Digitally Enchanted Wear: a Novel Approach in the Field of Dresses as Dynamic Digital Displays

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ABSTRACT
We introduce the term Digital Dresses as Dynamic Displays as an emergent field in the domains of Wearable Computing and Embodied Interactions. This recent approach consists of turning clothing into visual - and sometimes audiovisual - displays to enable novel forms of interaction between the wearer, the viewer, the tangible clothing and the embedded content. In this context, we present Enchanted Wearable, a new optimized low cost approach to create Digital Dresses as Dynamic Displays. Enchanted Wearable is a technologically embellished and augmented garment containing a portable rear dome projection system that transforms the clothing fabric into a blank canvas displaying audiovisual content. With this system, we create a new form of expression through clothing to reflect identity, personality, emotions and inner states of the wearer. In this paper we first present the growing field of Digital Dresses as Dynamic Displays, then we survey and analyse existing prior art in this field using a specific list of characteristics: display technology, wearability, interactivity, brightness, context. Finally we present the design and technology behind our new Enchanted Wearable system and explain how it brings new perspectives to the field.

CCS CONCEPTS
Human-centered computing Displays and imagers; Collaborative and social computing devices; Ubiquitous computing; Applied computing Performing arts; Hardware Emerging interfaces;

Author Keywords
Wearables, projection, wearable computing, augmented fashion

INTRODUCTION
The history of clothing reflects that the development of useful, protective, and ergonomic features coincides in parallel with the development of aesthetics and fashion. In different societies, clothes have always been at a point of tension between a liberating sense of self expression and a pressuring urge to follow social trends [21]. But whether they reveal social hierarchical status or offer the opportunity to present a unique, personal sense of aesthetic, clothes can always be seen as displaying information about the wearer [9]

Figure 1. Enchanted Wearable dress, credit to National Geographic [12] for the projected content

In the past, personal choices of the wearer were mainly expressed through the choice of clothes they bought, the way they matched different items, added accessories or altered the clothes. But with the advent of new available technologies on the mass market, as well as the rise of the Do-It-Yourself (DIY) community, more tools and techniques have become available to create more personal, reflective and dynamic fashion. Many artists and technologists have explored ways to create new synergies between clothing and technology. Clothes are not static anymore but can be dynamic and the same piece of clothing can perform a wide range of different looks to match and represent the ever-changing inner states and desires of the wearer. Now, from one press of a button, your dress can be made longer for a work event, or shorter for an evening out, using dynamic pneumatic actuation [24]. Additionally, you can change the color of the fabric interactively using chromatic inks [30]. By adding LEDs, speakers, sen-

TEI 2018, March 18–21, 2018, Stockholm, Sweden.

http://dx.doi.org/10.1145/XXX.XXXXX

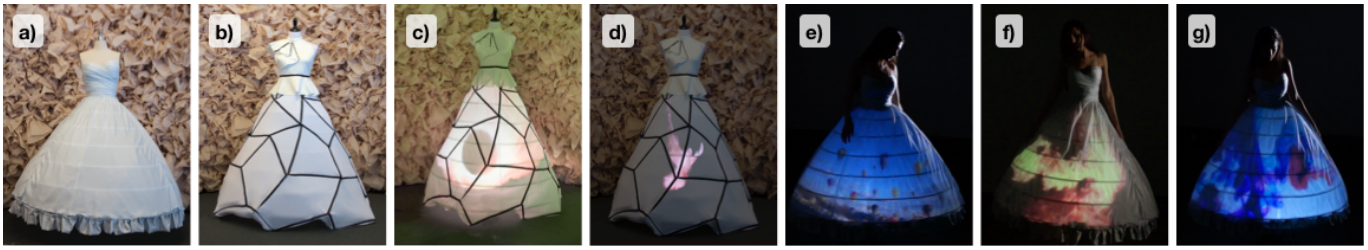

Figure 2. The two instances we build of the Enchanted Wearable system and examples of visuals content being projected. a) "Fablur" garment without projection; b) "I is Plural" garment without projection; c) "I is Plural" garment with projection of a setting sun animation, credit to wazdowls [33] for the projected content; d) "I is plural" garment with projection of an caged bird to symbolize the how clothing can become a form of opression for women, credit to dizi sever [8] for the projected content; e) "Fablur" worn by a user with projection of hot air baloons, credit to National Geographic [11] for the projected content; f) "Fablur" worn by a user with projection of fire, to represent heated mood of the wearer, credit to the Citrus Group [13] for the projected content g) "Fablur" worn by a user with projection of ink animation to represent cold mood of the wearer, credit to Abracadabra TV [29] for the projected content

sors and other electronics, users have the potential to bring a sense of empowerment to the way they dress.

This paper focuses on Digital Dresses as Dynamic Displays (D4) that use either color-changing pigments, direct lighting sources (such as LEDs), or projection to bring changing visualization on the surface of the garment. We can already see a movement to extend D4s out of the realm of performance art and into everyday life with commercial products such as T-shirts containing LED reacting to sound levels [34]. We believe that it is not only the trend of personalisation that justifies the need for the democratisation of D4 but also a need to enable users and primarily women with a sense of control, choice and potential for projection for and of the inner states.

We created two projects using the Enchanted Wearable system: "Fablur" and "I is plural" (see Figure 2). *Fablur* is a piece of clothing that performs itself revealing the inner feelings of the wearer. *I is Plural* is a participative art-fashion that reflects the diversity of a community and also the plurality present inside each of us. Both pieces are wearable tech installation that uses the Enchanted Wearable system to represent the links between individual and collective feminine conscience. With these projects, we discuss the technology behind the Enchanted Wearable system as a reproducible approach to create Digital Dresses as Dynamic Displays.

TECHNICAL BACKGROUND

Many breakthroughs have been made in the last few years in the domain of wearable technologies. The miniaturization of powerful batteries and the mass production of microchips have enabled the development of embedded systems to be worn closer and closer to the body. In the 90s, early work from Steve Mann [22] paved the way for modern embedded and embodied technologies.

In terms of general philosophy, the Enchanted Wearable system borrows from previous work in the field of projection based augmented reality. When thinking about the affordance of the interface and about gestural vocabulary, projects such as SixthSense [23], a projector based wearable gestural interface or LuminAR [20], a projector-camera system designed to use the traditional incandescent bulb interface as a power source, were inspirational. We also learned, from previous work in gestural interfaces with fabrics, how to use properties of fabric in the interface [19].

When creating the Enchanted Wearable system, our objective was to create a portable projection system by attaching a projector inside the dress. For the optics system, we drew inspiration from Hayden and Novy's Narratorium[15]. In this project, a system of mirrors and projectors reflect dynamic interactive animations on the 4 walls of a fabric tent creating an immersive environment called Dream Room. Interactions in the room are controlled by the voice to offer a novel approach to storytelling. For our project we use the same type of system to obtain rear projection on the inner surface of the fabric, kept in a dome shape by a custom made hoop skirt. This required a portable optical bench that is precise enough to create a focused high resolution image but also flexible and robust enough to allow for motion of the dress when the wearer walks and moves. We acknowledge the existence of other display technologies such as shape changing displays like Ishi's shape changing display [10] or Daniel Rozin's pompom mirror [17], but we choose not to include them as dynamic digital display because we have not yet seen wearables versions of these.

Technologies used to develop D4 systems broadly fall into three different categories: direct lighting, indirect lighting and color-changing materials. Direct lighting systems use displays generally made with LED strips or arrays. This is made possible by smart control systems such as one wire protocol of LED arrays or matrices. The recent development of lumaLive (a process that allows manufacturers to seamlessly integrate LEDs into fabrics) and Flexible Organic LED displays (FOLED) [26] offer good potential for textile based dynamic projects. Indirect lighting systems use front or rear projection to create images on a blank canvas. Finally, color-changing materials are based on electrochromic, thermochromic or photochromic pigments.

The choice of display technology will inform many other design decisions. Direct lighting systems have generally lower resolution but higher brightness. Color changing systems can have a lot of latency and generally remain low resolution but require less power. Projection systems offer better resolution but often at the cost of brightness and portability. Most projection based D4 systems use very big powerful projectors that are decoupled from the gown. These projects use projection mapping and because of this, the user's freedom of motion is constrained. Sometimes such systems even require the gown to stay absolutely immobile at a specific location.

As we can see, for an optimal result, D4 systems require a combination of design choices. We chose the following criteria to classify and evaluate our system and previous instances of D4 systems: display technology (LED/projection/color-changing); wearability (static on a mannequin/ limited range of motion/fully portable), interactivity (not interactive/reactive to inner or outer signals), brightness (low, medium, high), context (research/DIY/production/Haute Couture). We will keep those criteria in mind both in our review of previous work and in the description of the design of our system.

DIGITAL DRESSES AS DYNAMIC DISPLAYS: A SURVEY OF THE FIELD

This project draws inspiration from previous artistic and technological experiments. In this section, we review several past instances and efforts in this domain. At the end of this section, we classify the different cases according to the design criteria presented above: display technology, wearability, interactivity, brightness and context. The systems described range from haute couture dresses to performance costume to academic research projects. Because of this, it was difficult to obtain consistent and in depth information about each case.

Very early work from the 50s can be considered as instances of D4s (see Figure 3-a) [32]. Atsuko Tanaka "electric dress" worn by the artist and first exhibited at the Museum of Contemporary Art, Tokyo in 1956 uses about one hundred colored lightbulbs to create a post-modern kimono covering the artists to symbolize the gap between tradition and modernity. The piece built in the context of performing art is very bright as suggests the reconstituton of the dress in 1986 but because of the cables connecting the bulbs to power, it is not fully portable. In this system, the flickering lights are not interactive.

We believe that the first proof of concept of Digital Dresses as Dynamic Displays using projection was introduced in Jacques Demy's 1970 film Donkey Skin (see Figure 3-b) [7]. The film features a Dress colored with the weather: a magical gown whose colors and patterns look like an ever changing blue sky with moving clouds. This analogy effect is realised using an external projector on the film set. The result is bright enough to be seen in bright daylight, but the system is only portable inside a constrained area.

D4s have recently made their mark in fashion art production with the explosion of musical and theatrical shows of massive scale, they are used both as costumes and parts of the sets. For instance, while performing the ballad "Feel the Light" from the animated film Home, American singer Jennifer Lopez wears a very large circular skirt that serves as a canvas revealing special effects and images of the movie's animated characters projected onto the dress (Figure 3-c) [5]. Stylist Rob Zangardi and Mariel Haenn designed this dress that came to life as part of the singer's performance intending it to be both aesthetically pleasing and functional and allowing the animation to be projected onto the dress. The dress has only been shown in a very dark space which leads us to believe that the dress is not bright enough to be shown in daylight. Also the singer stays immobile on stage which suggests that the projection mapping on the dress is not actively tracking her position but only calibrated to a specific location.

Fashion designers Ece Ozalp (Figure 3-d) [1] and Frank Sorbier (Figure 3-e) [18] have also showcased Digital Dresses as Dynamic Display systems as a way of marrying Haute Couture with new technologies that portray projection mapping and audiovisual installation as performative fashion. In both cases, the projection mapping is not actively tracking the garment and the gown has to stay immobile. In the case of Ece Ozalp, the dress has only been showcased on a mannequin. Designers Nicola Buttari and Martino Chiti have taken this performative fashion approach to another level, adding interactivity to the design with the sonic addition (Figure 3-f). In their creation Performa [2] , the visuals react to sounds, changing patterns and formations on the surface of a white dress. This system allows the wearer to be able to change what they are wearing by making some noise. Again, in those three cases, the brightness seems to be in the medium range as the dresses have only been showcased in very dark environments.

The "Bee Dress" by Steven Guthierrez (Figure 3-g) [14] is a rare example of projected garment where the light sources are attached to the garment. In this case the dress has general illumination from a central light but only has projection on a small surface in the front part of the dress. The system does not seem to contain any interactive part and the illumination level seems to be medium level.

In recent years, direct lighting systems have gained some attention in the experimental fashion world. Hussein Chalayan's Video Dress project (Figure 3-h) [31] contains 15000 LEDs embedded beneath the fabric. The Video Dresses are portable with high brightness. However, the resolution is still very low and the current model is not interactive.

The LED galaxy dress from CuteCircuit is another example of an LED garment (see Figure 3-i) [6]. The dress is currently exhibited in the "Fast Forward: Inventing the Future" exhibit at the Museum of Science and Industry in Chicago. It contains 24000 LED and offers a high potential for interactive behaviors even though only one mode has been displayed to the public. This dress can be seen as a blank canvas of electronic components that could allow users to program different behaviours in the system.

In addition to LED and projectors, color changing inks have also been used to create dynamic digital displays on clothing, for instance, L Calder's thermochromic TUTU that is controlled by Kinect and Arduino (Figure 3-j). This garment display is low resolution and the interactions are delayed due to

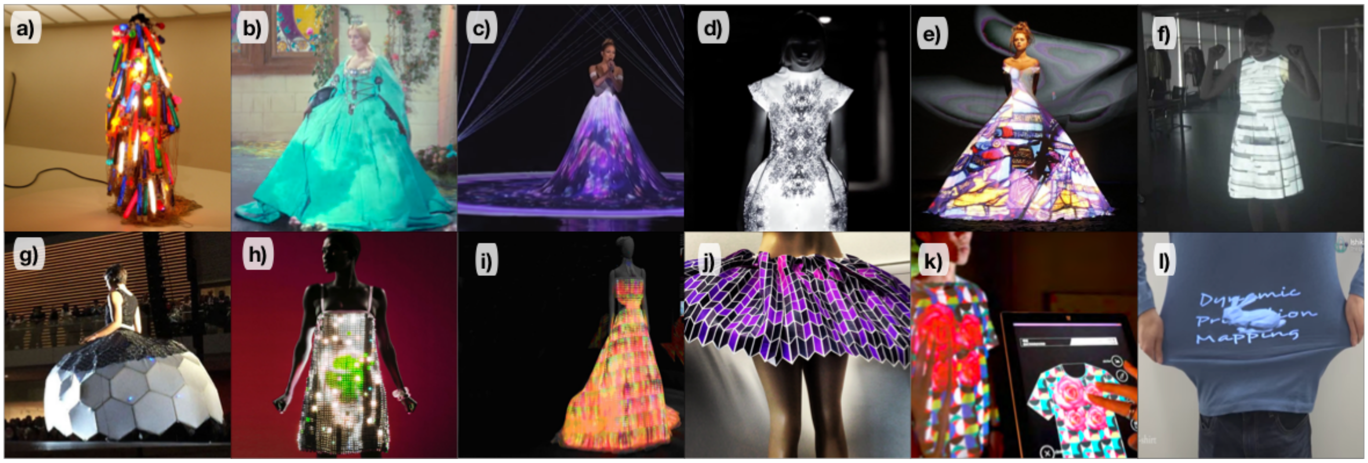

Figure 3. Examples of Digital Dresses as Dynamic Displays: a) Atsuko Tanaka "electric dress", b) Jacques Demy's Donkey skin; c) Jennifer Lopez's "Feel the Light" dress; d) Ece Ozalp's What is Real?; e) Frank Sorbier's dress; f) Nicola Buttari and Martino Chiti's Performa; g) Steven Guthierrez's "Bee dress"; h) Hussein Chalayan's Video Dress ; i) LED galaxy dress from CuteCircuit; j) L.Calder's "Thermochromic TUTU"; k) Mirror Mirror system; l) Ishikawa Watanabe Laboratory dynamic projection system

Name	**Year**	**Display Tech**	**Wearability**	**Interactivity**	**Brightness**	**Context**
Atsuko Tanaka's electric dress	1956	light bulbs	limited range	no	high	art show
Jacques Demy's Donkey Skin	1970	front projection	limited range	no	medium	show costume
Frank sorbier's dress	2012	front projection	immobile	no	medium	haute couture
Hussein Chalayan's Video Dress	2012	LEDs:15000 individual LEDs	fully portable	no	high	haute couture
CuteCircuit's LED Galaxy Dress	2012	LEDs:24000 individual LEDs	fully portable	no	high	haute couture
L.Calder's "Thermochromic TUTU"	2013	thermochromic inks	fully portable	yes: arduino controlled	high	design experiment
Steven Guthierrez's "Bee dress"	2014	rear front projection	fully portable	no	medium	art show
Jennifer Lopez's "Feel the Light" dress	2015	front/top projection	immobile	no	medium	show costume
Ece Ozalp's What is Real?	2015	front/side projection	on mannequin only	no	low	haute couture
Nicola Buttari's Performa	2015	front/side projection	immobile	yes: reacts to sounds	low	design experiment
Mirror Mirror	2016	front projection	limited range	yes: motion and action	medium	HCI research
Ishikawa Watanabe Laboratory system	2016	front projection	limited range	yes: wearer motion	medium	HCI research
Enchanted Wearable system	2017	rear dome projection	fully wearable	yes	medium	HCI research

Table 1. survey of the field of Digital Dresses as Dynamic Displays organized in chronological order

the speed of the chemical reaction but the brightness is not affected by ambient lighting [3].

HCI researchers have been developing new Digital Dresses as Dynamic Display prototypes exploring novel interactions using real-time cloth simulation. The Mirror Mirror system [25] (Figure 3-k) is a virtual fitting room containing a mirror display that allows the users to virtually draw on their T-shirt by adding colors to their reflection in the mirror. This interactive system uses live projection mapping so the user can move freely within a small area. Currently limited to t-shirts, the system is not portable but allows for a broad spectrum of interactions and for the users to generate creative ideas to personify their garment. Another system from Ishikawa Watanabe Laboratory in Japan (figure 3-l) presents dynamic projection mapping that allows projection onto deformed t-shirts [4]. The system uses a high-speed projector, which projects images up to 1000 frames per second. The t-shirt surface that is used as a screen is first marked with invisible IR ink to enable sensing of the projected images. These infrared targets restrict any distortion of the images onto the T-shirt.

While these systems create magical dynamic illumination effects on the dress, the portability remains limited such that the wearer is often unable to walk around. The ones that support projection mapping on free-moving 3D surfaces require sophisticated setup containing motion capture stage and external display or a powerful projection systems. The survey results of D4s are presented in Table 1 in a systematic way. After presenting the design of our system in the following section, we will come back to this table and discuss the uniqueness of our system. As most of the instances reviewed are not described in detail in research papers, we fill this table to the best of our knowledge and would be very grateful for any correction or comments.

DESIGN OF THE ENCHANTED WEARABLE SYSTEM

The Enchanted Wearable system is at the intersection of optics, projection mapping, computational art, wearable fashion and experience design. Each of these domains present their own design challenges that at times were in opposition to each other, and we sought to find a balance between the different criteria to construct the optimal prototype.

Optics

The design and implementation were a challenge from an optics point of view as we had to invent and build a lightweight wearable optical bench that was still precise and robust enough to produce a compelling visualization. The optical system consists of an aluminum bar to serve as optical bench, a laser projector and a half sphere concave mirror mounted on custom made adjustable mounts (see figure 4). We did an exploration of different projectors to determine the best one for our situation. We had to decide between LCD or laser projection. We reviewed and tried several models of small portable LCD projectors (UO smartbeam, AAXE, brookstone) as they offered better brightness, but they raised issues when trying to keep the image in focus. Indeed, the distance between the fabrics and the mirror needed to be constant and identical for each point. This was not possible because the fabric needs to be fluid and follow the motions of the wearer.

We decided to use a laser projector and, even though the luminosity is theoretically smaller (only 32 lumens for the Sony MP-CL1A compared to 300 lumens for the AAXA P300 Pico), the perceived brightness of laser projectors is higher than the measured brightness. For the mirror, we had to find the smallest possible radius in order to keep the distance projector-mirror as short as possible

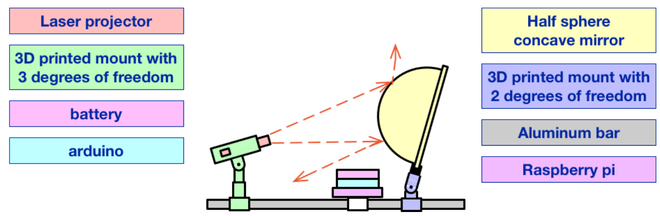

Figure 4. Optics of the Enchanted Wear system, the different elements are color coded and details of the process can be found in Figure 5

Fabrics and Dress Design

For the choice of material and textile, we had to find a compilation of material that is opaque enough to hide the inside components and to keep the laser beam from reaching the eyes of the public, but transparent enough to reveal a high quality image. The system had to project high definition image in focus and to be light, robust to the fluidity and relative motion of the different parts of the system.

The system also required to be easily stretchable to cover a half sphere. We chose a thin transparent crinoline covered by a layer of silk. The shape of the skirt had to allow for enough projection surface without reducing the wearability.

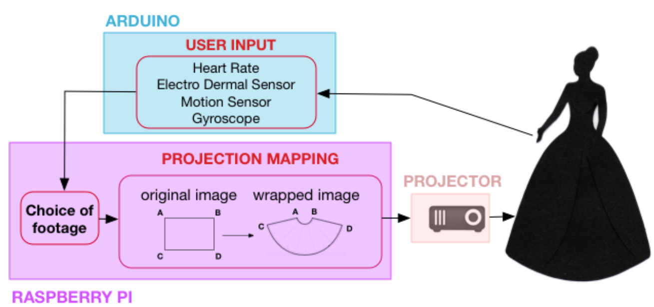

Figure 5. System diagram of the Enchanted Wear System, the input signals measured by the Arduino are processed by the Raspberry Pi to choose the footage to be projected. The footage is then warped into an arc and projected on the dress.

Software and Hardware

The project also contained a software aspects in order to map the content on the surface of the dress. We use projection mapping to warp the image around the dress while keeping the correct aspect ratio all around the 3D surface. To create the projection warp, we used the same pattern used for the pattern cut in the fabric to make the skirt. The hardware of the system uses an embedded computing system (Raspberry

Pi) and an Arduino micro-controller for sensing (see figure 5).

User Experience and Interaction Design

The system is wireless and portable and enables the wearer to walk freely with the garment. Due to the attachment, the skirt and image will slowly undulate with each step of the wearer but the whole system and focus will remain robust to motion and present a crisp image despite small variation of relative distance between the components. The rear projection system reaches about 80% of the surface of the dress (about 300 degrees) (see Figure 6) and the final position of the system avoids casting shadows of the legs when the wearer is immobile.

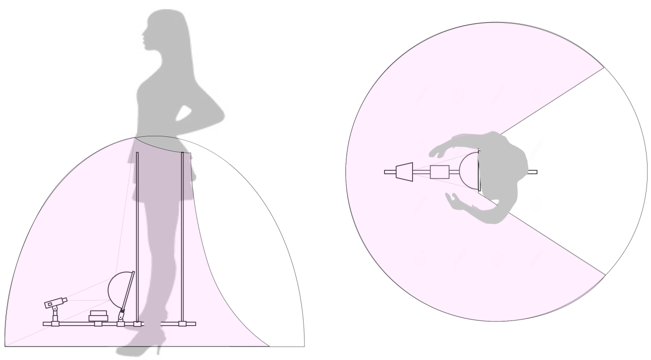

Figure 6. Side and Top view of the Enchanted Wearable system attached to a wearer with a belt, the pink area represents the surface covered by projection

The experience of the wearer and the experience of the viewer are quite different. The wearer doesn't have a full view of the dress but is in control of the system. Some of the interactions and proof of concept scenarios we have designed so far target the self perception of the user. For example, projecting different pairs of legs on the dress create an augmented reality effect of body transfer illusion [27]. Projecting multiple pairs of legs reflects the plurality of agents present inside each individual. We also play with the perception of the wearer's body by projecting a skeleton or a fetus on the surface of the dress. For the audience, the view is more complete and the illusion effects seem embodied in the user naturally. These illusion effects are not meant to be realistic but add an important interactive embodied effect to the aesthetic experience.

Using affective computing technologies [16] based on heart rate or electro-dermal activities, we can change the projected content to metaphorically match the inner state of the wearer. For example we can project blooming flowers or different seasons on the dress to represent different moods. By adding gyroscope and motion sensors to the system we can also create abstract visuals following the motions of the user and the different pan, tilt and roll motions of the dress. All those different interactions aim to bring a level of creative storytelling to clothing. The dress is telling a story which literally wraps around the main character.

Figure 7. Different seasons can be displayed on the dress to represent the mood of the wearer, credit to wazdowls [33] for the projected content

Figure 8. Augmented reality effect for body transfer illusion, credit to Rebecca Kleinberger and Eddie Talavera [28] for the projected content

EVALUATION AND DISCUSSION

In this section we come back to the variety of design criteria applicable to the conception of D4s and apply them to survey and evaluate the various previous work presented in the section *Digital Dresses as Dynamic Displays: a Survey of the Field* As we explained in the technical section, finding the balance between those criteria provides fertile ground for the creation of D4 systems.

The criteria we use to categorize previous work are: display technology, wearability, interactivity, brightness and context.

Display Technology

As described in Table1, the choice of display technology includes LEDs, projection and color-changing inks. We acknowledge the existence of other display technologies such as shape changing displays but choose to not include them in our survey. The choice of display technology informs the criteria as LED are generally brighter but with lower resolution. Projection and color changing inks also tend to blend more naturally with fabrics as they are indirect lightsources. Most examples we could find of previous D4 systems use projection over other display technologies. For our Enchanged Wearables system we also opted for projection as this allowed us to obtain better resolution and a smoother visual effect. The projector we use is a laser projector to avoid optical focus issues.

Wearability

In the previous examples shown in Table 1, we can see that the level of wearability varies a lot. Some pieces have only been displayed on immobile mannequins and never actually worn by people such as Ece Ozalp's "What is Real?" or some of Hussein Chalayan's Video Dresses. In most cases, using projection, the system is not actively tracking the wearer but is only passively targeting a specific area and the wearer has to stand immobile in that area. This is the case with Frank Sorbier's piece and Carrie Underwood's Grammy's dress. The advantage of the Enchanted Wearable system is that the projector is attached to the Garment so our system is fully wearable. The only other example of a fully wearable garment is Steven Guthierrez's "Bee dress" for which it also seems that the projector is attached under the hoop skirt. In this case the dress has general illumination from a central light but only has projection on a small surface in the front part of the dress while the Enchanted Wearable system reaches 80% of the surface of the skirt.

Interactivity

As we can see in Table 1, most examples found in haute couture and art shows are not interactive but only play back prerecorded animations. We believe that D4 systems are particularly interesting when they are interactive and allow for real time changes and modifications with the mood and the will of the wearer. We can distinguish two types of interactive systems. On the one hand, the systems that react to internal signals such as heart rate, motion, electrodermal activity, etc. On the other hand, the kind of system reacting to external signals such as ambient sound, button pressed, weather, etc. Both qualities of interaction seem interesting for the development of D4 systems. We can see in Table 1 that, currently, only examples from HCI research explore the dimension of internal interaction mainly detecting movement. Our system is the only one that seeks to express inner psychophysiological activities through dynamic display clothing. This way the user is empowered, by being in charge, regulating emotion and controlling the expression.

Brightness

The perceived brightness depends on the absolute luminosity of the system but also on other factors such as darkness of the environment, surface of projection, etc. LED systems are the brightest. Color-changing inks are not sources of light but are less influenced by outside lighting than systems using projection. We evaluated the brightness of prior works by looking at video and photographs of the systems. Generally when the garments are only displayed in a very dark environment we assume that their brightness is only low or medium. Brightness was a challenge for us as most small projectors have low luminosity. This explains why, among the designs we surveyed, most of the ones using projection decouple the projector from the dress, making the system not fully wearable.

Context

The survey of the field ranges across several disciplines, from haute couture to art show and costume creation to DIY projects and HCI research. It was important for us to consider all those contexts to survey the field as they influence each other in pushing the boundaries of wearable computing.

Limitations and Future Work

The Enchanted Wearable system was displayed at five different occasions (three times on a mannequin and twice on a live model). Each time it required either an enclosure to avoid ambient lights or to exhibit the garment outdoor at night. We received very positive feedback both from the audience and from the wearer. The quality and luminosity of off-the-shelf portable laser projecters is continuously improving and we believe that in the near future we will be able to deploy our Enchanted Wearable in brighter and brighter environments and also use darker fabric color for the garment.

We believe that the approach chosen for the Enchanted Wearable system is novel and overcomes many of the short comings of other approaches. However the versatility of the design is limited to dome-like projections, which implies the garment design is constrained to bell-like shaped skirts. Although using actrive projection mapping we were also able to cover more varieted shapes such as cones, balls or more irregular hoop skirt shapes.

From the exhibition, we received feedback regarding the ergonomy of the system. With the current system, the wearer can walk and turn but is still limited in his/her movements. With our first instance, the model gets quickly tired as they could not sit while wearing the dress. With our second instance, we changed the rotation of the system to allow the user to sit on a high top stool. For the next itteration we wish to make the system more ergonomic to be used for dancers, theatrical performances and as a more convenient real life ceremony garment

CONCLUSION

This paper introduced the term Digital Dresses as Dynamic Displays, an approach consisting in turning clothing into audiovisual displays. We surveyed the field considering prior art according to five characteristics: display technology, wearability, interactivity, brightness and context. We then presented the design and technology behind our new Enchanted Wearable system and explain how it brings new perspectives to the field.

ACKNOWLEDGMENTS

The development of the Dress Installation ”I is plural” was funded in part by a Director's Grant from the Council for the Arts at MIT.

Additional we wish to thank William Collins, Sunny Jolly, Dan Novy, Yoav Reches, Diana Robinson, Shantanu Sina and Akito van Troyer for their help and support in the development of this project.

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