stitching threads, that alter their appearance and/or interactively deform constituent fabric, making the *seams* hide and reveal new aesthetics might

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also be thought of as a productive play on the idea of seamless and seamful interaction [6].

The objective of our exploratory experimentation is to find novel and user-friendly ways to embed subtle and silent organic movements and actuations that do not disturb people or require constant attention as with other interfaces such as light emitting displays [27]. We present our learning through making in several techniques that explore machine-sewing copper wire, nitinol shape-memory wire and thermochromic thread. Moreover, we introduce the novel technique of re-training shape-memory wire on the bobbin of the sewing machine to create self-crumpling fabrics. Finally, we present our BacterioChromic artefact, crafted using our developed techniques that embed it with morphological actuation as a case study with some insights on how people perceived its materiality and interactivity. Our work contributes a set of appropriations and exploits that can be adopted by others to support the making and crafting of soft-interfaces with morphological capabilities.

In summary, this paper makes the following contributions: 1) Introduces several novel techniques for embedding morphological actuation into fabrics i.e. machine-sewing shape-changing materials such as SMA wires and copper wire with thermochromic-dyed threads; 2) Presents a new SMA austenite shape-training method i.e. coiling the wire directly on the sewing machine's metal bobbin as the memory shape; 3) Identifies the 10 parameters that directly affect the intensity of fabric deformation when sewing SMA is used for embedding actuation; and 4) Showcases and evaluates an interactive artefact crafted using these techniques.

RELATED WORK

The most recent work on e-textiles [17] defined it as fabrics of stitched circuitry with electronic components. The majority of previous e-textile research focused on activating LEDs or motors [19, 22, 5], creating *robotic* fabrics [57]. Although some have explored crafting sensors [34, 37, 58], investigating actuating fabrics has been limited and difficult to replicate. Taking this work further into realising self-morphing fabrics using replicable methods has not been investigated before, aside from online tutorials and blogs stating that machine-sewing shape-changing wire (i.e. SMA) cannot be done [54] and therefore such e-textile applications are not yet ready for mass production and consumption [14].

Actuating fabrics as *computational materials* [48] have been motivating research in the fields of both wearable technology [3, 53] and interactive interior spaces [28, 33]. Motivations of such research come from the opportunity to create multi-aesthetic artefacts [10] using colour-changing and shape-changing materials that embody dynamics and playfulness, reflecting more subtle and poetic [2] aspects of the identity of both people and places.

Embedding colour-changing actuation within fabric can be achieved using thermochromic [11, 29], photochromic [46], hydrochromic [2] and electrochromic inks [52], leveraging digital technology beyond the *neon* era. Thermochromics, in particular, can be electronically controlled used a heating agent (e.g. conductive thread, copper wire, nichrome, etc). In this sense, some used thermochromics for designing fabric animations using conductive thread [41, 29], while others dyed the conductive thread with thermochromic pigments to achieve sensing-actuating textiles [23, 11]. However, the drawbacks of conductive threads include its high resistance, fraying and being uninsulated, potentially causing short circuits.

Unlike servo-motors and stepper-motors that create a disturbing sound, weight and rigidity for everyday materiality, other shape-changing techniques can create morphological effects that are calm, quiet and appropriate for everyday use. Shape changing materials such as thermal-responsive SMA wire can be an alternative solution for creating interesting deformations [12, 59], not only because of its subtle shape-changing effects, but also due to its light weight, experiential transparency, silent operation and organic expression [4]. Examples of previous work that explored the use of SMA wire with fabrics include the Kukkia and Vilkas actuating dresses [3], wrinkling trousers [47], the Textile Mirror [10] and the Shutters curtain [9], which all used hand-stitching to fix SMA wire to their fabrics. Alternatively, Vili [50] proposed 'yarn-spinning' for creating actuating textiles by *incorporating* SMA strands within fabric yarns to enhance both the functionality and aesthetics of interior textiles such as curtains and room dividers.

Machine-sewing techniques have been used for textile actuation in very limited work. For instance, Bern [1] envisioned the design of actuating plushy toys, but only *simulated* them and stated that "this actuation complexity is clearly well beyond current fabrication capabilities". Animating Paper [38] vaguely used "sewing" SMA –mentioning no machines– and Kono [22] proposed using strings and "sewing methods" to make shape-changing fabrics, but still actuated the fabric deformation using rotating servo-motors to pull the strings.

Other crafting methods used include hand-embroidering copper wire [36], hand-sewing soft sensors [51, 32] and crocheting conductive thread using chain stitches [21]. Recently, research has looked into machine-sewing sensing yarns [31], machine-embroidering conductive thread for e-textile connections [17] and machine-sewing copper wire as a safe on-skin electric connections [20], all excluding the potentials of shape-change. Sprout I/O [8] has briefly introduced SMA to textile techniques not only by hand-stitching SMA wire to felt fabric but also intertwining SMA spun yarn with Teflon to curl a fur strand down taking advantage of its soft properties and textural changes. Other previous work that explored SMA wires, or springs, fixed both ends only to the soldered connections of the circuit without any sewing to the fabric [7, 47].

TECHNIQUES FOR CRAFTING FABRIC-MORPHOLOGY

In this research, we focus on machine sewing: 1) copper thread, 2) thermochromic-dyed threads, and 3) SMA muscle wire, as these materials are *thread-like* and can be both physically and electronically *i)* actuated, *ii)* used for sensing (using their capacitance as conductive materials), and *iii)* sewn directly onto or woven within textiles. We used a standard brother AE17000 sewing machine for sewing, and a Janome MemoryCraft 350e digital embroidery machine, with its CAD software for embroidery. SMA Flexinol wire was supplied

Figure 2. Technique 1: Machine-sewing copper thread to light mesh fabric with a thermochromic fabric layer on top.

Figure 3. Technique 2: a) Dyeing light-coloured threads with dark thermochromic pigments, b) drying, c) bobbins in room temperature, d) bobbins when heated (changing back to their original colours).

from RobotShop.com, the 0.1 mm copper enamelled reel was supplied by Sourcingmap (Amazon), and the thermochromic pigment from Rapidonline.com. Such materials thereby create unprecedented seamless and seamful interaction [6] with fabrics and everyday soft objects. In this sense, we adopt a ‘Research through Design’ [42] methodology to explore creative ways of embedding organic actuation and deformation in fabrics aiming towards novel opportunities of future uses, expressions and design possibilities not previously associated with textiles [40]. We describe in a condensed format, the results of almost 100 experiments, summarized in 10 techniques, which were reproduced and observed for a repetitive behaviour.

Technique 1: Machine-Sewing Copper Wire

Copper enamelled wire with 0.1 mm diameter is as thin as thread and can be used for embedding actuation in e-textiles in various ways. For example, Posch et al. [36] used copper enamelled wire to embroider coils creating a few logic gates as 1-bit displays using electro-magnetic shape-change. Their approach was delicate and interesting, yet unique and difficult to replicate. We wanted to develop a simple technique to help anyone sew their own actuation. After realizing how hand-stitching copper wire can have its complications in terms of time and breakage, we believed using a sewing machine could be a simpler idea. Copper enamelled 0.1 mm wire can be easily used for loading the bobbin case of a sewing machine and can be threaded smoothly through the sewing machine’s needle. Any normal thread spool can then be used to stitch the copper. We tested different stitches and found the basic straight stitch to be perfect for thin feeds, while the tight satin stitch (resembling embroidery) was ideal for thick covering. One method is to stitch it directly onto thermochromic fabric, but the copper seam will be visible. Another is to use a thin mesh fabric underneath thermochromic fabric to reveal its hidden pattern and achieved different results, see Figure 2. Once connected to power, the thermochromic fabric glows around the stitched seams revealing another colour. Once disconnected, the fabric slowly returns back to its monochromic colour. Machine-sew copper wire can be also used to activate colour-change in normal fabric (not thermochromic) in the same way. After stitching through, the fabric can be screen-printed or hand-painted along the seams with thermochromic paint, allowed to dry, then activated. We found that angular flat brushes achieve better results in painting fabric with thermochromic pigments than pointed round brushed, due to its thickness. The fabric seams immediately change colour around the printed or painted pattern along the copper seams, revealing the fabric’s original colour or pattern underneath. Alternatively, we explored other fabrication methods with this technique such as *tie-dyeing* fabric with thermochromic pigments and ice cubes (the latter being commonly used in tie-dyeing to allow gradual colour absorption). The results were not as expected, as thermochromic pigments are not inherently fabric dyes, but it still made creative and interesting colour-changing patterns. Fabric painting allowed us to explore the interplay between the pattern-changing print and the fabric’s original pattern.

Technique 2: Machine-Sewing Thermochromic Thread

Given that neither conventional fabrics are thermochromic, nor painting fabric is easy, we developed a much simpler solution that achieves the same previous results: machine-sewing thermochromic thread. Similar to any normal yarns, thermochromic thread can be machine-sewn. We dyed some light-coloured cotton threads with darker thermochromic pigments, see Figure 3. We followed the standard usage of thermochromic pigments (described in the user manual of most suppliers) where all inks are accompanied by a binder, mixed 50/50 with the ink, to produce the desired amount of useable ink/dye. Light-coloured cotton thread and dark-coloured thermochromic pigments together achieve the best results. The dyeing process starts by soaking thread for at least 30 minutes in a shallow bath of thermochromic dye (Figure 3.a). Then, the thread is taken out and dried overnight on layers of tissue paper (Figure 3.b). Afterwards, the thread is subjected to bobbin winding for use with the sewing machine (Figure 3.c). Any hard crumbles or dry pieces should be removed before or during this step. Finally, thermochromic-dyed threads on bobbins can be tested using heat, changing back to their original colours (Figure 3.d).

This technique can be used independently (reacting to ambient heat) or concurrently with Technique 1, where thermochromic threads are the main thread spool of the sewing machine, and copper thread fills the bobbin case. In this technique, the sewing machine stitches *controlled* colour-change directly into any kind of fabric. Once connected to a battery, the fabric seams transition from one colour to another. Similarly, an embroidery machine can be used to stitch colour-changing embroideries using thermochromic-dyed thread. We used a digital embroidery machine to produce numerous colour-changing embroideries designed on the illustrating software. Apart from colour-change, and to demonstrate further effects, two approaches were tested: *hiding* and *revealing*. When using dyed thread with a matching colour to the fabric, seams seem seamless, but reveal once actuated. Alternatively, stitching fabric with thread that has a matching ‘original’ colour causes

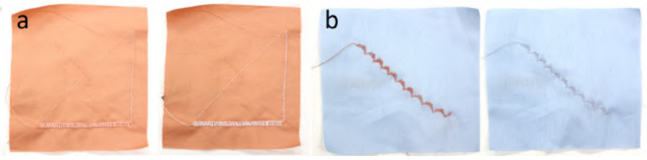

Figure 4. Machine-sewing thermochromic-dyed threads (in the spool) with copper enamelled 0.1 mm thread (in the bobbin) where the stitched pattern (a) reveals and (b) hides.

Figure 5. Gradual colour-change of (a) white and (b) pink knitted yarns dyed in blue thermochromic pigments.

the seams to be contrasting/visible, then hidden once activated, see Figure 4. Another fabrication method that can be used in the same sense is knitting with yarn that is thermochromically-dyed, either using a knitting machine or knitting needles. Copper enamelled wire can be either knitted with the dyed yarn or weaved through the knit after finishing (see Figure 5).

Technique 3: Machine-Sewing SMA Wire

In the same way of filling the sewing machine's bobbin case with copper wire, we explored machine-sewing SMA wire. We mostly used Flexinol HT 0.006" and 0.010" muscle wire as our Shape-Memory alloy actuators. Such SMA wire is pre-trained to shrink by around 4% of its total length and flatten when adequate current flows through and heats it up (around 0.4A and 1A respectively). This causes the wire to usually erect (lift and bend outwards) along with the material it is fixed on. Alternatively, SMA springs retract significantly (up to 80%) causing compression or creasing deformation of the material to which they are affixed depending on its affordance. SMA wire can also be re-trained to actuate in any desired form by heating it on a fixed mould of that required shape up to 400-500°C for a few minutes then immediately quenching it in cold water to *remember* that shape. Once the electric current flows through the SMA wire, it begins to reveal the deformation effect it is trained upon and this essentially causes the fabric to undergo physical movement according to the applied stitching form and sewn stitches. We used and tested different stitches and stitch forms until we obtained the best results through zigzag short and tight stitches fixing the SMA wire in a U-shaped pattern.

In general, SMA wire is much harder to control as it physically tends to loosen and wobble due to its unique alloy, so it cannot be firmly bent or tightened. However, by using thin 0.006" Flexinol wire, firmly gripping the ends in one's fingers to avoid its unrolling, working quickly and accepting that the wire will somewhat loosen, it is applicable to achieve neat seams using SMA wire. Once stitching is done, both the wire and thread should be cut, leaving 1-2cm of the wire to allow electronic connection. Figure 1 shows how SMA wire was rolled around the bobbin and loaded into the bobbin case of the sewing machine underneath the presser foot. Then the bobbin wire stitched the spool thread neatly on a tight zigzag stitch through a U-shape pattern. In this example, we consumed 20cm of this wire that has 55Ω/m leaving us with 11Ω for this piece. When applying 410mA (the recommended current for this wire) using 4.5V, the wire couldn't move as the fabric around our pattern forced too much weight, pressure and stiffness beyond the pull force of the wire (321 grams). In such cases, the pattern needs to be free, so a cut-out should be formed around the pattern allowing the stitched pattern to move freely by bending when connected.

Technique 4: Parametric Machine-Sewing SMA Wire

To investigate the relationship between different stitches and the shape-changing actuation effect, we held systematic experimentations of over 60 swatches with different combinations of the different factors that impact the deformation to understand their effect. Various parameters played a role in the equation of fabric actuation resulting in different deformation effects. These 10 SMA deformation parameters are:

1. **Type of fabric**: The more malleable it is, the easier it is for the wire to deform the fabric. However, the type of fabric (determining its stiffness, rigidity/elasticity and weight) is correlated with the type of desired actuation e.g. firm fabrics can bend, while lighter ones can twist, (un)roll and crumple. Rigid fabric should be chosen for controlled actuation, while light-weight fabrics can support organic deformation. Flammable fabric should be avoided when sewing SMA.

2. **Type of thread**: Certain types of threads may have different impacts on the tension of the wire fitted on the fabric and therefore the deformation effect when connected. We found that loose thread minimizes deformation while tight-able thread maximizes wire pull-force and thus amplifies fabric deformation. For precaution, the thread type used should not be flammable to avoid catching fire if the wire gets unexpectedly heated too much.

3. **Type of stitch & its tightness**: the shape and tightness of the stitch that fits the SMA wire to the fabric is of significant importance. In general, the wire needs to be held tight to deform the fabric when actuated. However, if it is too tight it will not allow any deformation to take place. On the other hand, loosely fitted SMA wire will deform between stitches without causing visible deformation in the fabric.

4. **The pattern of stitching**: The most significant parameter that affects resultant deformation is the shape of the wire traces when stitched onto fabric. It has been agreed between practitioners that one of the most successful patterns that causes visible shape-change is a U-shape pattern. This pattern maximizes the pull-force of the wire causing the material to bend upwards when the wire actuates, acting like an arm muscle that can lift objects upwards by contracting. Other patterns can cause the wire's pull-force to be distributed in uneven loads minimizing its actuation capability.

5. **Type of wire**: SMA wires are commercially available as Nitinol, Flexinol, muscle wire or smart wire, and can be as malleable and thin as normal thread (e.g. 0.15 or 0.25 mm) with pulling force ranging between 320 and 900 grams at 410mA and 1050mA respectively (see Table 1). If high current (more than the recommended by the manufacturer)

SMA Product (Supplier)	*Diameter (mm)*	*Resistance (Ω/m)*	*Current (mA)*	*Pull-force (g)*
BMX750 (TOKI BMX)	0.075	1000	100	5
Flexinol 0.006" LT (Muscle Wires)	0.15	55	410	321
Flexinol 0.010" HT (Muscle Wires)	0.25	18.5	1050	891
Nitinol Wire (Smart Wires)	0.5	4	4000	3500
Smart Niti Spring (Rapid Education)	0.75	2	3000	500

Table 1. Examples of SMA wires commercially available.

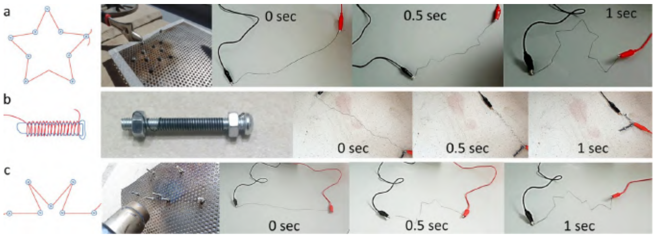

Figure 6. Training SMA wire to remember different shapes.

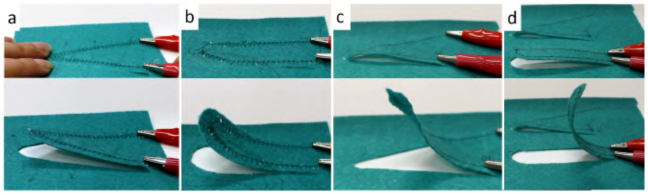

Figure 7. Technique 4: Parametric machine-sewing SMA wire to fabric over a U-shape pattern using a loose zigzag stitch (a: pointy, b: curved) and a tight straight stitch (c: pointy, d: curved).

is applied for more than 10 seconds, the wire may burn. Thicker SMA wire usually has a much higher pull-force which can deform fabric more intensely, even when it's heavier. However, thicker SMA wire requires significantly higher power. Accordingly, thicker wire increases the deformation boundaries but simultaneously adds rigidity and stiffness to the fabric that might affect its malleability, affordance or texture.

6. **The austenite form** (trained shape): The *memory* shape that the SMA wire has been trained (i.e. heated up to 400-500°C) to remember when activated by 40-90°C is called the austenite form/state. The austenite default shape of off-the-shelf SMA wire is a straight-line; that is, it flattens unfolding itself and often slightly shrink by 4% of its length when connected to electric current. This shape can be changed as required if the wire is re-trained to remember a new shape. Most SMA actuates repetitively for millions of cycles, but if high stress or strain is imposed, the actuation only lasts for a few hundred cycles. This parameter can dramatically change the SMA wire actuation behaviour resulting in different deformation effects for each different austenite form, i.e. trained shape (see Figure 6).

7. **The martensite form**: SMA wire is very malleable and hand-deformable in room temperature (when no electric power or heat is applied). This malleable state is called the martensite state. In this idle state, the wire accepts any physical deformation applied to it. Once the wire is connected or heated, it returns back to its memorized austenite shape. However, the deformation is not always consistent and is often affected by the martensite form. That is, the shape-change is affected by the manipulation applied to it earlier. In other words, if the wire is bent, rolled or twisted by force, then actuated, it will unbend, unroll or re-twist itself back. This allows a variety of repertoires between people and actuating soft artefacts in the form of a conversation where physical input affects output.

8. **The fabric orientation**: As the pull-force of thin SMA wires are relatively not high enough, the fabric deformation is significantly affected by the seam orientation. The fabric might not be able to actuate vertically, but could on a horizontal surface, where it's not working against the gravity. Also, non-spring SMA can only deform the fabric towards the side it's stitched on, not the other way. Gravity can also be used to work with the design (rather than against it) if utilized as the reverse mechanism, pulling the contracted SMA back down while cooling achieving a two-way actuation.

9. **Length of wire**: Although used as thread, the length of consumed wire determines its resistance, thus the amount of electric current it draws according to Ohm's Law ($V = I \times R$), consequently affecting the deformation effect that occurs. For example, a 20cm pattern of a 55Ω/m wire forms 11Ω requiring 4.5V for its recommended 410mA. However, a 50cm long pattern stitched with the same wire forms 27.5Ω requires 11V to be able to draw its recommended current. The deformation of SMA of length between 15 and 50cm was observed to be the highest.

10. **The distance between the seam (SMA wire) and the edge of the fabric**: The same combination of all previous parameters may work if the pattern is stitched by the edge of the fabric, but may not work if placed in the middle of the fabric, as more weight will be applied on the wire beyond its pulling-force. This is the reason why, in most cases, a cut-out around the pattern is essential to allow the deformation to take place.

For instance, by altering two variables (the type of stitch, and the pattern of stitching) and fixing other parameters, insights can be drawn on how to optimize the SMA machine-sewing technique. By experimenting with different stitches, we found the straight stitch, the satin stitch and the zigzag stitch to be efficient, with tighter stitches causing more dramatic deformations. Through testing different patterns, we found that the more curved the pulling end is, the more the pulling-force of the wire is maximized. Figure 7 compares the four combinations of two patterns (triangular pointy peak, round curved peak) and two stitches (wide zigzag and tight running stitch).

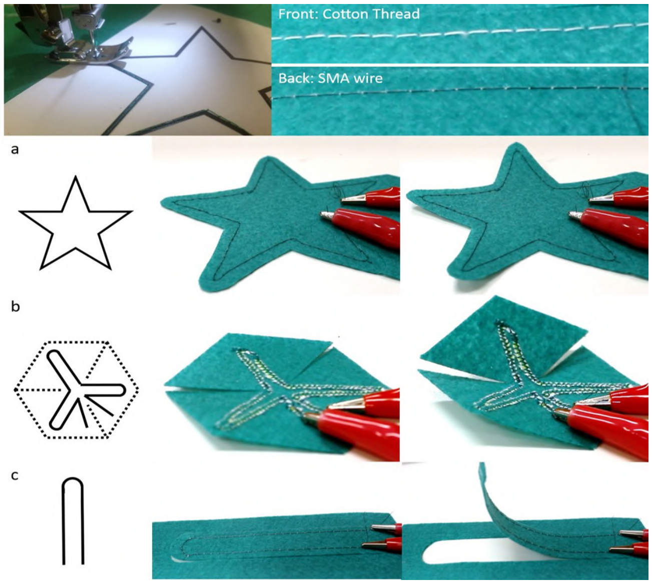

Figure 8. Technique 5: Using Sewing patterns in machine-sewing SMA wire to create complex shapes.

Technique 5: Sewing-Patterns for Machine-Sewing SMA

The great benefit of using a sewing machine rather than hand-stitching SMA wire is the ability to rapidly design and prototype different shape-changing effects. We can now machine-sew actuation directly into fabric and rapidly and systematically compare different patterns and shapes. 'Marking' is a standard practice in sewing and can be used to trace a shape-changing template or transfer an SMA pattern to the fabric using tailor's chalk or fabric pencils. Using *paper patterns* is also an old traditional sewing method for cutting fabric to desired sizes and is a natural step to learn when sewing garments, and soft artefacts. Consequently, we utilized and re-purposed these same methods to enable the creation of complex shape-changing patterns. This technique enabled us to simply follow the lines while machine-sewing SMA wires into various curves easily. Figure 8 shows some paper patterns we have machine-sewn using SMA wire, including a star shape, a hexagonal inner shape and again a U-shape. Comparing the resultant actuations of different stitched patterns yielded a conclusion that the latter pattern is most effective in terms of visibility of deformation.

Technique 6: Controlling Fabric Deformation

Learning from Technique 3 how the U-shape pattern worked nicely, we went on to try different versions of this pattern. We learned that by changing the size of the pattern to a narrower width and longer length, more visible variations of shape deformation can be achieved. Learning through making helps us develop understanding often in better ways than other scientific approaches. For example, we learned by coincidence, that a bend can be controlled at a particular desired part of the fabric through less weight at this part. Figure 9.a shows a scrap that actuates in a right angle bend at the point where less fabric strain is found. Figure 9.b shows how the pull-force is maximized (compared to Figure 8.c) when the pattern gets narrower, allowing more grip, causing swirling. By changing the parameter of the martensite state (i.e. twisting and untwisting Figure 9.b by hand), the same piece deforms in a different way by twisting itself instead of swirling. In this technique, the fabric relaxes back and obeys gravity once no electric current flows through the wire. However, the deformation is repetitive and the resultant actuation is the same every time. Such techniques can be used when the actuation output needs to be designed and performing in a specific constant way to achieve a certain task or display a specific message to a user e.g. a cushion's corner can bend twice notifying one that something has happened. Such actuation needs to be consistent and can thus be achieved in one of these controlled deformations.

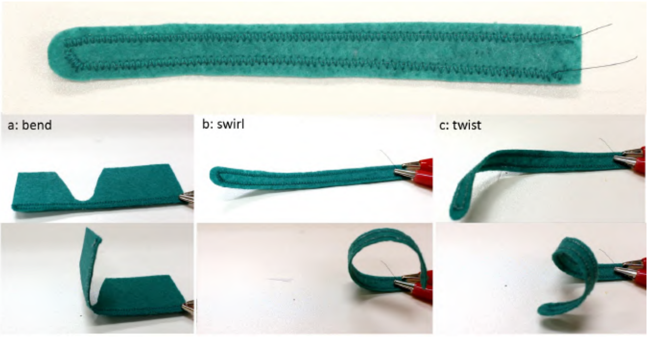

Figure 9. Technique 6: Machine-sewing SMA wire over a U-shape pattern using a tight zigzag stitch (a: bend, b: swirl, c: twist).

Technique 7: Manipulated Fabric Deformation

Rather than controlled actuation, we were interested in the unexpected ways SMA wire deforms the fabric in a non-computerized but more organic behaviour. To allow such free-style actuation, the martensite state parameter (i.e. hand manipulation input before actuation) can be manipulated and light-weight fabrics can be used to avoid rigid repetitive deformation. In this technique, other parameters (such as the stitch, pattern and wire) are fixed to the most effective ones we have found so far. Figure 10 shows deformations resulting from a) swirling, b) rolling, and c) folding hand manipulations of the fabric. Results informed how autonomous behaviour of SMA actuated fabrics can often yield more interesting forms and organic shape-changes depending on user direct manipulation as opposed to programmed consistent outputs. This technique can suit applications around wearables where people deform their garments in different (free-style) and unique ways.

Technique 8: Machine-Braiding Trained SMA Wire

To achieve a crumpling fabric deformation, the wire needs to significantly contract (not just bend, swirl or twist). Relevant previous work in material science has looked into training SMA wire to remember a certain austenite shape [45]. Therefore, SMA wire can also be customized into remembering a specific desired shape by training the wire in a mould, fixing it to that shape and applying 500°C of hot air for a few minutes [45], or a naked flame for a few seconds. For this technique, we re-train the wire to remember different austenite shapes then machine-braid it on top of the fabric. For example, a wire actuating into a spring shape can be achieved by rolling

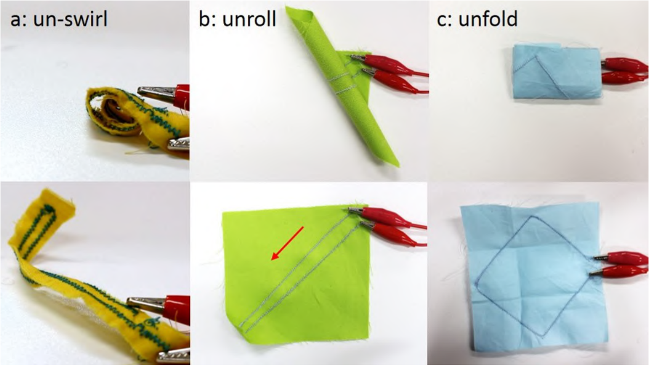

Figure 10. Technique 7: Machine-sewing SMA wire then hand-manipulating the martensite state (left), and after actuation (right).

the wire around a screw (to achieve a spring coil shape) then heating the wire using a hot air gun for 5 min in direct contact, or a candle flame for 2 min. It is required to throw the wire immediately afterwards in cold water in a process called 'quenching' for the training to take effect. Some have recommended repeating this process numerous times to train the wire, but we found that it does remember from the first time.

Once the wire is physically-programmed to remember this spring shape, we can stitch it to the fabric. However, it is difficult now to roll the wire around the bobbin as it has bends of a different diameter (from the screw). To machine-sew this wire, we use the conventional machine-sewing technique called 'braiding'. Similar to adding decorative embellishments to fabric such as ribbons and thin braids, we use the spring-trained wire on top of the fabric to be fixed using the sewing machine's tight satin stitch. Although using a braiding or a couching foot would be suitable for this, we used the basic presser foot which worked fine. If the wire could not deform the fabric at all, it is likely that the fabric is too heavy and firm to be deformed. A cut-out close to the seam will solve this problem. Another austenite memory-shape to train SMA wire (than a spring coil), is a zigzag shape. Figure 11 shows a 16cm long zigzag-trained SMA wire machine-braided on top of a cotton fabric swatch. When activated, the fabric deforms in a wavy form creating a different shape-change deformation than all the previous techniques.

Technique 9: Machine-Sewing Bobbin-Trained SMA Wire

Based on previous techniques, the idea can be developed to investigate a new possibility: why aren't SMA wires pre-programmed directly on the machine's bobbin? In other words, training the SMA wire while rolled on the bobbin, using the bobbin as its mould, then placing the bobbin (with the spring-trained wire) directly inside the sewing machine. This technique is much easier than braiding the wire on top of the fabric and results in new kinds of deformations. To hold the SMA wire from jumping out of the bobbin, the two ends can be carefully closed with an adjustable wrench tool, then the bobbin SMA can be trained, and be ready for sewing. When using this bobbin then to machine-sew a tight zigzag-stitched square pattern, the SMA -once actuated- crumples the fabric (Figure 12). However, when machine-sewing the bobbin-trained SMA wire in a narrow U-shape pattern using a satin stitch, the fabric rolled around itself once connected (Figure 13). In all these techniques, the SMA wire is intertwined with the normal thread, causing the fabric deformation at the *seam*, only visible from the back, and is entirely *seamless* from the front of the fabric.

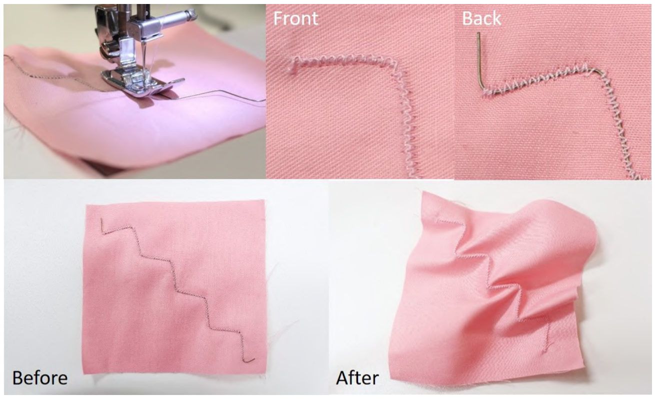

Figure 11. Technique 8: Machine-sewing zigzag-trained SMA wire (top), before and after actuation creases the fabric (bottom).

Figure 12. Technique 9: Heat Training SMA wire in the bobbin to a spring shape. After actuation, the fabric crumples itself inwards.

Technique 10: Machine-Sewing Shape-Colour-Change

By combining Technique 2 with Technique 9, colour-change and shape-change can both be achieved simultaneously. In this technique, thermochromic-dyed thread is used on the top spool pin, all the way through the thread guide, the take-up lever and the needle. On the other hand, the bobbin is filled with SMA wire that can be re-trained in a spring austenite shape for a contracting actuation. With a tight zigzag stitch, to hold both threads in place, and prevent excessive thread consumption (as with the satin stitch), we experimented this technique on different fabrics and threads. As with Technique 2, using matching colours of fabric and thread, will hide and reveal

Figure 13. Technique 9: Machine-sewing bobbin-trained SMA wire with thread. After actuation, the fabric rolls around itself.

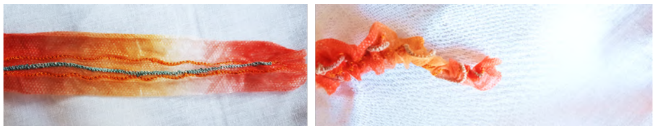

Figure 14. Technique 10: Machine-sewing bobbin-trained SMA wire with thermochromic thread. After actuation, the fabric seam changes both its shape and colour.

a contrasting seam that swirls, bends, rolls or crumples once actuated, according to the SMA trained shape, as in Technique 9. Figure 14 shows one of the samples in a vibrant coral colour fabric and teal thermochromic dyed thread, that changes both shape and colour simultaneously once connected.

CASE STUDY: TECHNIQUES IN USE

To demonstrate the use of the techniques presented, a case study was carried in which we crafted a meaningful and usable artefact utilizing morphological fabrics. Herein, we describe the design process and evaluation of 'BacterioChromic', which was a piece of interactive wall-art designed with morphological capabilities, changing its patterns, colours and shape (see Figure 15). Beyond responding to a specific brief (see below), the discussed crafting techniques allowed us to explore a future of interior spaces that can be artfully dynamic and adaptive. We used the mentioned techniques of fabric painting with thermochromic paints (Technique 1), machine-embroidering thermochromic-dyed threads (Technique 2), bobbin-training SMA wire (Technique 9) and machine-sewing SMA wire (Techniques 3, 4, 7, 8 and 10).

Design Concept

Inspired by the patterns of bacterial growth in petri-dishes, BacterioChromic was designed as a wall-art piece, as part of the 'Living with Adaptive Architecture (LWAA) Exhibition 2018'. The concept behind this crafted artwork was to simulate the interaction with bacteria in the surrounding space, to help stimulate awareness and discussion around Anti-Microbial Resistance (AMR). Designing tactile and living artefacts that respond to environmental stimuli is potentially valuable for raising people's awareness in both public and private spaces. We saw an opportunity to realise this, in an aesthetic form as an ambient display i.e. part of the interior space, rather than the more expected charts and graphs encountered in health communication. This artefact had a dual purpose of allowing us to concurrently speculate on how future interior spaces might be dynamic and adaptive, and not purely for structural or functional purposes, but for visualizing the unseen.

Crafting & Implementation

Shape-change was embedded in loose strands of thin fabric resembling a type of resistive bacteria, by machine-sewing Shape-Memory Alloy (SMA) wire to the fabric. Learning from our experiments, we utilized the parameter values that were recorded in SMA parametric design to achieve the best results in terms of deformation intensity (Technique 4). That is, thin light-weight fabric was used to help reduce any additional weight hindering the pulling-force of the SMA wire. Then tight zigzag stitches were used for machine-sewing the SMA to the fabric using thermochromic-dyed thread that changed colour simultaneously as the SMA actuated and heated to change-shape (Technique 10). Organic actuations were achieved by manipulating the martensite (Technique 7) and austenite forms (Technique 8) using machine-braiding the SMA wire directly on top of the fabric. The U-shape sewing pattern was used to realize the desired form and deformation of the bacteria-like fabric strand. To achieve two-way shape change, SMA wire that is pre-trained as *straight* was machine-sewn to one side of the fabric, while bobbin-trained SMA (Technique 9) as a *spring* was machine-sewn to the other side. The choice of the wire was also carefully made, as thin 0.006" SMA was used for bobbin-trained retracting spring side, a thicker 0.010" SMA was used in its default straight austenite, to have a stronger pulling-force (891 grams) enough to unfold the strand again from the other side. As a result, when each side is controlled in sequence -in response to user touch input- the fabric strand appears to be living, blossoming and unfolding and then rolling itself back, crumpling in organic imprecise patterns and forms.

Figure 15. BacterioChromic wall-art exhibited at the LWAA 2018 Exhibition responding to touch by changing its patterns, colours and shape.

Colour-change was embedded through thermochromic-dyed threads and machine-embroidering them to the fabric (Technique 2) in bacteria-driven patterns that react to user input. A digital embroidery machine was used to embed different morphochromic shapes on plain white cotton fabric, see Figure 16. The *digitizer* software of the digital embroidery machine allowed illustrating the design then automating the embroidery onto any fabric. Both thermochromic fabric and normal fabric (painted with thermochromic colours) were also used (Technique 1) to achieve colour-changing digitally-designed microbial patterns on the fabric itself rather than on the embroidered patterns. To compensate for any skipped stitches by the machine due to any errors in its program, hand-stitching filled these minor gaps to obtain a neat finish. Sensing was achieved using conductive fabric sewn and layered underneath the top fabric layer, utilizing capacitive-sensing in close proximity in

Figure 16. Machine-sewn and embroidered colour-changing bacteria-driven patterns with thermochromic-dyed threads.

seamless interaction, with no visible electronic components. Crumble microcontrollers [39] were used to control each *petri dish* individually due to their thin and small size and motor outputs which we programmed to control the thermal-responsive actuation of shape-changing and colour-changing materials in response to capacitive-sensing. High-current MOSFETs were used to allow enough power to be drawn from the back-mounted batteries to the SMA and heating wire. With most of the circuit being threads on top of the fabric wall-art, the rest (the microcontroller, transistors and battery) was less than 9 mm thick, and was *stitched* to the back of each hoop and hung on the wall with no external cables or power source needed. This enabled visitors to perceive it as a crafted wall-art, but also appreciate its interactivity once approached.

Exhibition & Audience Interaction

Over 6 weeks, BacterioChromic was installed as part of the LWAA 2018 Exhibition at the Lakeside Arts gallery in Nottingham, UK. Around 1285 members of the public were reported to have visited the exhibition during this period. The lead author was present for some of these days and took field notes, made video recordings, observed visitors' interactions, and spoke to visitors about their experiences. Through their questions, comments and reflections, visitors gave us insights into designing similar artefacts. This engagement gave us a better understanding of the potentials and limitations of the crafting techniques we had deployed. Further, we audio recorded informal interviews with 6 visitors who were happy to discuss our research further. The exhibition was visited by a diverse audience (age, gender, background, family groups, individuals) which provided a wider perspective on the engagement with our artefact than inviting participants to a lab setting. Inside the gallery, BacterioChromic was placed beside other actuating interior artefacts, but those which rely on mechanical actuation i.e. using rotating servo- motors. This gave visitors useful context on differing forms of actuated interior spaces.

Many visitors expressed curiosity about what was causing the shape-change, how the fabric was shifting its colour and where the batteries were (if any). Also, video recordings showed unexpected proxemic user behaviour, ranging from gently touching, pointing, poking, stroking, pulling strands, warming up with hand palms and even blowing at it. Blowing, in particular, is an unusual interaction with a wall-art piece, yet at least 5 visitors were observed using it as a playful and unusual interactive experience, happily enjoying the colour-change their breath caused and the gradual fading back of that colour-change in the embroidery afterwards, see Figure 17. We also noticed that interestingly, small-sized circular shapes in the pattern received a lot of pointing/clicking as if they were mentally associated with *buttons* that afford pressing. Pulling the shape-changing free fabric strands was particularly unique in the fact that every interaction manipulated its martensite state, therefore, changing the resultant deformation. These interactions caused the output actuations to vary in form and intensity, depending on the exerted input. While some visitors were amazed by unexpected organic deformations in the fabric itself, others were disinterested and impatient to wait for a few seconds to perceive a visible output.

Post-Exhibition Reflection

Based on our observations, field notes, video recording of public engagement and audio-recorded informal interviews, we were able to gather data and insights into the potential value and impact of using these techniques to produce morphological actuation in interactive artefacts.

Aesthetic vs. Hectic

Participants acknowledged and thoroughly discussed the design concept presented, but mostly valued the fact that no 'demanding' technology was used to convey it. Encountering BacterioChromic and its gentle patterns of revealing and hiding colours and moving fabric, participants felt that it was communicating a message about AMR, and generating an experience that was pointedly different from normal health communication. People appreciated the interactivity of an aesthetic object, that does not appear to have any 'offensive' technology, as a means of communicating a serious medical problem of public concern. For example, one visitor stated that *" as an aesthetic object, you can live with it without having to live with lots of offensive looking warning signs."* (V1) which points to how we should potentially design technology that avoids the appearance of digital devices, if we need and/or want people to enjoy 'living' with them. Another visitor highlighted how this seamless interaction of a non-device-looking object gives it its value: *"you could get carried away putting more and more technology into it, it doesn't have sensors and wires, it's got simple interaction"* (V3).

Organic vs. Mechanic

The *organic* and *slow* morphological transitions of patterns and movements were also described by many visitors as being more *natural* versus the *mechanical* actuating objects placed beside BacterioChromic. Although the silent and slow actuation of BacterioChromic made it look as if it was *"alive"*, it also caused it to be, at times, unnoticeable and gallery visitors passed it by whilst it actuated and failed to grab their attention. Several people were observed advising their friends or family members to *"wait and see"* as it slowly morphed, after a user's interaction. Whilst some walked away perceiving this actuation as too slow, others described it more poetically, articulating its morphological actuation as *"the breeze of the air"*, suggesting that it might *"remind us of sea waves"* (V5),

Figure 17. Interactions with the BacterioChromic wall-art through different tactile manipulations e.g. touch, stretch, and blow.

or that it *“looks like a sea creature”* and reminds one of *“sitting in the woods, where everything is moving around you”* (V6). Most likely, these *organic* interpretations would not be drawn from motor driven actuators or LED e-textiles, not only because of their sound and flashing light, but also due to their rigidity and lack of naturalness.

Crafted vs. Mass Produced

The *crafted nature* and *making* of the BacterioChromic was a conversation topic among some visitors. Most were surprised by how the fabric itself changed its shape or colour. Yet the behaviour of different elements of the piece presented new possibilities to them, away from mainstream product design. A designer who visited the gallery reflected on how she realized that the actuation was stitched into the fabric itself, and that this made it -unlike any other interactive object- *“move naturally, depending on where and how you touch it.”* (V5). This reflects the quality of crafting methods as techniques for embedding actuation in soft artefacts as opposed to the previous work on shape-changing interfaces. Other visitors suggested other soft artefacts that could be weaved with actuation like BacterioChromic, including garments, cushions and gorilla knitting in public spaces. Some compared it verbally to IKEA products to point out the apparent differences between its crafted individualised and bespoke quality versus *“mass production and mass design”* (V6). All these examples emphasize the value of craftness when designing interactive actuating artefacts.

DISCUSSION AND CONCLUSION

This paper is an exploration of machine-sewing actuation seamlessly and the impacts of doing this. We have introduced a range of novel techniques of machine sewing and physically programming actuating threads/wires into fabrics. Our techniques enabled both the colour change of seams and soft shape-changes such as bend/unbend, swirl, twist, roll/unroll, curl, crumple and crease. From observations of experiments sewing SMA to fabrics, 10 parameters were realized as the impacting factors that control the deformation intensity: fabric type, thread type, stitch type, sewing pattern, wire type, wire austenite, wire martensite, fabric orientation, wire length and its distance to the fabric edge. In developing 10 techniques for machine sewing actuation, we have productively built upon the work of Hamdan [17] and other previous work on e-textiles that generally focused on LEDs and motor-based actuation by sewing conductive threads. Thus, our techniques for sewing shape-changing and colour-changing threads represent an evolutionary step towards the ultimate goal of providing a high-fidelity experience to users, designers and researchers. This paper also extends previous work on SMA shape-change by examining deformational parameters affecting the fabric’s morphological effect. Finally, we designed and exhibited a case study evaluated by members of the public, which shows the potentials of creating aesthetic artefacts with colour-changing and shape-changing capabilities, crafted in seamless ways, moving beyond intrusive technology and mass produced devices.

These findings evoke design opportunities that pave the way for a vast amount of future work on actuating *everyday* soft objects, contrasting previous notions that argued for a need to create novel computational composites and peculiar materialities. Applications include shape-changing, colour-changing and haptic soft interfaces ranging from wearables and garments to interactive soft furnishing. Machine-sewing actuating threads will change the topology of how such interfaces are designed, crafted and manufactured, on a scalable level. Designers and researchers can now use such techniques to create predictable, replicable and scalable rapid prototypes and designs. In addition, this should also inspire crafters and tech-makers to develop “sewing books” of different *seamless seams* that can change their colours or shapes using various sewing patterns in an array of real-world artefacts. Once non-technical designers learn and understand how smart threads can be sewn into their designs (not just wearables, but also soft furnishings such as a chair arm or a pillow case), this might bring us to a brave new world of interactive possibilities.

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