**ARTIST’S ARTICLE**

**Drapely-o-lightment**  
An Algorithmic Approach to Designing for Drapability in an E-Textile Garment  
LOE FEIJS AND MARINA TOETERS

Drapely-o-lightment is a skirt created as an exploration of the integration of electronics and clothing. This prototype was made as a tool for research into design techniques that work well with components that conform to today’s standards for the manufacturing of electronics. The design takes into account not only the inclusion of squares in the visual design but also the tactile and visual properties of hard components in a traditionally soft medium. The fabric colors were chosen based on the OLED light effects. The skirt is the result of a collaboration between high-tech fashion, corporate electronics and academic industrial design.

**MOTIVATION**

The field of techno-fashion is developing rapidly. The contributions come from fashion designers such as Hussein Chalayan [1], who use technology to promulgate their views on fashion or even on society. Developments are also driven by needs in sports [2] and medical research [3–5], supported by progress in electronics, materials and tools. There are also interesting developments in multimodal textile interfaces [6,7] (see recent overviews [8,9]). Schiphorst develops examples illustrating how our own body data can be used to create and share awareness in an intimate way in a social space [7]; we consider this worth exploring.

Most of the technological research on sensor networks and on-body networks seems motivated by medical objectives: monitoring for heart patients [3], unobtrusive monitoring for at-risk babies [4], seizure detection for epilepsy [5] and so on. Advancements in technology make it easier and easier to measure all kinds of body signals. Although the medical objectives are very worthwhile, we also want to bring the idea of self-expression to the attention of the technology developers. Traditional garments are not only used for functional reasons (warmth and protection) but also can convey messages about identity, state of mind, social status, etc. The covering and exhibiting of more or less intimate body areas is an important issue both in the fashion world and at a personal level. Similarly, the possibilities of showing or sharing new body signals—such as muscle tone in Philips’s fractal [10], breathing patterns (see Schiphorst’s “exhale” [7]) or, as in our Drapely-o-lightment skirt, heartbeat—will become worthy of exploration. In Drapely-o-lightment, we added an element of interactivity to give the garment a kind of soul; it detects approach, not only in exhibitions but also when a person wears it. This almost gives the skirt the appearance of having its own will, which makes it more interesting and valuable.

Our work fits the vision put forward by Linda Worbin [11]. Although current combinations of textiles and computational technology are usually tools for design and speeding up production, Worbin predicts that, in the near future, computational technology will be an active component even after production, during use. This is the case in our project: A special Voronoi algorithm and a laser cutter were essential for design and production, and the Arduino and the OLEDs are also active computational technologies during use. The result of our explorations is the skirt shown in the Article Frontispiece.

Drapely-o-lightment was shown at various venues in the Netherlands and at Pretty Smart Textiles at Textiles Open Innovation Centre (TIO3) in Ronse, Belgium [12]. In this article we describe Drapely-o-lightment’s background, the design process, the result and the lessons learned. The article targets readers in fashion innovation as well as designers and technologists developing new sensors and actuators to be used close to the human body.

**TECHNO-SQUARES**

At present and in the near future, we face the prospect of working with discrete components to be embedded locally in limited numbers in more-or-less conventional fabrics. Many of these traditional components are manufactured as squares or rectangles. Important examples are organic light-emitting...
diodes (OLEDs), solar cells, QR codes, PCBs (printed circuit boards) and magnets, a few examples of which are shown in Fig. 1. In theory, these could be manufactured in other forms, but in practice they are most often squares. We call them techno-squares.

The design challenge we wanted to explore was the integration and interplay of textiles (with their inherently soft nature) and the techno-squares (with their typically hard nature). At present, the electronics industry is offering square OLEDs of increasing size, giving rise to the important question of how these can be embedded. In the future, perhaps in 10 years, the industry may produce very soft, lightweight and flexible woven OLEDs, which will give rise to new design questions. The challenges of embedding techno-squares are twofold: first, visually integrating the techno-square into the fabric so that it appears to belong there rather than being an island or alien body; second is the drapability of the fabric/patches combination.

The key properties in which textiles and techno-squares differ are: color, form, weight and flexibility. Accepting the fact that techno-squares are not easily changed, as in our case where the OLEDs are given, we decided to work by adapting the color and structure of the textiles. The color was the easiest part (see the next section). For the structure, an important design decision we made was to make the textile less flexible in order to mimic the material properties of the techno-squares, but in a way that still made it both soft and drapable. We added a segmented type of stiffness to the fabric by working with a top layer of patches. Of course this influences drapability, which became a main theme of the work.

COLOR AND MATERIAL

We looked at the organic light emitting diodes in various states and under various conditions, searching for color/fabric combinations that appear visually similar to the OLEDs. Each OLED has several light levels: bright, off or any brightness level in between (dimmed). When off, an OLED appears as a small mirror; it may be light or dark depending on what is reflected. Given the OLEDs' metal components, we decided to pick fabrics with a metallic look. We took four colors approximating those of the OLEDs at different intensities (Fig. 2). The basic skirt itself (a silver-colored substrate) is 100% polyester weighing 87 grams/m². The patches are one layer of polyester glued onto a stiff cotton interlining.

DRAPABILITY

Before we met and decided to do a project together, Toeters was already exploring fabrics with patches, ways of cutting and attaching the patches, the visual effects of various patterns and the impact on drapability. The main reason for doing so was the availability of laser cutters and the desire to explore what can be done with them. Feijs worked with his design students and with Christoph Bartneck and Jun Hu to develop Escher-style tilings, where the pieces were cut with a laser cutter. The most important learning goals were to teach geometry to the design students [13]. Those tessellations had not yet been used for garments, however. When we met in early 2012 and decided to exchange ideas on textile tessellations, we tried to create tessellations in pure Escher style. It did not take us long to find out that these are incompatible with good drapability.

Feijs suggested it would be easy to make smooth transitions from Escher-style figures to squares (for embedding the techno-squares). But we soon found that the typical Escher-style shapes would interlock, leaving no folding lines at all. Examples of patches similar to those used in the experiments are shown in Fig. 3. We made plots of the various experiments, measuring the folding radius for various directions. These experiments confirmed what Toeters was finding through more intuitive explorations: Surprisingly,
the pattern of regular equilateral triangles, as in Fig. 3(d), is the most effective for drapability. Toeters had done work with triangular patterns before, such as in *Triangle Coat*, shown on the issue cover [14], which was designed from body measurements.

**FROM TRIANGLES TO SQUARES**
With no conditions imposed, there are infinite possible transitions from triangles to squares. This means that there is some freedom of choice for the designer, and we propose a specific way of implementing the transitions, inspired by both natural animal skins and mathematics. These are connected in the theory of Voronoi diagrams, which describe certain cell structures in two dimensions. We propose a structure of patches, some of which are squares and most of which are triangular. The triangles provide for good drapability, whereas the squares can be used to embed techno-squares. In the next two sections we first discuss animal prints and then Voronoi diagrams and their connection to these prints.

**ANIMAL PRINTS**
Prints inspired by animal skins are a favorite theme in contemporary fashion. For an overview of the history and the meanings of animal prints, see Tanya Wilson’s *Animal Print* [15]. Their meanings have included evocation of the power of the animal, respect for hunted prey, association of the wearer with “the wild” and social status (because real animal skin was precious). Wilson, however, also notices that, with the advent of new production processes, the meaning of animal prints has shifted from wealth and status to a witty, playful, bold new message.

When exploring design options for *Drapely-o-lightment*, we felt that a loose and implicit reference to animal skin would be more interesting than a random pattern or a purely technical solution and that a link to nature would somewhat counterbalance the technical and future-oriented meanings carried by the OLEDs, the metallic colors, the presence of a microcontroller and the pure geometry of triangles and squares. At a more abstract level, our design may fit with the trend described by Li Edelkoort:

> Our relationship with the natural world will need to [attain] symbiosis if we intend to survive as a species, and by learning lessons from nature, we will be able to mimic its evolved forms, its mastered techniques and benefit from its proven knowledge. Our archaic roots will be transformed into contemporary ways of living, and in animistic fashion, we will connect with animals on entirely different levels. Mankind is after all a part of the animal kingdom [16].

**VORONOI DIAGRAMS**
In mathematics, a Voronoi diagram is a way of dividing space into a number of regions. A set of points (seeds) is specified beforehand, and for each seed a corresponding region consisting of all points will be closer to that seed than to any other. The regions are called Voronoi cells (Fig. 4).

Voronoi diagrams are related to animal skin prints in a practical sense: Many graphical designers and artists use Voronoi-based algorithms and tools to generate effects that resemble animal skin. A popular way of doing this is using the *Filter > Texture > Stained Glass* option of Adobe Photoshop (see Fig. 5).

In an informal sense, the visual similarity of lizard skin and Voronoi diagrams can be demonstrated by comparing the drawing of the real lizard in Fig. 6 with Figs 4 and 5. The lizard skin is not a true Voronoi diagram, because some of the cell borders are not precisely straight lines; however, there is a clear resemblance.
In computer graphics this resemblance is exploited in special algorithms for generating animal skins for animation purposes. See, for example, those by Marcelo Walter for the skins of various species of giraffes in his 1986 Ph.D. thesis [17]. This computer graphics work is inspired by biological research into how skin develops in real animals. One theory is the Clonal Mosaic Model [17].

**DESIGNING THE PATTERN**

We created the main layout of the skirt in Adobe Illustrator, using the straightforward tailoring of a standard skirt pattern for the basic skirt substrate. The size was 36 (European measure). For the patches, we subdivided a copy of this pattern by laser cutting. The patches were separated by borders of about 3 mm. We assigned the colors in a regular pattern as shown in Fig. 7 and the pattern was cut out with four different Illustrator files.

The pattern of patches was created with a special algorithm programmed in Processing (an open source Java-based platform also used for teaching in Technische Universiteit Eindhoven [TU/e]’s industrial design department). After some puzzling we noted that it requires a regular and symmetric hexagonal point grid for a Voronoi algorithm to produce equilateral triangular cells and that it takes a square point grid for it to produce square cells. We had to devise a smooth transition from a hexagonal point grid to a square point grid; details are presented in the Appendix. Using this, we created a large pattern consisting of triangles, except for 17 areas around a square. In total there are about 2,500 patches—mostly triangles, and 17 squares. Around each square are
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about 30 irregular polygons. Six of these squares actually contain an OLED, whereas 11 are there for pattern consistency and to prevent the upper skirt area from becoming boring (see Fig. 7). In the original pattern all the triangles are the same size. We mapped the pattern to the layout of the basic skirt by means of a subsequent straightforward geometric transformation, which necessitated using differently sized triangles.

REALIZATION

We transferred the total of about 2,500 patches manually from the four laser-cut fabrics to the skirt. The fabric was fixed by cotton interlining carrying a glue layer; the glue then had to be activated by hot ironing—a very labor-intensive process. The exact positioning was done with the help of a template: the network of 3-mm borders left over from one of the cuts.

We also discussed and played with various design options regarding the behavior of the light. We implemented two behaviors. The first is a scanning behavior: The six OLEDs go on and off, with smooth transitions, in a low-frequency rhythm of 0.3 Hz. The lights are not fully synchronous but follow each other with a 0.5-second delay between adjacent OLEDs, similar to the effects of breathing. The second behavior is a heartbeat pattern. This pattern is a double-blink, similar to the pulse pattern picked up by a PPG sensor or felt when feeling a person’s heartbeat. For the heartbeat behavior, all OLEDs work synchronously (so the effect is more pronounced and draws attention). It is technically possible to show the real heartbeat of a woman wearing the skirt by, for example, using a PPG or ECG sensor, but for demonstration purposes we implemented only a simulated heartbeat of about 70 beats per minute, as we were aware that the skirt would be shown at various exhibitions on a mannequin and not on a live model. We felt it was sufficient to refer to the possibility of showing body signals in a more abstract and poetic way. We programmed the simulated heartbeat in C using Arduino.

The possibility of interactivity also had to be part of the demonstration. There is a sensor to detect movement in the environment, so there is interaction even with a static mannequin. Visitors to the exhibit who approach the skirt trigger the heartbeat pattern. We used two light-dependent resistors (LDRs) and an Arduino LilyPad (a microcontroller intended for textile applications) to create this effect. The Arduino calculates a moving average light intensity level and uses that to detect fast changes in intensity. The LDRs are placed in a voltage divider circuit with distinct resistor values so that the detector mechanism works under both dim and bright conditions. In practice it is quite robust and will trigger the heartbeat when a visitor comes nearer than 0.5 meters. After about eight seconds of heartbeat operation, the skirt returns to scanning mode. We concealed the Arduino inside the skirt, near the lower seam, and made a small pocket to contain the rechargeable battery (900 mAh LiPo). The skirt functions for about two days and nights before recharging is needed.

Our efforts on the drapability of the patches have paid off, as shown in Fig. 8. The effect is not the traditional draping of smooth bias-grain garments, but it resembles the wrinkling effect often seen in architecture in modified geodesic domes (such as Massimiliano Fuksas’s “Blob’ building in Eindhoven [Fig. 9]) and in design (such as Mathieu Lehanneur’s ottoman “Bucky’s Nightmare”). The skirt is designed to be comfortable to wear. The wearer can sit, walk and dance without practical problems. The OLEDs are clearly visible during normal
in-house conditions and when daylight enters through the windows. However, in bright sunlight, the intensity of the OLEDs is simply not enough to make them visible. Note that it is an essential point in this design that the effect of the lights is subtle (and not screaming, “This is an LED skirt”). The dynamic effects of the breathing rhythm and the heartbeat certainly have aesthetic qualities that are hard to show in print (readers are referred to the online supplementary material).

RELATED WORK

The use of Voronoi diagrams, and structures resembling them, is not uncommon in architecture and design. In architecture these structures usually arise on curved surfaces. An example is the “emergent architecture” Summer Pavilion in Novosibirsk, Russia, by Tom Wiscombe (2007). In fashion, the Dutch company Freedom of Creation (FOC) creates “textiles” via 3D printing using structures such as interlocking rings, Mobius strips, chain mail, etc. Indeed, this offers an alternative way of mixing hard and soft materials while preserving drapability and was pioneered by Janne Kyttanen and Jiri Evenhuis in the Drape Dress in 2000 [18]. We agree that 3D printing is interesting, but we also believe that laser-cutting is at least as interesting; its possibilities are far from being exhausted (see also, for example, our innovative laser-cut fractal designs [19]). LED dresses were a main theme in Hussein Chalayan’s Autumn/Winter 2007–2008 collection. The “Day for Night” solar dress by Despina Papadopoulos of Studio 5050 [20] is made of over 400 white circuit boards in a rectangular configuration. This differs from our work in that the entire surface of Day for Night is covered. The Life Dress by Elizabeth Fuller [21] also has LED lights but, instead of the subtle embedding that we sought, the entire garment is covered with lights as with Day for Night. Day for Night also has a link to algorithmics, but uses the Game of Life online algorithm to feed the light pattern, whereas in our work the Voronoi algorithm had to run offline when generating the pattern. Of course the heartbeat pattern generator is also an algorithm, but it is of a different nature than the cellular automaton. Although Feijs has developed innovative cellular automata algorithms [22], they were not applied in the present project.

Using symmetries in fashion goes back to ancient times, but the first systematic explorations were done by H.J. Woods in the 1930s [23]. Similar patterns were explored by Escher [24], who is apparently more famous (particularly in the Netherlands, where N.G. de Bruijn organized the first exhibition of Escher for the World Congress of Mathematicians in 1954). Woods worked in textile research where he focused on the color pattern rather than on the folding and the drape of the fabric. Regarding the semantics of our pattern, we would also like to put it in the context of the epistemological theory of K. Kraft [25], who argues that, beyond the possibility that patterns are deployed as carriers of ornamental cultural values, there is the important perspective that all kinds of symmetries arise during the production process (knitting, plaiting, weaving, etc.). We envisage new textiles with very interesting symmetries where the story told by the symmetries is a more complex mixture of computer-aided design, computer-aided production, functional requirements and ornamental requirement. Drapely-o-lightment and our laser-cut fractal pied-de-poule [19] are examples of this forthcoming trend.

LOOKING BACK

In retrospect we are glad that the Escher-style tilings were not so drapable, because the resulting tiling pattern, with its reference to nature, is much more subtle. We learned that stiffened tiles with nonstraight edges tend to interlock rather than fold nicely at the edges. Before doing the experiments, we had an imprecise intuition that perhaps any tessellation would improve drapability, but then we found that the triangular pattern we ultimately chose outperformed all others (and certainly the Escher-like patterns).

More broadly, we can draw several conclusions about the process. We found that computer-driven laser cutting is a very valuable innovation and that its creative possibilities are far from exhausted, although 3D printing now seems to get more attention. We found that the embedding of technology in textiles in subtle ways is an important contemporary design challenge. We found that the difference in background between Toeters (fashion, fashion-technology, material innovation) and Feijs (electronics, software, mathematics) was the main reason that our cooperation led to something new. For example, Feijs could have continued doing tessellations as usual [13], but it would have been more of the same. We found that a rich and open studio environment (such as the setting of the TU/e industrial design department and its theme space of Wearable Senses) is an excellent meeting ground for initiating and executing multidisciplinary cooperative projects. We believe that the possibility of showing and sharing sensed body signals such as breathing, muscle tone, heartbeat and heartbeat variability is worth exploring—not only for medical reasons but as a new semiotic language and a way of sharing something intimate. We believe that new technologies such as laser cutting and welding instead of cutting and stitching will gradually find their way from experimental studios into factories. This is already happening in the area of sports, for example in constructing Nike shirts and laser-cut jeans patterns. One new technique worth exploring is the new type of 3D printer that can mix hard and soft (rubber-like) materials. Functional flatbed printing and coating on textiles [26] also interest us greatly, especially concerning surface design for the commercialization of our Drapely-o-lightment concept.

Finally, we were happy to benefit from open-source developments such as Processing, Lee Byron’s mesh library [27] and Arduino. Although mainstream modeling could be done well using standard tools such as Adobe Illustrator, every now and then tailor-made software (such as the algorithm described in the Appendix) is helpful for creating really new things. We are happy to make our Processing and Arduino program available to Leonardo readers on the MIT Press website for free use and modification as supplementary materials to this article [28].
APPENDIX: DETAILS OF THE ALGORITHM

After we discovered that a standard Voronoi algorithm requires a regular and symmetrical hexagonal point grid to produce equilateral triangular cells and a square point grid to produce square cells, the next question was: How can we make a smooth transition from a hexagonal point grid to a square point grid? We took inspiration from De Bruijn's pentagrids [29], but here the situation is much simpler: We need only a "duogrid." A duogrid is a set of vertical strips numbered \( i = 0,1,2, \ldots \) and a set of horizontal strips \( j = 0,1,2, \ldots \). A duogrid can be used to produce the \((x,y)\) coordinates of a hexagonal point grid and also to produce the \((x,y)\) coordinates of a square grid, as shown in Fig. 10.

The trick is to turn to algebra, as De Bruijn did, and in our case to construct a formula-pair that gives the \((x,y)\) coordinates for the hexagonal grid:

\[
x = 1\frac{1}{2}i + \text{odd}(j-i)\cdot\frac{1}{2} : 0 \\
y = \frac{1}{2}\sqrt{3}j
\]

where the notation \( c : 0 \) means if \( c \) then \( \frac{1}{2} \), else 0. And of course we have a very simple formula-pair that gives the \((x,y)\) coordinates for the rectangular point grid. Taking the same distance between the vertical strips as for the hexagonal point grid, the following gives the square point grid:

\[
x = 1\frac{1}{2}i \\
y = 1\frac{1}{2}j
\]

We combine the formula-pairs into one formula-pair:

\[
x = 1\frac{1}{2}i + \text{odd}(j-i)\cdot\frac{1}{2} : 0 \\
y = \frac{1}{2}\sqrt{3}j + \sigma \cdot (1\frac{1}{2} - \frac{1}{2}\sqrt{3})j
\]

which produces a hex point grid for \( \lambda = 1 \) and \( \sigma = 0 \) and which produces a square point grid for \( \lambda = 0 \) and \( \sigma = 1 \). For most \((i,j)\) we take \( \lambda = 1 \) and \( \sigma = 0 \). If we want to put one or a few squares near a target point \( A \) with indices \( i = i_A, j = j_A \) then we gradually change \( \lambda \) to 0 and \( \sigma \) to 1, locally near \((i_A, j_A)\). A point grid thus modified (and the resulting Voronoi diagram) is the one shown as above in Fig. 4. To convert the point set into a set of polygons, we used Lee Byron’s Processing Mesh library [27].

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Fig. 10. Duogrids of numbered seed points for a hexagonal point set (left) and a square point set (right). (© Loe Feijs)

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Acknowledgments

We thank Philips Research for their kind support; Jun Hu for the collaboration on Processing and tilings; Chet Bangaru, Jan Rouvroye and Willem Lammers for their support in use of the laser cutter; and Maarten Versteeg, leader of the Wearable Senses theme at TU/e.

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Manuscript received 9 January 2013.

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