Snowflakes: A Prototyping Tool for Computational Jewelry

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Figure 1: Three implementation with Snowflakes with different shape, layouts, input and output modalities and on different body parts

ABSTRACT

Smart-jewelry design has many layers such as comfort, ergonomics, fashionability, interactivity and functionality that create a complex design process, making the form exploration challenging. Various wearable prototyping tools were developed to overcome this challenge; however, they are usually textile-based and do not target smart jewelry design. To bridge this gap, we developed Snowflakes that differentiates from existing tools by *1) allowing designers to explore different jewelry forms, 2) incorporating external materials such as leather, 3) creating form factors that fit body parts with flexible connectors.* In this paper, we explain the design process of Snowflakes which is inspired by 7 design parameters (limbs, materials, grip, fastener, decoration, placement, form) extracted through the examination of non-smart jewelry. We also demonstrate three reimplementations and design concepts implemented with Snowflakes. Our exploration with Snowflakes contributes to the wearable community in terms of smart-jewelry visual expressions, interaction modalities, and merger of traditional and computational materials.

CCS CONCEPTS

• **Human-centered computing → Interface design prototyping**; **Ubiquitous and mobile devices**; **Interaction devices**; **User interface toolkits**; **Systems and tools for interaction design**.

KEYWORDS

smart jewellery, wearable technology, prototyping, maker, development, computational materials, design research, fabrication, research through design

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1 INTRODUCTION

The distance between computers and our bodies has been diminishing for decades. Through advancements in technology, they have grown into extensions of ourselves and become part of every moment in our daily lives. Technology has shrunk to the point that it can be easily attached to our bodies without encumbering us, leading to the widespread adoption of wearables. But wearing the

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technology has created novel concerns, such as aesthetics, wearability, and social acceptance that are not major design factors for other personal and mobile computers. As a result, aesthetics and wearability have become two critical factors of the wearable design process [13, 14, 33, 62]. Both aesthetics and wearability have been long-lasting concerns in the design of fashion apparel and accessories [40]. The addition of electronic components to the traditional materials used in apparel and accessories, such as textiles, threads, wires, chains, and jewels created new challenges for designers. Technology has differentiated the design process of smart wearables by necessitating the consideration of a computational layer [15]. Current tools and tool kits that can help designers incorporate these new dimensions are scarce, especially when it comes to smart jewelry design.

To fix this, we developed Snowflakes, a toolkit for smart jewelry prototyping inspired by and studied through the form factors of non-smart jewelry. Previously, there have been several studies, projects, and commercial products [5, 20, 30, 45] that aimed to help a non-technical audience explore the electronic parts of wearables. The LilyPad Arduino [5] is one of the most popular examples, and has paved the way for tinkering with textile-related materials while combining them with electronics. Other examples include educational tools [29, 30, 46], modular wearable products and concepts [4, 10, 38] and similar electronic boards and sensors [7, 20]. Still, although these products have eased the process of making electronics work and understanding their underlying mechanisms, they have had shortcomings in two main territories: *First*, tools such as the LilyPad Arduino still require an understanding of electronic assembly methods such as soldering before starting to tinker and produce products. *Second*, tools that are more accessible do not emphasize aesthetic concerns, such as the exploration of different shapes, layouts, body parts, and visual expressions that will be created with the addition of electronic components.

The Snowflakes toolkit has been made to resolve these shortcomings as a modular prototyping kit for designing fashionable smart jewelry. It can fill these gaps because 1) it is designed with a mindset that will allow designers to experiment with different form factors (shapes, layouts, and types of jewelry) that are inspired by the examination of non-smart jewelry, 2) it creates a design space in which outside materials can easily be incorporated in the exploration phase, and 3) it provides flexible connectors for creating form factors that can easily fit different parts of the body. In that sense, Snowflakes helps designers create smart jewelry in forms that have not yet been explored due to the lack of tools needed to experiment with computational and material aesthetics. Existing tools do not emphasize form factors exclusive to jewelry design, such as earrings and necklaces, nor the shapes and layouts of specific smart jewelry ideas. In other words, we argue that prior tools fall short in providing an expressive match [48] to the form exploration and interactive features required in the design of interactive jewelry. Thus, the purpose of Snowflakes is to support designers during the exploration process and let them experiment on forms and interaction aesthetics by arranging jewelry layouts on different parts of the body with various types of interaction modalities.

In light of this information, this paper's contribution is threefold. 1) We put forth 7 design parameters through the examination of non-smart wearables, 2) present the Snowflakes toolkit and explain its workflow thoroughly, and 3) construct a design space by demonstrating different smart-wearable prototypes created with Snowflakes and reimplementing three previous smart jewelry concepts [1]. Through these contributions, our study does not only introduce a novel wearable prototyping toolkit but also reveals the design process that provides the framework for other researchers and designers to design smart jewelry.

2 BACKGROUND

2.1 Exploring Aesthetics on Wearables

Fashionability is a critical aspect of designing wearables. Currently, many commercial smart wearables and jewelry products are designed for providing different aesthetic customizations to suit the wearers' style. Still, most of these customizations are usually for the non-electronic parts of these wearables such as watch straps, chains, or casings. Thus, much of their aesthetic appeal derives from those non-electronic parts, such as the straps of smartwatches [9]. However, the addition of computational materials such as sensors, actuators, LEDs, movable parts such as motors, and other electronic circuits creates opportunities for the exploration of a new design language. This novel visual language has been explored since 1960, starting with the glowing dresses of Diane Dew [19], but a design movement that implements computational visual cues into wearables is not prevalent in the current market.

Current design trends in interaction design and the maker movements emphasize the exploration of the form-related language of computational materials. The Computational Composites concept [63], introduced by Vallgårda, sees interaction design artifacts as holistic materials that should be designed with both electronic and non-electronic parts in mind. In that sense, the design should go through material explorations [16] that include tinkering with computational materials such as cables, circuits, and other forms of interactive components. Studies on wearable design and smart jewelry have moved in a similar direction. For example, Genc et al. [15], explored the involvement of computational materials in fashion design process to understand their part in the design process and how they can affect the resulting forms. Similarly, Tomico et al., also studied different aspects of these computational materials to see how they shed light on the next generation of fashionable technology [62]. A study by Devendorf et al. [11], with a title including the phrase "I don't want to wear a screen," clearly put forth that the traditional understanding of embedding electronics without considering a fashion design approach may not be preferable to users.

Although the new generation of fashion designers have adopted an approach that intertwines electronic developments and fashion design, the material exploration phase is more challenging than conventional accessory design because placing, rearranging, and playing with the form-related qualities of electronic components takes a lot of effort. Moreover, designing interactive features and understanding how they will contribute to the overall aesthetics and form of the product is still challenging. Such design requires a lot of professional knowledge and artistic freedo m in both the non-electronic and electronic layers [59]. Thus, apart from development tools such as the LilyPad Arduino or Adafruit's Circuit Playground

Express, extensive effort has been put into developing wearable prototyping kits. The main purpose of those kits is to diminish the technical barrier between designers and wearables and make the iterative design process easier and faster for seasoned wearables designers.

2.2 Wearable Prototyping Kits

Most prior work on wearable prototyping kits has focused on textile-based development. After reviewing the textile-based tool kits, Posch et al. [51], reported that wearable kits are useful for creating personal expressions through artwork and design, and for educational settings to teach basic electronic concepts to the non-expert audiences. Prototyping kits that would make electronic development more accessible to audiences with less knowledge in electronic assembly and coding are relevant to many other contexts, such as paper prototypes [52], tangible Internet of Things objects [35], and children's education [12, 34, 55]. By lowering the learning threshold of computational design and the production time of interactive prototypes, these tools aim to enable rapid and iterative experimentation for new interactive concepts [18].

Some kits aid in crafting wearables and art projects. For example, YAWN [61] is a kit that removes the need for basic electronic assembly methods such as soldering with the introduction of textile-based electronic modules. Similarly, BodyHub [50] is a jacket for designers to explore different output and input modules on the jacket's predefined sockets. Mannequette [56] is another project that takes this approach further by introducing design and development tools for people from various backgrounds (e.g., fashion design, engineering) to tinker and collaborate on designing electronics-embedded fashion artifacts. The main idea behind Mannequette is to create an environment where different parties can communicate with each other without a need for coding or assembly knowledge. This overcomes several prevalent problems in wearable design, such as limited technology literacy, lack of vocabulary for creative expression, and issues regarding wearability. Wearable Bits [25] is another project in which users can snap together various textile modules with an actuator and sensors to build soft wearable prototypes. The results from the series of workshops they conducted suggest that users can try out the interactive features on the body to help participants to iterate their approach by acting as both the wearer and the observer. When it comes to textile-based approaches, Rapid Iron-On User Interfaces [32] is another project that allows designers to print electronic circuits on clothes that include various input and output elements such as sensors or lights.

Another branch of wearable prototyping kits focuses on different groups of people such as children and adults. For instance, MakerWear [31] is a modular wearable prototyping tool for children. iCATch [46] is a physical and wearable toolkit that combines textiles with modular electronic components and aids in exploratory learning for children. On the other hand, Craftec [24] is an Arduino-based crafting kit for the elderly. Although it is a general-purpose crafting kit without a specific focus on wearables, one example it was used in featured textile-based wearables.

All in all, these efforts demonstrate the need for tools that remove barriers like technological skills and technology literacy of designers in wearables design. Although there are plenty of different approaches regarding the development of toolkits for wearables design, they are mostly focused on textile-based wearables and development tools for smart jewelry and accessory design. But toolkits that take jewelry form factors into account to enable the exploration of various types of jewelry on different body parts are scarce.

2.3 Prototyping Kits for Smart Jewelry Design

Smart jewelry design holds an important position in the field of smart wearables. Many wearable products exist in the form of jewelry and accessories, such as rings, bracelets, watches, and necklaces. According to a report from Silina & Haddadi [57], half of the 187 smart jewelry products they reviewed belong to the glamor and fashion market. Therefore, the aesthetics of smart jewelry are an important aspect for consumers. The variety of different products combined with the plethora of form factors affords distinct types of input and output modalities and broad design space. This rich design space has been investigated by many studies, highlighting aspects such as form factor [53], body placement [21] (which was also expanded to other types of wearables with a very comprehensive body mapping by Zeagler [65, 66]), self-expression [44], private/public communication [21], customization [23], and interaction possibilities [26, 44, 53].

In this direction, a very comprehensive study called "Gehna" [1] has explored possible interaction sequences with different types of jewelry such as rings, necklaces, and earrings and revealed various possible actions, such as moving a pendant along its chain, twisting a ring, and hovering over an earring. These input modalities can be coupled with many different output modalities and each output modality can create distinct form languages when combined with the rich design space of non-smart jewelry. Another example along these lines is Memento, a pendant locket designed by Karin Niemantsverdriet in collaboration with Maarten Versteeg [28]. This locket captures the soundscape of the moment and place when opened and stops capturing when closed. When the back lid is opened, which is facing the wearer, it starts to play the recording. Memento is an impressive example showing how jewelry-specific interactions, as demonstrated by Gehna, can be combined with computational interactions to result in novel expressions.

Several design tools aim to help designers capture the aesthetic features of jewelry design. For example, Sparkly [47] is a toolkit that allows designers to combine the visual output modalities, such as LED lights, with the sparkling nature of gemstones. Although not for jewelry design, another interesting project by Kao et al., DuoSkin [27], demonstrates a rapid prototyping method for deploying skin-based electronic tattoos. However, compared to the textile-based wearable design and development kits, to the best of our knowledge, there is not a prototyping tool to help designers explore different jewelry types, shapes, layouts, and interaction modalities in a straightforward manner.

Existing wearable prototyping kits do not focus on helping designers in the exploration of jewelry forms because none of them are flexible enough to prototype jewelry-type forms on the body, nor have they reported a design process that adopted the design space of non-smart jewelry. Therefore, Snowflakes is unique in that

Figure 2: Left: Form parameters from our investigation database (images taken from pinterest.com), Right: Fastener Types

it is centered around the exploration of jewelry forms with the addition of computational input and output, and the only toolkit that allows designers to try smart jewelry forms anywhere on the body. In the following sections, we will explain the design process of Snowflakes by drawing on the design parameters created through the examination of non-smart jewelry, describe the technical properties and working mechanism, and demonstrate reimplementations and original designs as proposed by the commonly adopted toolkit evaluation methods in HCI [36].

3 DESIGN PROCESS

3.1 Examination of Non-Smart Jewelry

The design process of Snowflakes started with an examination of non-smart jewelry. We intended to understand the form factors of jewelry designs and then work towards a design that can satisfy these form-related qualities, such as shape or jewelry type. For laying out a design space and creating a concept that can satisfy a wide area in this space, we have examined 270 different pieces of non-smart jewelry on Pinterest.com and created 7 different parameters by iteratively coding them according to the steps of visual content analysis [3]. The concept designer started to code the visuals that are parsed from Pinterest.com with the keywords "jewelry, anklet, armlet, necklace, ring, and bracelet" and coded them in order. Every time a new code emerged, the set was coded from the beginning to incorporate it. The final version of the design space was created through several iterations (samples can be reached from bitly.com/wearthefun). Analyzed items included 20 neck-worn, 26 hand-worn, 27 foot- and leg-worn, 49 finger-worn, 65 wrist-worn, and 83 arm-worn pieces of jewelry. There is a variance among the number of limbs, but our coding did not reveal new parameters on these pieces except for the limb, which can intuitively extend to other limbs. Pinterest has also been used as a visual repository for content analysis by several previous studies [17, 49, 58]. The resulting design parameters which led to Snowflakes are as follows:

1. **Limbs** parameter is concerned with which body part the accessory is worn on. The most common codes in this parameter are arms, ankles, fingers, feet, and neck, but can be expanded to other body parts, such as head, chest, toes.
2. **Materials** parameter is used to categorize accessories according to their materials, like gold, silver, leather, rope, wood, etc.
3. **Grip** parameter refers to the fit of the accessory. Primarily, it refers to either end of the spectrum, such as *tight* if it fits snugly around the limb, or *loose* if it has a more relaxed fit.
4. **Fastener (Figure 2 - Right)** parameter classifies jewelry according to different fastener types. Subcategories of this parameter are buttons, clips, ties, finger rings, and flexibility of the accessory itself to fit around the limb.
5. **Decoration** parameter refers to the material and type of decoration on the accessory. Our current categorization encompasses decorations such as non-precious, semi-precious, and precious stones, pearls, seashells, metal pieces, metal figures, strings, cloth figures, glass figures, plastic figures, feathers, chains, and embedded shapes.
6. **Decoration Placement** parameter stands for the position and the arrangement of decoration pieces on the jewelry. Static refers to fixed objects while Dynamic represents moving objects such as dangling parts.
7. **Form (Figure 2 - Left)** categorizes the form of traditional jewelry into 7 different categories.
   - **Lines:** Adornments with continuous lines in their forms.
   - **Chain:** Adornments with a chain assembly as the main body.
   - **Eclectic:** Adornments consisting of distinct pieces as a base structure.
   - **Imitation:** Adornments that directly reflect a real-world object like a flower, sword, etc.
   - **Patterned:** Adornments consisting of patterns.
   - **Bulk:** Adornments designed with pieces brought together as a mass.
   - **Geometric:** Adornments featuring repetitive geometric shapes like squares or hexagons.
   - **Irregular:** Adornments that do not form a regular pattern.

The examination of non-smart jewelry was more of an informal preparation for the ideation process. Still, it guided our low fidelity prototyping process (see section 3.2) by allowing us to conform to jewelry design properties. Especially the subcategories of each

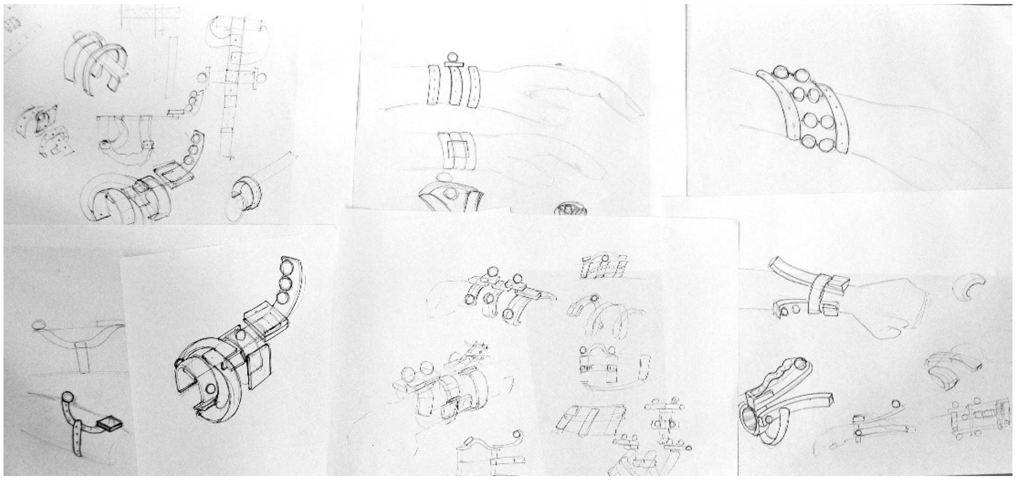

Figure 3: Early Ideation Sketches for Snowflakes

parameter can be extended in the design process (e.g., different limbs, fastener types, and materials).

3.2 Experimentation with the Experience Prototype

The design parameters extracted from non-smart jewelry guided our initial ideation process for a computational smart jewelry prototyping kit, resulting in the concept of Snowflakes. The design process followed a common diamond model. By drawing on these parameters, we first organized a one-hour brainstorming session among colleagues to generate ideas and sketches (Figure 3). After working on these ideas, through sketching and hands-on prototyping, we were able to draft various new ideas and create several concepts. Next, the concept designer (first author) of the Snowflakes toolkit worked independently on possible solutions to fit the design parameters defined in the former stage. The ideation process resulted in the Snowflakes experience prototype which is a modular prototyping kit for smart jewelry. To test the possible jewelry types Snowflakes can afford according to the above parameters, we 3D-printed non-functional experience prototypes and tried out different types of wearables. Figure 4 shows three examples of the different types of wearables we have tried (this part of the study has been previously published in CHI 2018 as an extended abstract and presented as a poster [22]). In these examples, each figure corresponds to the following parameters:

1. **Figure 4-a** *Limb*: Arm, *Material*: Plastic, *Grip*: Loose, *Fastener*: Flex, *Decoration*: Electronics, Shapes, *Decoration Placement*: Static, *Form*: Bulk
2. **Figure 4-b**: *Limb*: Arm, *Material*: Plastic, *Grip*: Tight, *Fastener*: Finger Ring, *Decoration*: Electronics, *Decoration Placement*: Static, *Form*: Lines
3. **Figure 4-c**: *Limb*: Arm, *Material*: Plastic, *Grip*: Loose, *Fastener*: Ties, Decoration: Electronics, *Geometric* Shapes, *Decoration Placement*: Dynamic, *Form*: Geometric

Our trials with the experience prototype of Snowflakes revealed that the current forms of the individual modules were capable of being attached to each other in many ways and could create distinct forms. We also saw that the empty spaces and holes existing in the design (which were originally implemented to add flexibility to the plastic material) allowed the addition of external materials such as strings or threads that, in turn, allowed us to form fasteners such as a finger ring (Figure 4-b) or design a dynamic decoration placement (Figure 4-c). However, these holes in the body were a concern for the working prototype implementation because they might have created challenges in placing electronics inside. Still, even if it is not possible to place holes in the body in the final form, we have learned that the design space should be open for external materials for more flexible experimentation and prototyping. In the final implementation, we also realized that we should look for ways to incorporate more materials to affect the aesthetic, such as leather or jewelry parts.

Following the trials with the experience prototype, we conceived an implementation plan. This plan envisioned each Snowflakes module as a part to which different sensors, input, and output elements could be attached (Figure 4-d). Moreover, we speculated on two different connectors: conductive and nonconductive. The conductive connectors would be for building the electronic structure while the nonconductive ones would add more modules to alter the physical form of the product (Figure 4-e). The details of this implementation plan can be read in our previous non-archival publication [22].

This low-fidelity experience prototyping step allowed us to validate the form of the Snowflakes and helped us envision the features and workflow of the working prototype. During the implementation phase, some of the features were implemented differently than we had originally anticipated. As a result, the low-fidelity prototyping phase proved critical to progressing toward a more consistent and solid implementation that still corroborates with the aims of the project in the beginning.

4 SNOWFLAKES

The realization of the working prototype has been achieved by the collaboration of researchers with design (second author) and

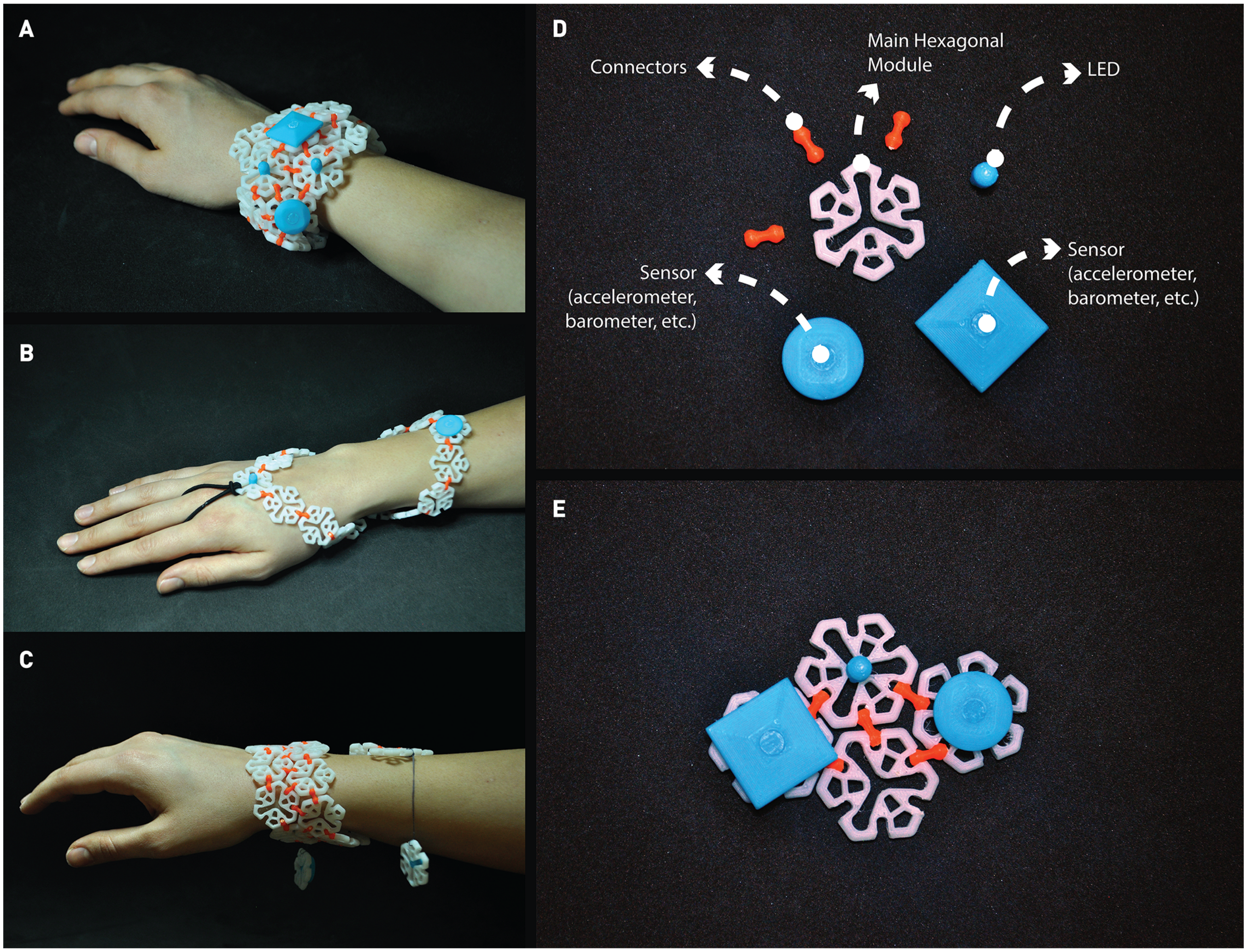

Figure 4: Different Jewelry Form Trials (A, B, C), Components (D) and Assembled Form (E) of Snowflakes

engineering (third author) backgrounds, after going through many iterations while consulting the concept designer (first author) and senior researchers in engineering (fourth author) and design (fifth author).

Our original plan was to design stand-alone Snowflakes modules that power themselves. Also, every module was planned to include a mini processor. We reconsidered this plan as it would be expensive and inefficient to manufacture standard modules embedded with a battery and microprocessor. Instead, we implemented a modular design that includes multiple types of hexagon-shaped *base modules* (main, battery, and routing modules). Moreover, the experience prototype of Snowflakes included rigid connectors with spherical heads. These connectors allowed each hexagonal module to rotate in a wide variety of angles, resulting in the flexibility required to adapt to different body parts. In the working prototype, we substituted the spherical-headed rigid connectors with flat and flexible connectors because it would not seem possible to provide a stable connection with spherical-headed connectors. Flat and flexible connectors provided a similar amount of flexibility to wear on different body parts. Also, instead of using conductive and nonconductive connectors, we decided to include only conductive *flexible connectors* to omit the phase of the electronic structure planning before prototyping. This was to make the toolkit more accessible to designers, who often do not have the technical knowledge to build electronic circuits. With this current design, the base modules with flexible connectors, let designers experiment with a variety of jewelry forms (as exemplified in the non-smart jewelry design space) by connecting them and while doing so, create an electronic infrastructure for interactive functionalities.

In addition to base modules and flexible connectors, we included several *interactive modules* that can be plugged into the sockets on the base modules to achieve interactive features, such as programming, wireless communication, and input/output. Furthermore, in the final design, we also included embellishment elements such as *3D-printed beads* and *ornamental casings* that can be attached to

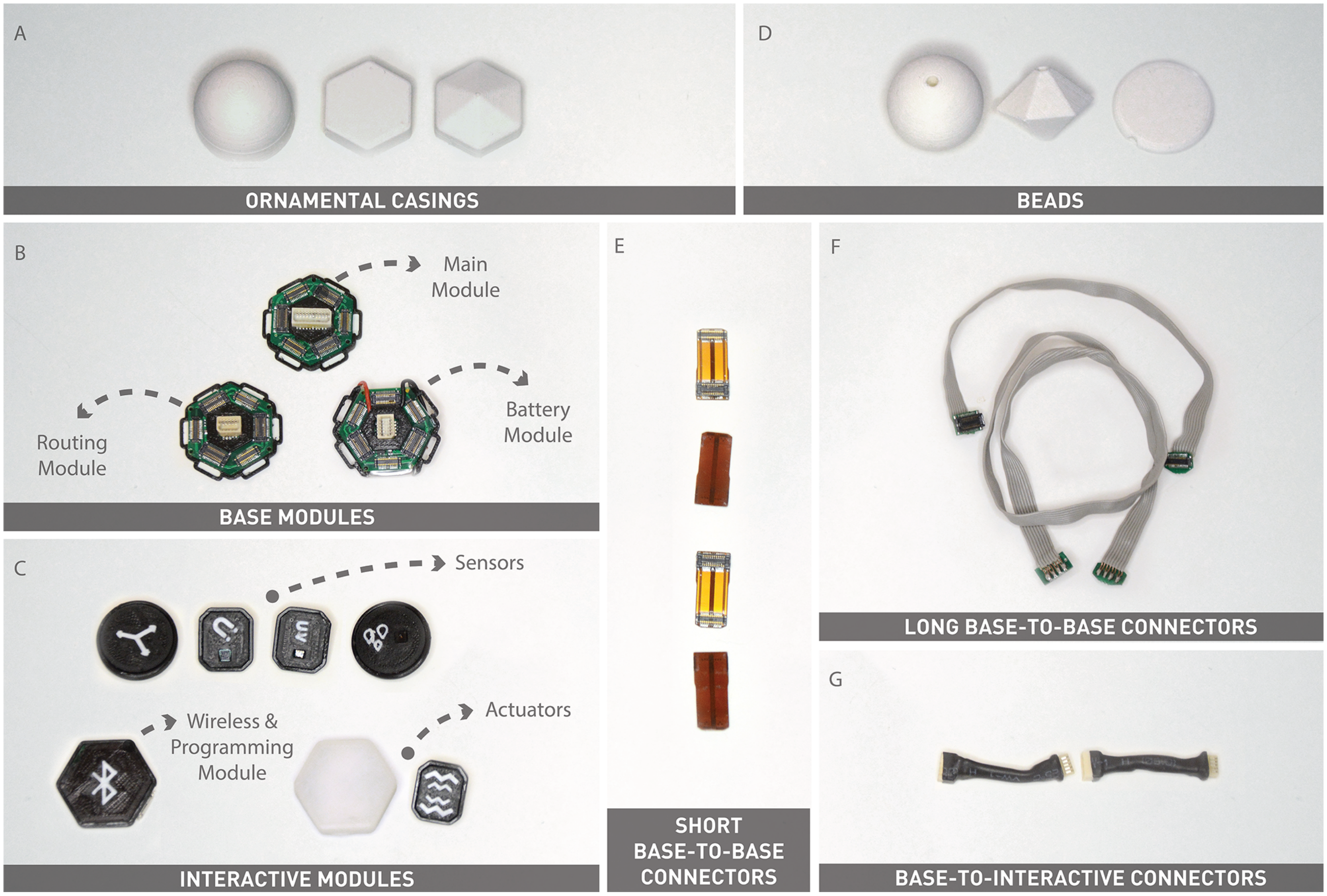

Figure 5: Snowflakes Toolkit. (a) Ornamental Casing; (b) Base Modules - Routing module on the left, main module in the middle, battery module on the right; (c) Interactive modules - Sensors on top, actuators on bottom right, wireless and programming module on bottom left; (d) Ornamental Beads; (e) Short base-to-base connector; (f) Long base-to-base connector; (g) Base-to-interactive connector

the hexagonal modules. The holes in the center of the experience prototype that enabled the incorporation of external materials such as threads were also replaced with hoops (Figure 5-b at the edges of the hexagonal modules. In the following sections, we introduce the implementation details of Snowflakes (see Figure 5).

4.1 Base Modules

Base modules (Figure 5-b) are hexagonal pieces (edge size of 11.86mm) with standard male and female connector sockets on each edge by order. The connector sockets on base modules are capable of carrying the standard 4-wire I^2C communication interface that includes power, data, and clock lines. This design allows many modules to attach to one another by using flexible connectors in between. The standard connection between modules lets designers easily explore the aesthetics and wearability of a piece of smart jewelry while providing electrical infrastructure without the requirement of technical knowledge of electronic assembly. Each type of base module has a 3D-printed casing with hoops on all edges to which external materials (i.e., small rings, strings, ropes, leather, or cloth) can be hooked. These holes also can enable the user to sew the base modules to fabrics if needed. There are three types of base modules in our toolkit: *Main*, *routing*, and *battery modules*:

4.1.1 Main module . (Figure 5-b) contains a micro-controller (Microchip ATmega32U4) that manages all communication between sensors, actuators, and a computer. In addition to the male and female connectors at the edges, this module also has a connector on the top surface for plugging in a Wireless and Programming Module (see "Interactive Modules" section). This allows the user to program the prototype through cable or wireless protocols. For designs that are planned to work as standalone jewelry, the main module can function completely without the Wireless and Programming Module if a battery module is present.

4.1.2 Routing modules. (Figure 5-b) are used to create a base and padding for the entire smart jewelry setup. Designers can connect a main module and a battery module with multiple routing modules to experiment with the form of smart jewelry, such as fitting different limbs, adjusting grips, and modifying form parameters.

In addition to exploration, routing modules can distribute the electrical connection. Each routing module has a PCB that transfers the energy and data from other base modules through male and female sockets on the edges. Routing modules also have standard I^2C connectors on both top and bottom surfaces, which are used for plugging interactive modules into routing modules. These connectors conduct I^2C communication between the interactive modules.

4.1.3 Battery module. (Figure 5-b) is an alteration of the routing module, manufactured by assembling a voltage regulator on the standard PCB design of routing modules. The battery module is the power source of the smart jewelry prototypes. Therefore, it should be included in all prototypes. In the current design, a separate Li-Po battery (3.7V, 85mAh) with a cable connection is used. However, our design is flexible and can include various battery options, such as on-board batteries (coin, Li-Po, etc.) and external batteries of different sizes and capacities.

4.2 Flexible Connectors

4.2.1 Base-to-base connectors. (Figure 5-e-f) These connectors are used to connect the base modules, both physically and electronically. There are two types of base-to-base connectors in the kit:

Short connectors (Figure 5-e) are made out of flexible PCBs. Each short connector has either a male or a female connector socket at its two ends. These sockets are identical to the ones on each base module (Figure 5-b). The length of the short connectors was defined based on the size of the base modules. Therefore, when multiple base modules are attached via short connectors, the distance between the modules and connection points is identical.

Long Connectors: Additionally, the kit involves long base-to-base connectors 5-f) made out of flexible copper wire. The long connectors let designers distribute modules further away from each other. The flexibility of the long connectors also creates the possibility for use as grip elements by wrapping them around limbs. These connectors can be found at 4cm, 8cm, and 12cm lengths.

All base-to-base connectors are capable of carrying I^2C signals therefore we only need one of them between two base modules. Using more base-to-base connectors than necessary for electrical connection provides rigidity with reasonable size. Also, using more connections for I^2C signals makes the electrical connection more reliable. If any line of the connection is broken, data still can reach the module from another connected path.

4.2.2 Base-to-interactive connectors. (Figure 5-g) The kit also contains *base-to-interactive connectors* for achieving designs that need to bridge the distance between base and interactive modules. The edges of these connectors include the same kind of male and female I^2C connectors on the routing and interactive modules. They are 2cm thick and made of copper wires. These connectors open up the possibility of using interactive modules as dynamic decoration elements, as examplified in Figure 4-c.

4.3 Interactive Modules

While the combination of base modules and flexible connectors lets designers experiment on overall aesthetics and wearability factors, the *interactive modules* (Figure 5-c) embellish prototypes with interactive features. For that purpose, we custom-designed several actuators and sensors that can be plugged into the routing modules. The aim here is to enable designers to quickly implement functionalities, such as defining input/output. All the interactive modules use I^2C protocol and require up to 3.3 V of power: Sensor modules include an accelerometer (Analog Devices ADXL345), a magnetometer (ST Microelectronics IIS2MDC), a relative humidity and temperature sensor (Sensirion SHT31), and an ambient light and UV sensor (Silicon Labs SI1133). Haptic (Texas Instruments DRV2605L) and RGB modules (Texas Instruments LP55231) are implemented as actuators. In addition to the actuators and sensors, we included a Wireless and Programming Module" to enable programming through wireless communication in the prototypes. This module uses the Raytac MDBT40 module for a Bluetooth Low Energy connection. Unlike other interactive modules, it can only be plugged into the socket on the main module. All interactive modules have 3D casings that are custom-designed depending on their sizes.

4.4 Ornamental Casings & Beads

Ornamental casings (Figure 5-a) are 3D-printed pieces that can be attached to any hexagonal module (e.g., base modules, LED modules, etc.). In the toolkit, there are a variety of ornamental casing shapes such as spherical, cylindrical, and diamond. All stone casings were printed with white ABS and Transparent PLA materials that also transmit light. The users can put stone casings on modules by replacing the modules' original casings, meaning the user should first take off the casing of, for instance, a routing module and put the stone casing on the bare PCB. Additionally, our toolkit included 3D-printed *beads* (Figure 5-d)in shapes similar to ornamental casings. Both ornamental casings and beads are to embellish the Snowflakes' aesthetics. Other types of ornamental casings with more complex jewelry shapes can also be produced to use as decorations, such as plastic figures or forms that fall into the "imitation" category of the form parameter.

4.5 Software

The current version of the toolkit (the main module) is programmed through the USB interface on the Wireless and Programming Module. As the main module has a popular Arduino capable microcontroller, we currently use Arduino IDE for development. Also, all sensor chips have ready-to-use Arduino libraries, ensuring that development efforts mostly center on the implementation of interactions between the sensors and the actuators.

5 EVALUATION OF THE TOOLKIT

In this part, we will introduce three novel design concepts and three reimplementations made with Snowflakes to evaluate the capabilities, practicality, and shortcomings of this toolkit. Previous work by Ledo et al., indicates that demonstrating implementations of new concepts and reimplementing previous work is an effective evaluation strategy [36], and one that has been used by several previous studies in HCI [2, 37, 41].

Figure 6: Left: IlluminEar in dim state, Middle: Changing colors with the head movement (green), Right: Side view of IlluminEar

5.1 Applications

Using Snowflakes, designers and developers can experiment with smart jewelry on a variety of levels, such as interactivity, fashionability, and functionality. In this section, we present a set of new design concept implementations that demonstrate the flexibility of our prototyping kit with different forms and interactivity explorations as well as the capability of integrating outside materials. In each application, we present the initial idea, how the prototype is constructed, its connection to non-smart jewelry design parameters, and the lessons learned.

5.1.1 IlluminEar. IlluminEar is an ear piece that augments the expression of head movements with lights (Figure 6). The piece has multiple stone-like ornaments and when the wearer moves their head, the ornaments react to the movement both by swinging and changing color. The main idea behind this implementation was to experiment with ear jewelry using Snowflakes and to explore the relationship between earring as a smart jewelry and head movements as an input. We also wanted to understand the different types of materials that can be used alongside electronics.

An important aspect of implementing IlluminEar was to achieve dangling parts. For this, along with short base-to-base connectors, some links between base modules were achieved with long base-to-base connectors. The flexibility of the long connector did not only illustrate the dangling effect on the IlluminEar, but also provided a loose grip mechanism. To achieve a stone-like appearance, we covered base modules with ornamental casings. Also, to experiment with other materials in combination with Snowflakes, we wrapped a coated wire with a furry material around the long flexible connectors. The interactive features included two LED modules and an accelerometer. The LED modules were programmed to change color when the wearer moves their head. Although the interactivity aspect did not require the use of additional interactive modules, we plugged a UV sensor into the outer side of the jewelry to add more dangling pieces for visual aesthetics.

IlluminEar corresponded to following jewelry parameters: *Limbs:* Ear, *Materials:* Plastic, gold, and fur, *Grip:* Loose, *Fastener:* Flex *Decorations: Jewelstones, electronics*, *Decoration Placement:* Dynamic, *Form:* Eclectic. This concept allowed us to experiment on a different limb and add to the experience prototype phase. We were also able to incorporate external materials, such as jewel stones, and experiment with the interactions between light, movement, reflections on the skin, and external materials.

5.1.2 Rhythm Shoes (Figure 7). Rhythm Shoes, jewelry worn on the ankle, aim to turn walking into a playful experience. The jewelry lights up according to the beat of the music the wearer listens to. The wearer, then, tries to synchronize their steps to the rhythm of the lights. For each accurate step that matches the rhythm, Rhythm Shoes vibrate and light up with a rewarding pattern. Although the main goal of Rhythm Shoes is to gamify a mundane daily activity, walking, it might also be used for dance training like Music-touch shoes [64], which was a wearable device developed for hearing-impaired dancers.

Visibility of the Rhythm Shoes to the wearer was an important concern since the aim of the design was to visually augment the steps of the user. Therefore, we decided to design Rhythm Shoes in a big, bulky manner in a way that it can be seen easily by the user while walking. To achieve this, the prototype involved seven base modules, an ornamental casing on one of the routing modules, and additional sensors and actuators. We also used small pieces of the ornamental wire wrapped around small connectors between the base modules. Ensuring a tight fit was another essential factor for comfort while walking. Similar to IlluminEar we used a long

Figure 7: Left: Materials used for the implementation of Rhythm Shoes, Middle and Right: Rhythm Shoes with naked feet and trainers

connector wrapped by an ornamental wire in between two of the base modules to compensate for the fit requirement. This was also supported by a thread attached to the hoops on the edges of two base modules. In terms of interactivity, the Snowflakes setup included an LED module and a vibration module as functioning interactive modules. Although the scenario required synchronization between the rhythm of a song and the light, our purpose here was to create the experience of how this interaction would feel. Therefore, instead of putting in the effort to implement a fully working prototype, we programmed the LED to light up in sync with the BPM of the music and added some random instances where the accurate step indication occurs. These enabled us to understand the experience.

With Rhythm Shoes, we wanted to move to another type of limb: feet. This project implemented these jewelry patterns: *Limbs:* Foot, *Materials:* Plastic, ropes, fur, *Grip:* Tight, *Fastener:* Tie *Decorations: Fur Balls, electronics, plastic shapes*, *Decoration Placement:* Static, *Form:* Bulk. We wanted to try a completely different approach compared to IlluminEar with Rhythm Shoes. We experimented with different interaction sequences and altered the device aesthetic by trying out distinct parameters.

5.1.3 PubliNeck.

The main aim of the PubliNeck concept (Figure 8), interactive jewelry for receiving notifications, is to experiment with the public/private nature of the feedback on a jewelry form factor. Usually, vibration is considered as a private channel of feedback, whereas the light is publicly visible. PubliNeck adds a twist to this nature by hiding the light feedback under the garment: From the outside, the jewelry seems like a necklace. However, it extends beneath the shirt, where light and vibration feedback stones are situated. Since the light stone is not visible from outside, it creates surprising public feedback by appearing behind the fabric (Figure 8-d).

To implement the PubliNeck, we used a decorative cord in combination with a Snowflakes setup. The decorative cord was constructed like a pendant necklace. It also was used to extend toward the belly and wrapped around the belly for fitting. The Snowflakes setup included four base modules on which an LED and a vibration module are attached. To test the effect, we programmed both to be activated randomly with 2 minutes.

PubliNeck was a slightly different take on the jewelry design since a part of it was always not visible. Jewelry patterns that apply to this concept were: *Limbs:* Neck and Torso, *Materials:* Rope, leather, plastic *Grip:* Tight, *Fastener:* Tie *Decorations: Electronics*, *Decoration Placement:* Static, *Form:* Lines, Hidden. PubliNeck provided an interesting insight into our parameters. Normally, jewelry

Figure 8: Left: Materials of PubliNeck, Middle: Outside look of PubliNeck, Right: Hidden look of PubliNeck

is designed to be visible, and therefore determining the form parameter is rather straightforward. However, the addition of electronics led us to design a part of the jewelry to be visible only at certain times. Thus, "Hidden" might be added to form parameter and further categorization for public and private information might be needed in the context of smart jewelry as also suggested by previous work with spectator experiences [54] and playful wearables [6].

6 REIMPLEMENTATIONS

In this section, we describe how Snowflakes can be used to reimplement interactive jewelry examples from a previous study called Gehna [1]. We chose this work as it provides a wide range of examples of how our tool can be used to resolve aesthetic concerns and explore interactive features.

6.0.1 Gehna. Gehna [1] focused on examining the design space on jewelry-based input techniques. The authors demonstrated a collection of explorations with conventional necklaces and earrings, exemplifying how structural elements in jewelry designs can enable touch-based and/or manipulation-based input methods when they are augmented with computational materials. Among their various demonstrations, we focused on three of the regular types of jewelry (grape necklace, hoop earring, and pendant necklace) and reimplemented them with Snowflakes to acquire the input techniques the original authors experimented with (lifting and moving gestures as well as proximity input). Our prototypes also highlighted the various output alternatives that can be added to the original implementations.

The grape necklace included six round metal plates, forming a grape-like shape hanging from the neck of the wearer. In one of their implementations, the authors embedded an accelerometer-gyroscope module in one of the plates. This enabled experimentation with manipulation gestures, such as lifting the necklace by using the neck as a hinge. To reimplement this prototype, we created a similar grape form by using five base modules and two beads (Figure 9-1C). Snowflakes were attached to a chain by using small rings for connecting the chain to the holes on the edges of base modules. Apart from the base modules, the Snowflakes setup consisted of one accelerometer module to recognize lifting gestures. In addition to the accelerometer, we included an LED module that was programmed to grow brighter when the necklace is lifted (Figure 9-1).

Like the grape necklace, the authors of Gehna also experimented with lifting gestures on a hoop earring by using the same accelerometer-gyroscope module. For this implementation, we were able to implement an earring form factor by combining the Snowflakes modules with an earring hook. Our implementation consisted of an accelerometer, a magnetometer, and an LED module. While the accelerometer module let us demonstrate the lifting gesture, the magnetometer augmented the original prototype by sensing the proximity of a magnet, such as one worn on the wearer's hand (Figure 9-3B), to the earring. Also, the LED module was plugged into the inward face of the earring and programmed to reflect different-colored light on the skin based on both the proximity of the hand and the lifting gestures (Figure 9-3C). This setup not only imitated the original prototype successfully but also extended it with hovering gestures (also demonstrated as one of the possible interaction techniques in Gehna but on a bracelet) and with an output modality that allows designers to experiment with casting light on the skin (Figure 9-3).

In another implementation, the authors of Gehna experimented on gesture commands that can be achieved by manipulating the physical parts of a necklace. The necklace included a square-shaped pendant integrated into a long chain with a circular ball. By using ten resistors embedded in the chain and applying a small current, the necklace could tell the position of the pendant on the chain, thus enabling moving gestures. Instead of the current difference approach to detect the pendant's position, our implementation used the combination of a magnet and the magnetometer module in the necklace. We attached the magnetometer to one of the four connected modules as a pendant on the necklace. In addition to this pendant, we included beads, one of which had an embedded magnet (Figure 9-2D). The beads were able to move on the chain freely. In our setup, when the wearer moves the bead with a magnet on the chain, the magnetometer module senses the magnetic field change and detects the position of this bead in relation to the other. We also included a feedback mechanism with a vibration module that adjusts the vibration frequency according to the distance between beads (Figure 9-2).

The reimplementation phase focused on the interactive features of smart jewelry rather than the shapes, layouts, or types. Thus, compared to our design concepts, diversity in terms of the non-smart jewelry parameters were smaller. In terms of the necklaces, the main difference was in the form: while the Grape Necklace demonstrated a form closer to a *geometric* shape, the Pendant Necklace can be associated with the *lines* parameter. The hoop earring's form resembles the patterned form parameter and its decoration placement is dynamic, as its parts dangle when the wearer walks. It also uses a different grip, a needle, which is a common way of attaching earrings to the body. The fastener types, such as *clip* in the Grape Necklace, *tie* Pendant Necklace, and *needle* Hoop Earring demonstrate the benefit of the availability of external materials as they ease and diversify the ability to attach prototypes to the body.

7 DISCUSSION

Throughout our trials with Snowflakes, we achieved to implemented different types of interaction sequences, jewelry forms, and visual aesthetics that can be worn on the distinct parts of the body. Therefore, Snowflakes proved to be an effective toolkit that aligns with the initial goals of our design process. It allowed us to experiment with various aspects of the seven design parameters we created and promised a broader design space that can be shaped with the addition of computational parts.

Based on our experiences with Snowflakes, we argue that Snowflakes contributes to reducing development viscosity [48] for exploring the look-and-feel, role, and implementation dimensions of the design ideas [39]. In terms of look-and-feel, the modular structure enables jewelry type and shape experimentation with different limbs, such as the ear, neck, feet, chest, and even waist. For instance, although similar modules were used in Grape and Pendant necklaces, the shapes were different due to the different arrangement of modules. Also, Rhythm Shoes allowed us to experiment with a tight grip around the ankle due to the flexible connectors and small-sized

Figure 9: Reimplementations for Gehna prototypes [1] (1 - Grape Necklace, 2 - Pendant Necklace, 3 - Hoop Earring)

modules. Furthermore, the hoops on the edges of modules allowed the integration of external materials such as neck chains, earring hooks, wires, and leather strands, easing our prototyping process by expanding the possibilities we can explore, such as forming connections between the waist and neck, as in PubliNeck, or attaching decorations like the jewel stones on IlluminEar. The 3D-printed ornamental casings and beads also let us easily change the look and feel of the jewelry (i.e., using plain cylinders or spherical casings for different looks) and can be extended further by 3D-printing more complex forms (i.e., moving parts). Finally, the standardized connectors (based on I2C protocol) promised to extend the non-smart jewelry design parameters we introduced by enabling interactivities on the body without requiring knowledge of electronic assembly. They let us experience and understand the potential functions, as well as the input and output modalities of the designs by quickly changing the interactive modules (i.e., replacing one sensor with another) to create alternatives in the design process.

Compared to our experience prototypes that had one type of hexagonal module, we discovered that ornamental casings create a variety of opportunities in the ideation and experimentation processes of smart jewelry design. The overall form, as indicated by the form parameters, can already be altered in many ways with Snowflakes, but the ability to change the appearance of each Snowflakes module adds another layer to this process. We have seen that different casings lead to distinct visual expressions, and these expressions also change when the arrangements of the same casings change. The dynamic visual expressions paired with lights or vibration also add to the visual language. All these interventions create a rich design space, and Snowflakes remarkably improved our design process while trying to experiment in this space.

As indicated by Genc et al. [15], the addition of computational visual expressions such as lights reveals novel utilizations of conventional materials such as cloth. In their work, these additions created new ways of using cloth, such as including invisible layers as a part of the design process. Our concepts such as PubliNeck, IlluminEar, and the earring reimplementation of Gehna showed us that the exploration process should also consider the additional materials, placement on the body, and other clothes in the visual expression. The Snowflakes toolkit provides a lot of flexibility in such situations because although the overall form of the jewelry might be satisfactory, its relationship with the body or with other clothing articles may indicate changes to the envisioned design. With Snowflakes, different varieties can be quickly tested to expand the design exploration process from jewelry to include its surroundings and contexts.

When it comes to the shortcomings we faced during our trials, while the flexible connectors allowed Snowflakes to be placed on different limbs, they also prevented the creation of more rigid structures which are part of traditional jewelry form language according to the design parameters we extracted (i.e., rings, flexibility of the material as in the flex fasteners, etc.). This suggests that by forming tighter grips with flex fastener types, Snowflakes can be further improved by creating connector alternatives with different rigidities. Additionally, connectors with different levels of flexibility and more size variety could help us to experiment on different forms more effectively. For example, although we could design dangling decorations in IlluminEar to some extent, with more flexible connectors we could have obtained results closer to our vision with this concept.

Moreover, modules were too large to experiment with the smaller jewelry types that were part of our non-traditional jewelry examination, such as rings. The large size, predetermined shape, and plastic material of the modules also limited the resolution of form details (i.e., patterns or material appearances, such as metallic). For the same reason, the current state of the toolkit is more useful for exploring piece-based jewelry styles (i.e., eclectic, bulk, and chain), although external materials can still help extend the diversity of the visual language. Moreover, experimentation with novel computational materials, such as textile-based sensors [8, 42, 43] might be another interesting avenue to explore. Thus, production techniques for different sizes and materials, and the incorporation of external parts with distinct material properties are aspects that need to be improved to reach the desired level of Snowflakes' design capabilities.

Additionally, our trials with Snowflakes indicated that the interactive components in the exploration phase should be expanded further. Currently, we have visual and tactile output modalities, however, the boundaries of the smart jewelry design space can be expanded even further with output modules such as moving parts with motors, sound, smell, bioadaptive outputs such as EMG or EEG signals, and more unconventional modalities, such as air, as indicated by [60]. In light of these shortcomings revealed during our experimentation with Snowflakes, we posit that Snowflakes is a start as a tool that will allow exploration in the design space of smart jewelry, still, there are many directions in which this work can be expanded.

8 LIMITATIONS AND FUTURE WORK

Our current design works at 3.3V, though lower voltage implementations such as 1.8V are also considered. As we used standard I^2C protocol in Snowflakes toolkit, in theory, it is possible to adapt any I^2C sensor or actuator to the toolkit. The only limitation is the voltage range in which the sensors or actuators can work. To implement sensors at different voltage ranges, level-shifter circuits are required for the module designs. In the current design, the sensor and actuators that are implemented should be considered proof of concept.

Currently, it is possible to program Snowflakes through Arduino IDE. We specifically chose Arduino IDE since it is popular among tinkerers and makers, and there are plentiful resources in its online platforms that can help designers. However, we also are working to implement a visual programming interface that will increase the accessibility of the toolkit to a wider audience, specifically to designers without coding skills.

As a future work, we plan to organize workshops with designers and will get their expert opinions to understand the usefulness in the design process and reveal further improvement points. However, the current COVID-19 pandemic situation has not allowed us to organize collocated design activities and we did not have sufficient number of prototypes to deploy to different designers. The current methods we employed are also valid as indicated by Ledo et al. [36] and employed by many different studies [2, 37, 41]. Our current findings provide design insights for the wearable community and our design process can afford strategies for smart jewelry and prototyping kit designers.

9 CONCLUSION

In this paper, we introduced Snowflakes, a smart jewelry design and prototyping tool. We have demonstrated three reimplementations and three new design concepts that are prototyped with Snowflakes. To the best of our knowledge, Snowflakes is the first smart jewelry kit with its novel capabilities such as 1) forming different types of jewelry forms as indicated by the 7 parameters we extracted through the examination of non-smart jewelry, 2) allowing easy incorporation of external materials such as jewelry parts, strings, or threads, 3) being placed on the different parts of the body through its flexible connectors.

Our explorations with this toolkit revealed insights for design that can help the wearables and design communities. It is especially helpful for finding ways to merge traditional and computational materials, and in considering the relationships between smart jewelry and the body, other clothes, and the jewelry's parts. The ornamental casings and the visual expressions created by the different and interactive arrangements of those also proved to be an important element for the diversity in the visual language and computational aesthetics provided by Snowflakes. Snowflakes can provide designers with the opportunity to ideate and experiment on holistic smart jewelry concepts whose layers, such as input and output modalities, contextual relations, and materiality are all considered during the design process.

In our study, we have successfully reimplemented projects and also were able to make design explorations for new concepts, proving that Snowflakes is a tool that can ease the design process of smart jewelry. We also revealed some limitations, such as the need for different sizes of modules and more connector types varying in size and flexibility. We believe that the supported forms and designs can be increased even more, and the exploration process can become smoother with such additions. Moreover, to extend the target audience group to include designers without coding experience and decrease the development viscosity, a visual programming interface would be beneficial. Still, the current form of the Snowflakes toolkit promises a novel approach for the design process of smart jewelry. We believe that seven design parameters we extracted, working mechanism, features and the design process which were explained through the reimplementations and new concepts can shed light on the future direction of smart jewelry design and direct endeavors regarding the new designs of smart jewelry, prototyping tools, and visual expressions that can be created with the combination of traditional and computational materials.

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