

HotFlex: Post-print Customization of 3D Prints Using Embedded State Change

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Figure 1. a) 3D-printed object with embedded state-changing elements. The end-user can physically customize the object on-demand after it is fabricated. This enables user-tailored wearables, b) ergonomically personalized devices, and c) new kinds of interactive objects.

ABSTRACT

While 3D printing offers great design flexibility *before* the object is printed, it is very hard for end-users to customize a 3D-printed object to their specific needs *after* it is printed. We propose HotFlex: a new approach allowing precisely located parts of a 3D object to transition on demand from a solid into a deformable state and back. This approach enables intuitive hands-on remodeling, personalization, and customization of a 3D object after it is printed. We introduce the approach and present an implementation based on computer-controlled printed heating elements that are embedded within the 3D object. We present a set of functional patterns that act as building blocks and enable various forms of hands-on customization. Furthermore, we demonstrate how to integrate sensing of user input and visual output. A series of technical experiments and various application examples demonstrate the practical feasibility of the approach.

Author Keywords

3D printing; 3D modeling; prototyping; fabrication; tangible interaction; shape change; printed electronics.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI)

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INTRODUCTION

3D printing has revolutionized the fabrication of custom objects. It offers great design flexibility through digital modeling, enables fabrication of highly customized geometries, and makes it easy to realize objects with specific material properties [6]. However, this high design flexibility in the pre-print modeling phase stands in sharp contrast to the very limited design options that are available in the post-print phase. Once printed, a 3D-printed object is typically static, making it very hard or even impossible to further adapt and customize it.

For users this presents great challenges. Creating a digital model in a CAD tool requires domain-specific knowledge that end-users typically do not have. This is even more difficult if the goal is to make the object fit a given physical context, such as designing an object which wraps tightly around the user's arm. Lastly, printing a customized digital design requires access to a 3D printer, is time-consuming, and produces waste material. This stands in contrast to the directness of customizing an object through physical interaction. Physical interaction fosters experimentation, improvisation, and an exploration of the medium's capacity [23] and helps anticipate the final object's look and feel [30].

This paper contributes a new approach, which enables the end-user to customize, personalize, or re-model a 3D object *after* it is printed by using physical interaction. Our approach is based on embedding computer-controlled elements inside the object. These are printed in custom geometries and can locally change their material properties, to transition from a solid into a deformable state and back. This enables precisely localized parts of a 3D object to become deformable upon user demand.

This paper presents the following main contributions:

First, we present how the approach can be technically realized. We propose *Hotflex*, a computer-controlled composite structure that is embedded into the 3D object. The composite essentially consists of printed heating elements and surrounding structures which are printed with a material that has a low melting point. When the element is warming up, the surrounding material becomes viscous: the user can deform it. These structures are all printed in custom geometries and work in concert to enable a specific type of shape-change. As we will demonstrate below, this approach can be used to achieve an expansive range of post-print customizations, including very localized on-demand modifications and creation of shapes of high mechanical stability. In addition, it can be easily implemented using conventional printers and off-the-shelf hardware components.

Our second contribution is a set of structural primitives and functional patterns. Based on four basic principles, we present a set of ten functional patterns, which serve as building blocks for HotFlex objects. They allow end-users to physically customize an object in a variety of ways, upon demand and at precisely defined locations. This includes deforming the object's shape, altering the object's stiffness, translating or rotating parts of an object, and permanently connecting or disconnecting multiple pieces of an object.

Our third contribution investigates principles for user interaction with Hotflex objects. The novel customization capabilities of Hotflex offer many interaction possibilities for users. To support these interactions, we show how sensing of user input and visual output can be integrated with HotFlex.

Results from technical experiments demonstrate the shape-change capabilities of our primitives and validate the computer-controlled change of important physical properties, including softness, elasticity, and tensile strength. The results also demonstrate that heating can be used safely and realized even in mobile battery-driven implementations. To validate the practical feasibility of the approach, a variety of application examples have been successfully realized using Hotflex, including a shape-changing wearable device, interactive packaging, and a mouse that can be ergonomically adjusted to the user's hand shape.

RELATED WORK

Rapid prototyping of 3D-printed objects

Prior work has contributed to improving rapid prototyping of 3D-printed objects. For instance, a variety of approaches and tools have been presented that help laypeople to quickly design objects. SPATA [46] introduces augmented calipers and protractors that transfer real-world measurements into a 3D environment, while other work integrates real-world objects directly into a mixed reality design or fabrication tool [48, 47]. Tactum [13] allows users to design 3D-printable models using gestures on skin. KidCAD [11] enables users to create 3D models by capturing, modifying, and remixing existing geometries using a malleable input surface. Another stream of research has contributed means for reducing the time needed for printing a digital model, thereby significantly

speeding up the rapid iteration process [24, 2, 25, 42, 39, 7]. All these approaches have the common goal to improve digital modeling. In contrast, our approach supports customization and rapid prototyping through *physical* hands-on deformation of a self-contained object.

Using heat to remodel 3D objects

Heat is an obvious means to modify 3D-printed objects, since fused deposition modeling (FDM) 3D printing relies on fusing heated plastics. Hence, heating tools, such as heat guns, soldering irons, or specially developed tools like Retouch3D [17], have been used to manually melt an object's surface and make minor changes, such as removing from support material or correcting small defects. All these have in common that heat is applied manually on the outside of the object to perform changes. This contrasts with our approach of embedding heating elements that are localized, computer-controlled, and work in concert with specific geometric structures to realize desired customization functionality.

Shape-changing interfaces

A stream of shape-changing interfaces leverages computer-controlled actuation of objects [33]. For example, pneumatic approaches have been used to actuate 3D-printed objects [35, 44] and soft composite objects [51]. Also, shape memory alloys (SMAs) and shape memory polymers (SMPs) have been widely used as actuators [10, 27, 8, 16]. In contrast to these active actuation approaches, Hotflex enables passive shape-change for users to physically customize 3D-printed objects.

Particle jamming is more closely related to our approach because it allows an object to retain its shape after it has been modified. This pneumatic technique has been employed in HCI to realize a variety of shape-changing interfaces, including tunable clay [12], tangible tabletop interfaces [22, 21], and thin interfaces with tunable stiffness [29]. Particle jamming has the desirable properties of creating strong structures with short transformation times. However, the fabrication of jamming objects is difficult, particularly if geometries are complex. HotFlex offers an easier and faster means of fabrication using printing. Moreover, the shape change is permanent without requiring permanent negative pressure or another form of energy. Lastly, HotFlex offers additional degrees of freedom, allowing for permanently connecting and disconnecting components.

Interactive printed objects

Our work is further inspired by a current stream of research on interactive printed objects. Prior work on printed electronics has contributed enabling methods to fabricate interactive objects that feature embedded sensing and output capabilities [40]. This includes inkjet-printed capacitive sensors [18, 19], multi-touch and multimodal sensor surfaces [14], pressure sensors [34], TFEL displays [28], and thin-film actuators [27, 16]. Also, a set of approaches have been presented that support users in designing interactive objects with printed electronics, including digital design environments [36, 27, 32] and hands-on physical customization [26].

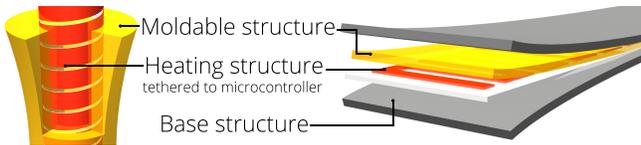


Figure 2. The HotFlex printed material composite consists of three structures. They can be realized as volumes (left) or thin layers (right).

3D-printed objects have been made touch-sensitive using embedded light fibers [50], embedded tubes filled with conductive ink [35], acoustics-based printed widgets [20], and 3D-printed conductors [5, 37]. Output on 3D-printed objects has been realized by redirecting light from a conventional display to the object surface using light fibers [50, 4]. We draw upon these input and output technologies to make 3D-printed objects using HotFlex more interactive.

HOTFLEX

This section introduces the basics of HotFlex and presents how it is implemented.

Basic Principle

HotFlex proposes the use of a printed material composite, which consists of three structures (see Fig. 2):

1. The *moldable structure* is used in parts that are to be modified after printing. It is made of a material with a low melting point.
2. The *heating structure* is embedded within the 3D-printed object and enables localized, computer controlled heating of the moldable structure. A thermistor is integrated for temperature sensing.
3. The *base structure* is used to realize non-modifiable parts of the 3D-printed object and to optionally encapsulate the moldable and heating structures. It is made of a solid or flexible material that can withstand high temperatures.

When the heating structure applies heat, the moldable material becomes increasingly soft. In this state, the structure can be deformed by applying an external force. This force can be generated by the user deforming the object, by gravity, or by releasing internal strain, for instance using an embedded spring. Once the moldable structure has cooled down, it returns to its solid state and permanently retains its altered shape, without consuming any further energy.

Robust functioning requires precise control of the melting process. To this end, we use a microcontroller for controlling the heating structures, while one or multiple integrated thermistors continuously monitor the temperature of the moldable structure. Heating structures can have a custom size and shape, and multiple structures can be embedded within an object and independently controlled. This enables precise control of the location that is to be customizable, including its size and shape.

Design

The three structures are combined in functional patterns. Each functional pattern enables a specific type of post-print

customization from a broad range of options, such as allowing the object to bend or to change its stiffness. A pattern is defined by the geometry of the material composite, the locations of heating elements, and the temperature to generate. We will present a variety of patterns below.

During design of the 3D object, the designer integrates one or more of these functional patterns into the digital model of the object. For our prototypes, we manually designed the geometry of the base and moldable structures using the CAD software Rhinoceros3D. Heating structures were designed in Adobe Illustrator. Future implementations could support the designer by automatically generating these structures to fit a given 3D model and desired modification possibilities, comparable to [27, 9, 3]. To this end, we have already started to partially abstract from the complexity by creating the patterns as reusable parameterized components in Grasshopper3D.

Of note is that designs that integrate HotFlex functional patterns can be made available in online repositories. This enables end-users who have no skills in digital modeling to simply download a model, print it, and then physically customize it to meet their personal demands.

Fabrication

In order to make the approach accessible to a wide audience, we chose to implement the principle using commonly available consumer-grade tools. We used a standard FDM 3D printer, a low-cost conductive ink-jet printer, and open-source Arduino microcontrollers.

Base and moldable structures

The base structure is made of commonly used 3D printing filaments. In our experiments, we have successfully used ABS, PLA, and TPE (thermoplastic elastomer, e.g., sold as *NinjaFlex*). For the moldable structure, we used PCL (polycaprolactone, e.g. sold as ESUN PCL Filament). PCL has the desirable property of a low melting point of 60 °C. In contrast, the base structure materials have a much higher melting point (PLA: 210 °C; ABS: 150 °C; TPE: 230 °C). We used a Makerbot Replicator 2 and Leapfrog Creatr HS printer to print the base structure and moldable structure and manually assembled the individual parts. We used both printers in parallel to speed up the fabrication of assembled parts. At 60 °C, PCL becomes increasingly soft as it transitions into a viscous liquid. While cooling down, the moldable structure stays deformable until its temperature drops below 45 °C.

Printed heating structure

HotFlex patterns apply heat through embedded printed heating elements. A heating element is a printed resistor, laid out in a serpentine pattern. It makes use of Joule heating, i.e., the resistor releases heat when an electric current passes through it. Heating elements are printed with conductive silver nanoparticle ink (Mitsubishi NBSIJ-FD02) on thin-film sheets (Mitsubishi NB-WF-3GF100) using a Canon Pixma iP100 printer [18, 19]. To allow for precise control of the temperature, a thermistor (TTF3A502F34D3AY) is attached onto the printed substrate next to the heating element with double-sided conductive adhesive tape (3M #9703).

The ink-jet printed heating structures are manually inserted into the 3D object during or after the 3D printing process. During the print process, the print can be paused and the heating structure placed in the object. Once the print continues the structure will be embedded in the object. For integration after printing, the structure can be slid into a cavity left open during printing. Alternatively, it can be attached on the outside of the object or placed between two parts during assembly. In the near future, 3D printers that are capable of printing conductive traces [45] are likely to render manual insertion of heating elements obsolete. The entire object can then be printed in one fully automatic printing pass.

For programmatic control of the heating process, we use an external Arduino microcontroller, which is tethered with the heating elements. It controls each heating element separately in a temperature feedback loop, by measuring the current temperature using the integrated thermistor and heating to the target temperature using a simple hysteresis cycle. The microcontroller measures the thermistor's resistance using a simple voltage divider circuit and calculates the temperature using the Steinhart-Hart equation [41].

The amount of heat released depends on the conductor's mass, its specific heat constant, and the power applied. We determined that a printed trace of 200 mm length and 0.7 mm width (covering a 20 x 10 mm² area) requires a current of 145 mA for reaching a temperature of 60 °C within 11 seconds at 9 V DC. A 1 mm thick piece of moldable structure completely melts in less than one minute at 60 °C and in 39 seconds at 80 °C.

For a mobile implementation, the microcontroller and battery can be embedded in or attached directly to the printed object. Since energy is only required while the object is being modified, even a regular battery can last a long time. Our experiments showed that a 9 V battery (5 Wh) contains enough energy for completely melting a moldable structure of 10 x 10 x 2 mm³ more than 150 consecutive times (at ambient room temperature). Using more powerful mobile energy sources, such as cell phone batteries (up to 12 Wh, e.g. Samsung Galaxy Note 4), the longevity can be extended further.

User Interaction

Once fabricated, the default state of the object is a passive state, in which it is not heated and no energy is required. Upon demand by the user or triggered by the system (the desired behavior is implemented by programming the microcontroller), the object turns into a customizable state: one or more heating elements are activated, allowing the user to physically customize the object.

Despite the relatively high temperature of 60 °C, the end-user can safely touch the moldable material. The same material is commercially used as clay material that allows for free hands-on modeling when it is heated [15]. This is possible because it has a high heat capacity and low thermal conductivity. It thereby differs from other materials, such as water or metal. The temperature on the outside of the object can be further reduced by adding an outer base structure that encapsulates the moldable structure.



Figure 3. Embedded input and output modalities: a) capacitive touch sensing, b) thermochromic display, and c) thin-film display.

To allow the user to control the customization functionality right on the object and to be aware of the element's current state, one or more input and output modalities can be embedded within the composite structure of a HotFlex element:

Embedded touch sensing (Fig. 3a) allows the user to manually activate and deactivate a HotFlex element. We implemented capacitive touch sensing by leveraging the element's heating structure itself. Inspired by [14], we use temporal multiplexing: the same printed resistor acts as a capacitive touch electrode for a short sensing interval (80 ms) between longer intervals that are used for heating (300 ms). We implemented capacitive touch sensing using the Capacitive Sensing Library [1]. We observed that heating has an insignificant effect on the accuracy of capacitive sensing, as it decreases the resistance by less than 5%. Once an element is activated, it transitions into the heating phase.

To inform the user about whether a HotFlex element is activated or ready to be deformed, we realized two types of embedded displays:

Embedded thermochromic display (Fig. 3b): A simple thermochromic display can be easily realized by leveraging a specific property of the moldable material: as the material gets warmer, it becomes more translucent. To increase the visibility of this effect, we have placed a colored sheet underneath the moldable structure. When cold, the moldable material is opaque and appears white (Fig. 3b left). At around 65 °C, it becomes fully transparent; the underlying sheet is clearly visible (right) and informs the user that the element is ready to be deformed. Optionally, a secondary display element can be integrated which provides visual feedback as soon as the element is slightly heated (outer ring in Fig. 3b center). We realized this with a thermochromic filament which becomes more transparent even at low temperatures of around 30 °C (Formfutura MagicFil™ Thermo PLA).

Embedded thin-film display (Fig. 3c): To realize a display that can be computer-controlled, we have integrated a PrintScreen thin-film display, which actively emits light

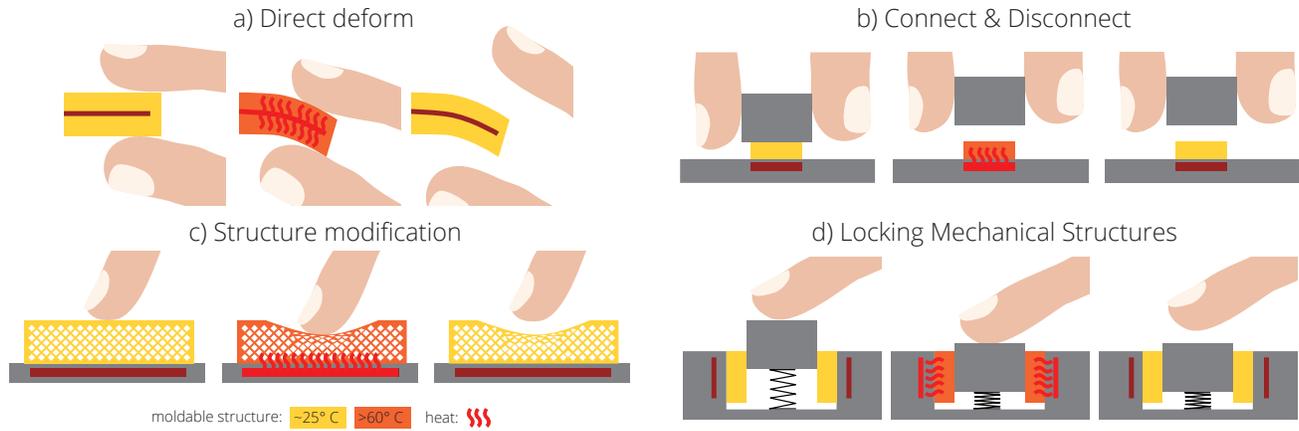


Figure 4. Deformation primitives enable four main types of object customization.

through the slightly translucent object. The display was screen printed onto the flexible substrate that contains the heating elements, following the method introduced in [28]. The implementation can use blinking patterns, a change in brightness, or dedicated icons to inform the user about the element’s current state.

PRIMITIVES AND FUNCTIONAL PATTERNS

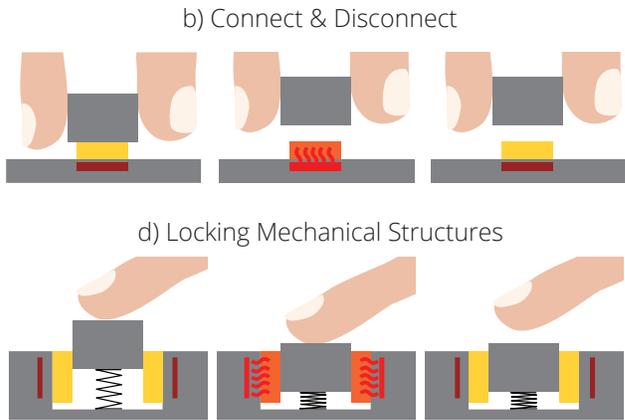
The HotFlex approach enables precisely controlled melting of moldable structures and can be used to implement a broad range of post-print customization. Through analysis of existing forms of object customization (on thingiverse.com) and through structured exploration of the HotFlex design space, we developed four deformation primitives: direct deform, connect/disconnect, structure modification, and locking (Fig. 4). These main principles enable a variety of functional patterns, which act as building blocks for customizable 3D objects. Each functional pattern realizes one specific type of object customization and leverages specific object geometries and heating structures.

Direct Deform

When warmed up, a piece of moldable material becomes like clay. It can be directly deformed by the user using physical interactions (Fig. 4a). In contrast to conventional clay, however, HotFlex enables users to make the object only partially deformable, at precisely defined locations, and to do so on-demand. We demonstrate the following functional patterns for free-form bending and folding of objects:

Free-form bending

To create a bendable structure, two structures of moldable material are placed on both sides of a thin film which contains the heating element (Fig. 5). The moldable material is stiff at room temperature and bendable when heated. Splitting the moldable structure into two layers has the benefit of faster heating and moreover protects the user from direct contact with the heating element. While it is not necessary to encapsulate the sandwich with an elastic base structure, we recommend doing so, as this presents two advantages: first, the structure is more robust to repeated bending, since the moldable material is kept in shape; and second, it allows for a higher heating temperature, as the user is not directly touching the moldable material.



It is possible to print multiple heating elements into the same structure, each having the same or different dimensions. This allows software to control, during use time, what parts of the structure should be deformable. For instance, we have realized a bracelet (see Fig. 15) that contains four separate heating elements. Each element can be warmed up on its own, allowing the bracelet to be deformed at this specific location. If all elements are heated at the same time, the entire band can be bent.

By changing the ratio between the moldable and base structures’ thickness, one can achieve different bending effects. For thick moldable (2 mm) and thin base (0.3 mm) layers, the overall structure deforms very easily and retains its deformed shape within seconds. For thinner moldable (1 mm) and thicker base (1 mm) layers, in contrast, the structure becomes elastic; while heated, it snaps back into its non-deformed shape, unless the user holds or maintains the deformed shape until the moldable material has cooled down. This produces strain in the base structure that can then be released upon reheating the moldable structure, producing a form of actuation.

The ease of deformation can be further controlled in software, by setting a slightly lower or higher temperature, since this directly influences the deformability of the moldable material. We have found the range of 55–70 °C to be most effective.

Placing the heating structure inside the moldable structure limits the set of possible deformations to the deformability of the heating structure. The heating elements are printed onto a sheet of coated paper. Hence, the overall structure is highly bendable, but cannot be stretched or compressed.

Folding

Folding is a specific case of generic bending: folding an object at a precisely pre-defined location, while the surrounding areas are left undeformed. This behavior is achieved by localizing a heating element precisely along the line where the object is to be foldable (Fig. 6).

We have realized a foldable prototype that uses a heating element of 8 mm length across the fold. The overall structure is 5.6 mm thick and can be folded around a radius of 2.5 mm, as illustrated in Figure 6.

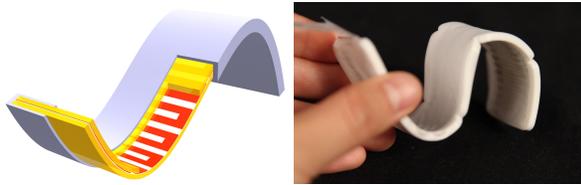


Figure 5. Bending: Heating element and moldable structure encapsulated by a thin base structure of flexible material (blue-gray).

Free-form 3D deformation

Detailed free-form deformation of an object’s surface can be realized by printing the outer surface with moldable material. For thin moldable layers, the underlying heating element is sealed from the moldable structure with a thin layer of base structure. When heated, the surface becomes soft and can be remodeled. We have realized a 3D-printed cat where the facial area can be customized by the end-user (Fig. 7).

Connect and Disconnect

HotFlex elements can be laid out so as to realize a firm physical connection between two objects, which can be split on demand. The basic principle consists of using moldable material as sort of glue between two objects. When heat is applied, this connection can be released or reconnected (see Fig. 4b). This offers a new way to customize objects through assembly of multiple parts.

Connect

A connector element consists of a heating element that is covered with a moldable structure, which is exposed on the object’s surface (Fig. 8). When the element is heated, another object can adhere to the moldable structure. It creates a firm connection when the material has cooled down, without requiring further energy. The other object can either be a connector element (in heated or passive state), or a conventional 3D-printed surface made of non-moldable filament.

The connect pattern is especially useful for objects that require a strong mechanical connection. In the validation section below we demonstrate that even a very small connect element can hold a mass of several kilograms. It also offers unique benefits for objects that require a thin connector, as no mechanical interlocking is required.

The strength of the connection depends on the connecting area and the thickness of the moldable structure. In our experiments, we could print the moldable structure as thin as 0.2 mm and still firmly connect two parts. Thicker moldable structures, however, can compensate for uneven surfaces or

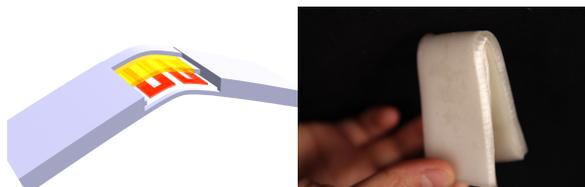


Figure 6. Folding.

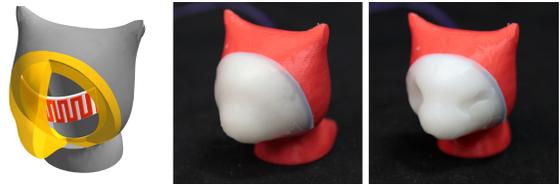


Figure 7. Free-form 3D deformation: 3D model, before hands-on modeling, after hands-on modeling.

non-matching shapes. The maximum thickness of the moldable structure is limited by the heating element’s temperature and desired activation time. Thin layers below 2 mm will melt within seconds at 80 °C, while thicker layers and lower temperatures increase the activation time to minutes.

Disconnect

Two connected pieces can be disconnected when heat is applied on the connector element. The two parts can then be separated by the user, by gravity, or by releasing stored strain. Gravity or released strain can be used to realize a form of computer-controlled actuation, for example to provide tangible feedback or notifications.

We recommend using temperatures of not more than 70 °C for disconnecting. At higher temperatures, the moldable structure may form strings between the objects while disconnecting. At lower temperatures we did not experience this issue.

Seal

A variation of the connect pattern can be used for sealing an object. For instance, sealing can prevent an object’s lid from being opened; it can also be used to make an object watertight. We have realized a 3D-printed box which features a lid that can be sealed (see Fig. 15b). To allow for watertight sealing, we laid out a continuous sealing element, which is a serpentine pattern (1 mm trace width) that follows the lid all around along its contour (see Fig. 9). The trace consists of a heating element covered with moldable material. Since the entire composite structure is digitally designed and fully printed, highly customized shapes can be sealed, for example a curved outline as illustrated in our box application.

Structure Modification

HotFlex can also be used for permanently altering the physical properties of the 3D-printed object, by changing its internal structure. To this end, the moldable structure is not laid out as a solid layer of material, but in a detailed 3D geometry. When heat is applied, this moldable structure can deform in a specific way that is defined by the geometry (see Fig. 4c).

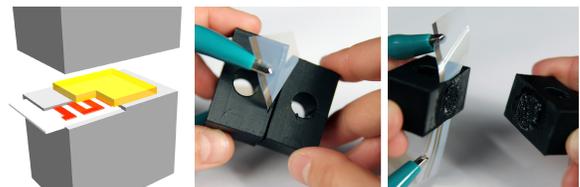


Figure 8. Connect and disconnect.

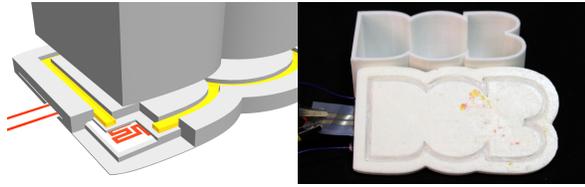


Figure 9. Sealing a complex contour: close-up cutaway model and realized prototype.

Fine geometric structures are widely used in 3D printing, for instance to realize different surface textures.

Increasing material softness

As an example of structure modification, we have realized a functional pattern that can change an object's stiffness. It transforms an initially stiff object, upon demand, into a softer one. This adds to prior work which has contributed specific 3D-printed geometries to realize (non-changeable) haptic properties [43, 38].

The pattern consists of a heating element that underlies a moldable 3D geometry, all tightly encapsulated in an elastic base structure. The moldable geometry is made of a repetitive structural pattern (e.g., a honeycomb or diagonal pattern) that has an infill percentage of less than 100% (see Fig. 10). In its initial state, the overall structure is stiff because the moldable geometry cannot be deformed. When heat is applied from the bottom, the moldable structure starts to melt, causing it to sink towards the bottom. This creates empty space between the moldable structure and the elastic top layer. The elastic top layer can be pushed further into the structure, causing it to be softer.

The desired stiffness change can be fine-tuned by varying the infill percentage of the moldable structure. Conceptually, there exists a one-to-one mapping between the infill percentage and the fraction of empty space that will be generated in the upper part of the moldable structure, e.g., a 40% infill allows the structure to reduce its height by 40%. In practice there may remain some small enclosures of air within the melted structure; therefore, we recommend to use a slightly lower infill percentage.

This functional pattern can be applied not only to soften planar surfaces. The moldable structure and outer base structure can be realized in pretty much any geometry, provided that a heating structure can be integrated so as to heat the desired area. We demonstrate this by integrating stiffness change into a non-developable surface of a 3D object, the mouse application presented below (see Fig. 15c).

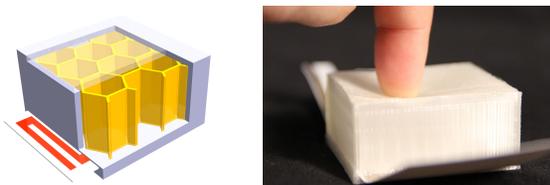


Figure 10. Increasing material softness: Cutaway model of initial state and image after heating.

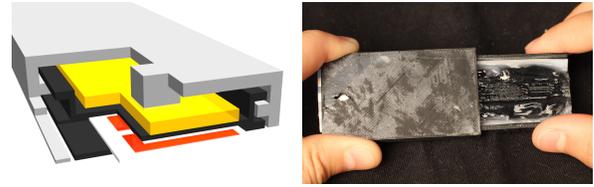


Figure 11. Translation: The pin on the top part (gray) locks to the moldable layer on the bottom part (black).

The temperature of the heating element should be at least 65 °C. At lower temperatures, the moldable structure may become soft but not liquid enough to sink.

Once the moldable structure has deformed, it cannot transform back to its initial 3D structure. Hence, the softening process is not reversible. However, the pattern can be activated multiple times for further softening.

Locking Mechanical Structures

Combining the HotFlex principle with commonly used mechanical structures, such as sliding mechanisms, joints, and hinges, allows their function to be locked and unlocked on demand. Figure 4d illustrates this primitive: the button (light gray) is locked in place by the moldable structure (orange). Once the heating element warms up the moldable structure, the connection is loosened and the button can be depressed. Once the moldable structure cools down, the button is held in place again.

One-dimensional translation

Translation is implemented using the locking primitive on a mechanical sliding mechanism (see Fig. 11). Two rails, left and right, enable the top part to slide on the bottom part. A layer of moldable material is laid out on the bottom part, with a heating element placed underneath. When cold, this moldable structure holds the top part in place through a contact pin that is affixed on the top part and extends into the moldable structure. Once the moldable structure warms up, the upper part can be translated along the rails.

This pattern generalizes to all sliding mechanisms that can incorporate a moldable locking structure and heating structure. This includes curved trajectories and non-developable geometries, as long as the heating structure can follow a corresponding developable approximation (i.e. it can be flattened onto a plane without distortion). It therefore enables a broad range of customization, including changing an object in size.

Similar to the connect pattern, the locking strength depends on the contact surface between contact pin, moldable structure, and bottom part. In our technical experiments, detailed below, we have found that the pattern generates high locking strength (>100 N force), while the object can be easily translated in the activated state.

Rotation around one axis

A similar locking pattern can be applied to other mechanical structures. We have realized a pattern for rotating an object part around one axis using a 3D-printed joint, e.g. to pose the limbs of a figurine. It is made of a simple rotating disk,

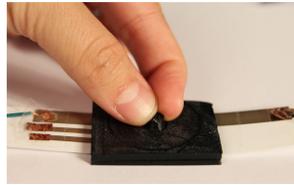
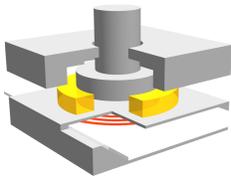


Figure 12. Rotation around one axis.

which can be locked and unlocked on demand by surrounding moldable material and an embedded heating structure, as illustrated in Figure 12.

Rotation around more than one axis

Rotation around multiple axes can be implemented using a ball joint structure (see Fig. 13). Placing moldable substrate between the bearing stud and the socket can lock the ball joint. For both rotation mechanisms the surface area of moldable material in-between both moving parts determines the physical strength of the connection. We realized a ball joint of 16 mm radius with 5 mm radius handles and a locking moldable structure of $20 \times 10 \times 1 \text{ mm}^3$.

VALIDATION

To validate the HotFlex approach and to assess its practical feasibility, we conducted six technical experiments and realized three application examples.

Technical experiments

We empirically investigated the core mechanical properties of each of the four HotFlex primitives. Moreover, we investigated effects of repeatability and timing.

Direct deform

To characterize direct deformation behavior, we tested the change in elasticity produced by the bending pattern. We tested prototype samples of the same dimensions as our bracelet prototype: 2.7 mm thick strip, with 1.6 mm moldable layer and 0.9 mm elastic Ninjaflex enclosing structure. We measured Young's modulus at room temperature and when the moldable structure was heated to 80 °C. To this end we affixed the strip on both ends, applied a mass of 2.5 kg at the center, and measured the resulting displacement in both conditions.

We identified a modulus of 0.21 GPa at room temperature and 0.12 GPa when heated, resulting in a considerable change of factor 1.7.

Structure modification

To test the stiffness change generated by the soften pattern, we measured the change of the force that is required for pressing into an object. We used a sample consisting of a 20 mm thick moldable structure (with a diagonal infill of 20%) and a Ninjaflex enclosure of 2 mm thickness. Our mechanical apparatus pushed a flat tip of 10 mm radius vertically into the sample and used a pressure sensor to measure the normal force required for the displacement. We measured the required force for a constant 2 mm displacement in the sample's initial state and after heating (2 mm was the maximum displacement possible in the initial state).

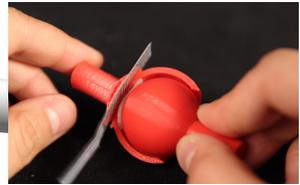
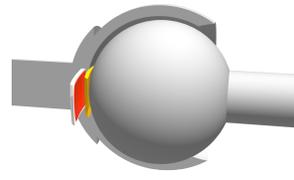


Figure 13. Rotation around three axis: implemented using a ball joint.

Initially, 67.6 N were required to press 2 mm into the structure. This was reduced to 41.1 N after heating the sample for 120 seconds at 80 °C – a reduction by 39%. The required force can even be significantly further reduced, but this requires heating for an extended period: after heating an additional 10 minutes, the force decreased to 23.3 N.

Locking

To determine the strength of mechanical locking, we tested an implementation of a sliding element (translation pattern). The sample measured 60 x 30 x 7.5 mm; the locking contact surface between both movable parts of the object was 60 mm².

We affixed the bottom part, which holds the heating element, and moved the upper part to its maximally extended position. We measured the force that is required for moving the element, both in the locked (room temperature) state and when heated to 80 °C for 45 seconds.

In the locked state, we measured it to withstand more than 100 N without moving even slightly (at which point we did not increase the force further). In the unlocked state, a force of 2.5 N, i.e. 40 times smaller, was sufficient to move the upper part.

Connect & Disconnect

We determined the mechanical characteristics of connect/disconnect with a sample consisting of two parts: one part implemented the connect pattern on a 10 x 10 mm² area with a 1 mm thick moldable structure. The other part featured a passive surface of the same size. We affixed the active part to the ceiling, with the connect surface facing down, and connected the passive part to its underside. We then successively added weight to the lower part.

The connection was capable of holding 8 kg (78 N) and broke when we applied a mass of 8.5 kg. When heated to 80 °C for 60 seconds, a force of 1 N was sufficient to separate the two parts, 1.25% of the required force in the non-heated state.

Repeatability

Repeatability of HotFlex interactions essentially depends on the ability of the moldable structure to retain its initial structure after repeated heating/cooling cycles and after being subject to external mechanical forces. For many patterns, repeatability is fostered by encapsulating the moldable material. The most critical case is the connect/disconnect pattern because it does not contain any encapsulation. This puts the highest demands on the moldable structure. We tested this pattern to identify a conservative estimate of repeatability of the functional patterns.

We heated up the connection between two pieces, successively disconnected and connected them 10 times, and let the

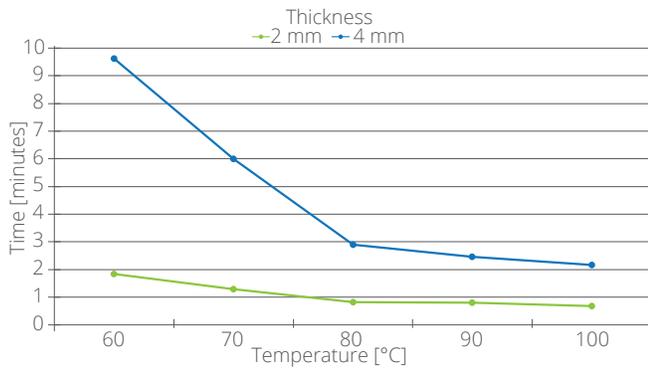


Figure 14. Heating time until the entire sample is fully deformable.

connection cool down. To ensure the pieces were correctly connected, we applied a mass of 5 kg for 20 s. We repeated this process 5 times, resulting in a total of 50 reconnections. Since we could not notice any degradation of performance in the sample, we stopped after these iterations. As a final test, we applied 5 kg of mass over a period of 24 hours, still resulting in a stable mechanical connection.

Melting time

We explored how temperature and geometry influence the required time for heating a piece of PCL, which is a property related to all primitives. To this end, we heated samples of 10 x 10 mm, 100% infill, and 2 mm and 4 mm thickness to the point where they were fully transparent, which indicates full deformability. We repeated the experiment for temperatures of 60, 70, 80, 90, and 100 °C. While full deformability is generally not required to enable modification, the onset of deformability is difficult to measure and full transparency therefore serves as a conservative estimate.

Figure 14 shows that the required time depends on the heating temperature and on the thickness of the structure. While a thin structure can be fully melted in less than one minute, time increases with thickness of the sample and reduced heating temperature. The results further show that the highest reduction in heating time can be achieved when increasing the temperature from 70 to 80 °C. This indicates that 80 °C is a good trade-off between low temperature and fast heating. Note that the temperatures here apply to the temperature of the heating element – the temperature at the outside of the object is much lower.

In practice, typical activation times of a HotFlex element are considerably shorter than the times reported here. We have tested here for full deformability of the entire moldable structure. However, in typical cases this full deformability is not required for shape change. Our rough estimate is that in most cases the element is deformable after only 20–30% of the times identified here.

Application 1: Shape-changeable interactive bracelet

As our first application case, we have designed and printed a shape-changeable bracelet. It provides the user with ambient notifications through an embedded LED (Fig. 15a). This prototype demonstrates how easily a user can physically customize HotFlex objects, e.g. adapt the shape to fit the user’s



Figure 15. Application examples. a) An interactive shape-changeable bracelet. b) Interactive sealable treasure box with embedded TFEL display. c) Ergonomically customizable mouse: cutaway rendering and prototype after customization (cover removed to reveal deformation).

wrist or transform it into other useful shapes upon demand, illustrated by the phone holder with ambient output (Fig. 15b). To this end, the bracelet contains two heating elements, which can be heated independently, implementing the bending pattern. It further shows how HotFlex can be implemented in a thin (2.7 mm) form factor including output elements and embedded touch sensing, allowing the user to control the customization functionality and accept notifications.

Application 2: Interactive sealable treasure box

A custom treasure box was printed in the shape of the user’s name (Fig. 15b). The lid has the sealing pattern embedded, allowing it to be sealed to the box (watertight). The box can be unlocked using a secret tapping pattern. This application illustrates how HotFlex expands the possibilities of makers to create highly customized interactive objects. To this end, a custom-shaped sealing element follows the box’s outline with moldable material integrated in the lid’s groove. An embedded capacitive touch sensor is used for capturing the tapping pattern and triggering the heating elements on correct entry. Printed on the same substrate, a TFEL display provides feedback on tapping and when the box is unlocking.

Application 3: Ergonomically customizable mouse

A 3D-printed mouse case (Fig. 1b) implements the soften pattern. It features a thumb rest, which can be ergonomically adapted by the end-user to fit her hand, allowing for a better grip and more comfortable use. The mouse case is realized in PLA with a thumb supporting structure of moldable material covered by a thin layer of elastic Ninjaflex. The moldable structure allows the user to freely personalize the softness at any location on the thumb rest. The cutaway rendering in

Figure 15c illustrates the embedded heating structures underneath the moldable structure. The image on the right shows the deformed moldable structure (flexible cover removed) after customization. The case is designed to fit on an existing electronics board of an optical mouse (Speedlink Fiori).

DISCUSSION AND LIMITATIONS

Scalability

The HotFlex approach, its primitives, and patterns scale for fabrication of small and medium-sized objects. Objects can be as thin as 1.25 mm (2 x 0.5 mm moldable; 0.25 mm heating and thermistor) and very small (trace width of heating element is 0.5 mm). Scalability to large sizes is limited by two factors: the maximum thickness of a moldable structure and maximum size of the heating structure. We have realized 20 mm thick moldable structures; these became slightly deformable after 2 minutes but needed more than 20 minutes to become fully deformable. The maximum size of a heating structure depends mainly on the energy source. A 9 V battery can power a 30 cm long and 0.5 mm wide heating trace at 0.15 A. Considering a maximum safe voltage of 60 V [49], a more performant energy supply can power traces up to 160 cm length. Using multiple elements in parallel reduces the voltage and increases the required current.

The maximum number of separately controllable heating elements is limited by the microcontroller. Our implementation using an Arduino uno can control 6 individual elements without multiplexing.

Energy consumption

Energy consumption scales with the heating element's size. We showed that elements up to 20 x 15 mm can be powered using a 9 V battery for more than 3 hours. Larger elements can be powered for shorter durations or using higher capacity batteries. There seems to be room for future implementations to significantly reduce energy consumption. First, other resistive materials, such as nichrome, are more efficient in heating. Second, the geometries of the moldable and heating structures of our prototypes have not been optimized with respect to energy consumption. Future implementations can optimize these geometries using physical simulation of heat localization and spreading.

Responsiveness

We showed that the time needed for heating is reasonable for small to medium-sized applications; for instance, the bracelet fully heats up in less than one minute. To improve responsiveness for larger applications, simulation and optimization of the heating process should be employed. The time may also be reduced by incorporating 3D-printed heating structures directly within the moldable structure.

Safety

Electric shock is prevented by implementing safety extra-low voltage (SELV) circuits with a maximum of 60 V DC [49]. These circuits are usually powered by batteries or power supplies that ensure user safety. Besides these precautions, the heating element should always be isolated (e.g. using a spray or tape isolator).

The moldable structure and base structure, insulating the heating element, are designed to ensure a safe surface temperature below 65 °C. For example in our bracelet, two thin layers of 0.9 mm moldable and 0.4 mm flexible material, reduce a 60 °C warm heating element to a maximum surface temperature of 48 °C. Higher temperatures are used in some of our prototypes to speed up the melting process. In this case, the surface temperature is reduced by increasing the layers' thickness or by reducing the heating time. For the bracelet example, the 0.9 mm moldable structure melts in 39 seconds at 80 °C, while the surface temperature does not reach 65 °C within 2 minutes.

Materials & Printing

The HotFlex approach generalizes to other combinations of materials, which may have higher or lower melting points. This opens up the possibility to explore other temperature ranges, melting behaviors, and material properties. In our implementation, the combination of PCL with ABS, PLA, and TPE worked well. Notably, PLA has a low softening temperature of around 60 °C, which might cause parts to deform while heating. We prevented this issue by avoiding placement of thin and fragile parts made of PLA close to the heating structure. Another possibility is to use formulations of PLA that can withstand higher temperatures, such as HTPLA [31].

The different melting points cause printing problems on current 3D multi-material printers. Since PCL has a very low melting point, it melts when the printer prints other materials onto it. For this reason, we used single-material printing and manually assembled the parts. It is very likely that future multi-material printers can solve this issue by employing better cooling techniques or by adapting the print path to avoid heating of already printed PCL parts.

CONCLUSION

In this paper, we have contributed a new approach to post-print customization of 3D-printed objects. It consists of embedding localized and computer-controlled structures that can change their deformation characteristics when heat is applied through embedded heating elements. We have introduced the approach and presented a set of functional patterns that act as building blocks for realizing desired customization options in a 3D object. Results from technical experiments and from practical application examples demonstrate the practical feasibility and show that the approach can be implemented using commodity hardware and supplies. Future work should investigate how end-users and designers appropriate the proposed technology. Further, an important technical challenge is printing HotFlex objects in one pass using multi-material and conductive 3D printing.

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