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XRtic: A Prototyping Toolkit for XR Applications using Cloth Deformation

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Abstract

This paper presents XRtic, a prototyping toolkit enabling real-world cloth deformations to be used in novel ways in eXtended Reality (XR) applications. XRtic was developed based on the insights gathered from semi-structured interviews with XR developers. It consists of custom-made actuators that can be attached to regular clothing, a controller bus system, and a controller interface. Using our toolkit, users can design and integrate different cloth deformation types synchronised with virtual content in a plug-and-play manner. Along with a technical analysis of the actuation behaviour of the XRtic actuators, we present the findings gathered from a user study with eight XR developers, focusing on the usability of the system and creative support. Overall, participants found it an easy-to-use toolkit that supports iterative and rapid prototyping, and enables cloth to be deformed in unique ways in synchronisation with XR applications. Based on the findings, we also report limitations and future work relating to our system.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interactive systems and tools—User interface toolkits; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual Reality

Figure 1: XRtic enables cloth deformations that are synchronised with the virtual contents in XR applications.

1 Introduction

In this paper we present a toolkit for cloth deformation for Extended Reality (XR) applications. XR uses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies to extend the virtual and physical realities that people experience [38, 56]. In order to improve immersion and realism in XR, many researchers have recognised the importance of 'rendered feedback', which aims to increase realism in virtual environments [9, 39, 60, 69]. For example, combining multi-modal feedback modalities such as tactile [15, 60, 69], smell [10, 11, 55], and taste [26] can create more realistic virtual applications.

However, haptics relating to a user's clothing are still largely under explored in XR. This seems a missed opportunity, as it is through clothing that users often feel the environment and their own body movements. When interacting with the external environment, it is often the user's clothing that is first to be contacted, even before the skin. For example, when walking through grassland or woods, one can feel leaves of plants striking along one's clothing; when in a cave, one might feel bats (or rats) touching one's back; when embracing someone, one can feel his/her body and arms pressing against one's own clothing; when growing-up one can feel that one's clothing is getting tight, etc. Considering this, cloth deformation that enables clothing to be dynamically modified has the potential to open up a rich interaction space. Therefore, in our research we aim to enable XR developers to render the effects of virtual environments on real-world clothing, in an easy and rapid way.

Recent research has shown several ways of fabricating shape-changing interfaces in substances such as paper [49, 50, 54, 76], soft materials [41, 51, 77], and textiles [46, 52, 73]. Textiles, in particular, are popular because specific properties of the fabrics can be used to enable diverse actuation types [46]. The deformation aspect of textiles has often been employed to enable artistic effects via clothing [19]; however, it has not been used to render feedback of deformation of clothing in XR contexts yet. Fabrication techniques involving shape-changing can be problematic and time-consuming for most XR developers, as they need to acquire specific knowledge, experience, and skills related to fabrication methods [2, 6]. By abstracting such technical difficulties of working with shape-changing materials such as SMAs, our work aims to enable XR developers to build and use cloth deformations that are responsive to virtual

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environments. This is done through a prototyping toolkit, which encapsulates expert knowledge and makes the process easier [2].

In this paper, we introduce XRtic, a prototyping toolkit that enables XR developers to introduce the feedback of cloth deformations into XR applications. XRtic is a fully functional implementation that comprises modular plug-and-play cloth actuators, a controller bus system, and a controller interface. XR developers can use XRtic to trigger cloth deformation based on certain actions or states of an XR application. In summary, our research makes the following novel contributions:

- System requirements gathered in interviews with XR developers regarding the development of the toolkit. These requirements reflect the methods and challenges of adopting fabrication techniques for shape-changing interfaces in virtual content development.
- The development of a prototyping toolkit that enables XR developers to add on-body feedback via cloth deformation. This toolkit comprises plug-and-play modular cloth actuators and a controller interface to control actuation signals and map the cloth actuators with the XR contents.
- Findings gathered from a user study with eight XR developers where we explored how XRtic supports adding cloth deformation to XR applications, how it considerably supports the creative exploration, and what are the challenges observed from using the toolkit are.

2 Related Work

2.1 Textile Actuation

Several approaches to achieve textile actuation have been explored using different methods [61], including: pneumatic actuators [37, 40, 81], mechanical linkages [5, 7, 30], and electric motors [1, 34, 57, 62]. *PneuSleeve* [81] demonstrated a fabric-based multimodal actuation mechanism using pneumatic pressure on a forearm sleeve that generated textile actuation such as compressions, skin stretches, and vibrations on the fabrics. *Rivera et al.* [57] showed techniques for combining 3D printing and textiles to achieve a new design space that enables functional properties (e.g., folding and bending) in textiles. They have explored several features such as the design primitives, adhered forces between the fabric and 3D printed elements, ways of 3D printing on fabrics, etc., to enable textile actuation using yarn-driven mechanisms. Although these methods allow diverse textile actuation mechanisms, they required an external power source such as a pump or a motor to control the actuators.

With the progression of the technologies associated with smart materials, such as Shape Memory Alloys (SMAs) [18, 27], textile actuation is becoming an exciting subject in the HCI community. The technological advantages such as high power-to-weight ratio [32], higher efficiency in large amplitude actuation [35], self-contained actuation mechanism [61] and mechanical flexibility [58] make SMAs popular in contrast to other textile actuation mechanisms. Sewing [47, 79], interlacing [4, 66], distinctly connecting [17, 21, 44, 45] and combining with 3D printing [46, 67] are some of the common ways of integrating SMAs into textiles to achieve textile actuation. A crafting method called *Seamless Seams* [47] enables integration of SMA threads into fabrics to generate morphological actuation in clothing. As well as sewing SMA threads into the fabric, it shows how to obtain diverse actuation types by changing the fabric stiffness using embroidering yarns in different areas of the textile. *Springlets* [20] and *Touch me Gently* [45] investigated coupling SMAs with sticker-like adhesive fabrics to achieve diverse tactile effects on the skin by actuating the adhered textiles. Despite the fact that these systems and fabrication techniques contribute in unique ways of actuating textiles, it is still necessary to explore plug-and-play approaches for enabling actuation in textiles.

Ueda et al. [73] developed a feedback method using the deformation of clothing that uses modular actuation bands with SMAs and springs. Inspired by this, in XRtic, we created a set of modular-based cloth actuators that are easily attached and detached. On the other hand, with the motive of having an easily customisable and versatile fabrication technique, *ClothTiles* [46] introduces a prototyping platform that can enable clothing actuation by combining flexible 3D printing on textiles and SMAs. It presents diverse ways of obtaining various actuation mechanisms on clothing by aggregating, scaling, and altering orientation aspects of the proposed modular actuating elements. However, a fully functional toolkit is required for novice XR developers, with a plug-and-play approach and a programmable power supply to dynamically control the cloth actuators and integrate them into different clothing items. In this project, we follow fabrication aspects of *ClothTiles* [46] to develop the cloth actuators for XRtic, and we made the cloth actuators easily attachable and reusable with ways of interfacing virtual applications in sync with them. Shape-changing interfaces that use smart materials such as SMAs has not been explored in the XR context to enable feedback via cloth actuation. Also, neither of the shape-changing interfaces mentioned above is fully accessible for XR developers. In XRtic, we propose a method for XR developers to enable actuation in clothing in a plug-and-play manner.

2.2 Prototyping Toolkits for Rendering Feedback in XR

Increased demand for rendered tactile feedback in virtual environment is notable as most virtual applications are solely visually oriented and lack non-visual feedback modalities [15, 65]. We identified several approaches that focus on enabling active [48] or passive [3] feedback modalities in virtual settings in recent literature. Besides visual and auditory modalities, these interactions incorporate multimodal sensory channels [12] such as haptic [43, 78], smell [11], and taste [26]. However, significant fabrication skills and knowledge is required to implement those interfaces [75].

With the growth of the do-it-yourself (DIY) community in HCI [14, 28, 33, 80], several prototyping toolkits have been created to enable developers from diverse domains to overcome the challenges of fabrication processes (e.g., 3D modelling, 3D printing, or chemical processes). As one of these early approaches, *Ruffaldi et al.* [59] presented a toolkit for rapid application development, targeting the integration of visual and haptic feedback modalities in virtual environments. A series of prototyping toolkits associated with vibrotactile arrays have become popular among research domains [31, 63, 64], and useful for conveying a unique set of sensory feedback on the skin. *VITAKI* [42] and *Stereohaptics* [24] are vibrotactile prototyping toolkits targeting prototyping and testing of new interactions for virtual reality applications and video games. They presented hardware and software elements that facilitate the overall functioning of the actuators together with the virtual contents.

In XRtic, we follow a similar hardware and software architecture to synchronize the cloth actuators with the virtual contents. Also, *VirtualBricks* [3] presents a LEGO-based prototyping toolkit for enabling physical manipulation in VR applications based on a modular design architecture that facilitates easy integration of *VirtualBricks* elements. Similarly, XRtic consists of modular components, allowing developers to employ easily attachable and reusable cloth actuators. This enables developers to achieve versatile cloth deformation behaviours based on their design requirements.

3 Design Requirements

Considering the several fabrication techniques used in cloth actuation [46, 47, 73], we wanted to understand the requirements to support XR developers to render feedback via cloth deformations. Therefore, we conducted semi-structured interviews in face-to-face open discussions. We recruited six XR developers aged between 24 to 38 years ($M = 30.67$, $SD = 4.81$). Five of them were VR researchers who had experience in virtual content development; two had intermediate experience in MR application development, and one was an AR content developer. No participant had prior experience in practising or fabricating shape-changing interfaces. Each participant spent approximately one hour of time in this session.

We chose *ClothTiles* [46] as a concrete example to initiate the discussion. Participants were provided with detailed information about the working principles, actuation mechanisms, and a step-by-step fabrication methods of it. In addition, participants watched video footage of the fabrication process and different applications. The participants were allowed to have hands-on experience with a pack of pre-prepared cloth actuators. This allowed them to understand how these actuators work, and get specific insights on how to create their own XR experiences. Below are the key findings we gathered during subject interviews.

A plug-and-play modular form of actuators is preferred:

Most of the participants (4 out of 6) stated that they do not want to be personally involved in designing customised actuators, even though that would allow them to customise actuator designs. Instead, they preferred a set of pre-designed actuators that can enable different kinds of actuations on clothing. P2 suggested LEGO blocks type actuators that can be embedded in fabrics. Also, some participants said that they would like to get rid of "*hardware complexities*" (P4) that occur during the development processes. In other words, they did not want to do wire stripping, soldering, and adhering. P4 preferred having easily plug-and-play-able hardware elements. Therefore, we decided to choose a subset of different actuators and made them plug-and-play (see *Figure 2*), as explained in detail in the following sections (see *Section 4*).

There are multiple feedback types that can be recreated using a shape-changing interface:

Participants envisioned a series of creative application scenarios using a shape-changing interface. Most participants (5 out of 6) imagined developing tactile interfaces together with the virtual contents. This may be due to the simplicity of interfacing the collide locations with the actuators during the application development (P5). Some of the example application scenarios they stated include: *fish therapy, wind simulations, soft touches, water ripples,* and *scratching*. P3 wanted to recreate the perception of the acceleration that occurs during take-offs and landing of flights in virtual flight simulators. Overall, participants were excited to use haptic suits enabled with cloth deformation actuators in their applications. P6 envisioned a haptic protocol associated with a shape-changing interface in the market in the near future, and that there would be virtual games and applications compatible with these interfaces.

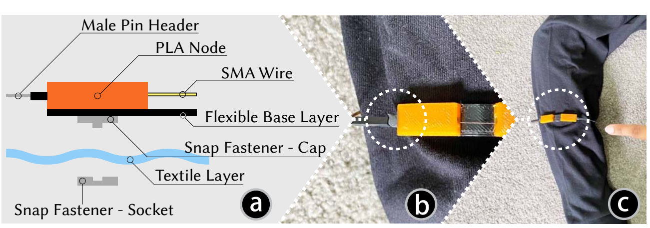


Figure 2: XRtic actuators consist of several sub elements: *SMA Wire* to generate the forces, *PLA Node* to contain the SMA wire in the rigid area of the actuator, *Male Header* pin to connect the SMA wire with the controller, *Flexible Base Layer* to maintain the structure of the actuator, *Snap Fasteners* to attach the actuators to the clothing.

Developers needed alternative approaches to avoid step-by-step fabrication processes:

There are specific skills and knowledge required for fabricating shape-changing interfaces [2]. It can be a challenge for some XR developers to undertake the fabrication process, despite having access to a detailed instruction sheet. In such cases, they wanted to avoid specific fabrication methods such as *CAD modelling, 3D printing, sewing, wiring, soldering*, etc. They wanted to spend more time in the virtual content development than in the fabrication processes (P1). Therefore, we designed our system so that the developers do not have to be involved in time-consuming fabrication processes. We redesigned the attachment mechanism to make attaching and detaching straightforward (see *Figure 3*).

A script-based API is preferred to interface the actuators with virtual contents:

Initially, we assumed that separate graphical user interfaces for developers to integrate the cloth actuators would be a good approach; however, we understood that the XR developers preferred a script-based approach instead, as they are already used to scripting in platforms such as Unity [74]. They kept emphasising simple ways to connect the actuators in sync with the applications digitally (P5). However, participants did not want to deal with the absolute numeric values of the controlling parameters, such as the voltage, current, and addresses of the actuators. P6 wished to handle the parameters of the actuators in a high-level manner instead of referring to numbers such as PWM values. Based on these insights, we propose a script-based approach to link the cloth actuators in sync with the virtual contents with high-level controller parameters.

4 XRTIC SYSTEM ARCHITECTURE

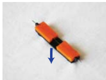
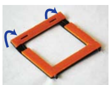
As highlighted in the previous section, there were particular requirements to consider when making cloth actuation accessible for XR developers. One of the main specifications was having modular actuators which can be easily attached and detached. Therefore, we developed an actuator bank with an easy attachment mechanism. XR developers also tend to avoid several processes such as soldering, and wiring, so they can spend more time doing the content development. Accordingly, we implemented a controller bus system that enables XR developers to connect the cloth actuators with the central controller easily. Further, we included a script-based API to interface the actuators with virtual contents using Unity with C# as scripting language which is preferred by XR developers.

In this section, we present a detailed description of the system architecture of the cloth actuators. The overall system comprises of an actuator bank, a controller bus system, and a Unity C# scripting interface. Also, we have proposed a workflow, a step-by-step guide, for XR developers to trigger actuators on clothing synchronized with virtual environments.

4.1 Actuator Bank

Based on the insights from previous studies, our goal was to provide XR developers with a set of actuators that they could use to easily create diverse types of cloth deformations. Therefore, we extended on prior work, *ClothTiles* [46], to develop an *Actuator Bank* with four different types of actuators as shown in *Table 1*. Actuators that can deform a textile in a particular smaller region can achieve a greater resolution in the textile actuation. Therefore, we included the *Tapper* in the *Actuator Bank*, the *Tapper* can move towards or outside the body in a specific clothing area. We also found out that moving the clothing from a garment edge (e.g., edge of a collar, hem of a shirt, and end of a sleeve) is an exciting option for XR developers to simulate various types of application scenarios, such as in wind simulations. For that, we incorporated the *Puller* that can pull or push the clothing from the edges. Furthermore, the *Folder* can fold the clothes along a straight line, and it accommodates creating

Table 1: The *Actuator Bank* which consists of four types that can execute different types of cloth actuations: (A) Tapper, (B) Puller, (C) Folder, (D) Compressor

	Actuator	Properties
A		The *Tapper* can be placed anywhere on the clothing, irrespective of the shape of the body part. As shown, it pushes the clothing towards the flexible base layer to create a pointy shape when the current is applied.
B		The *Puller* can be placed at the edges of the clothing. The vertex of the actuator must be closer to the edge. When activated, it drags the border from the attached point of the clothing away from the flexible base layer.
C		The *Folder* can be placed at relatively flattened surfaces such as the abdomen or back areas of the clothing. As shown in the image, it folds the clothing along a line across the flexible base layer when the current is applied.
D		The *Compressor* can be wrapped around a body part such as the arms, legs, neck, or the torso area. This actuator is a combination of multiple Tapper actuators. It squeezes around the applied body area when activated.

wrinkles on clothing. Dynamic compression in clothing has also previously been recognised to enable different emotion states in VR [53]. Similarly, we incorporated the *Compressor* actuator that can render compression on the clothing.

These actuators follow a modular-based design that can be easily attached or detached based on the developer's need. As shown in *Figure 2*, the Node part of the actuator was 3D printed using PLA (Poly-lactic Acid) 3D printing filaments, and the flexible base layer was 3D printed using *Ninjaflex* flexible 3D printing filaments (see *Figure 2*). The thickness of the flexible base-layer is 1mm, and the height of the PLA nodes was 3mm for each actuator. The *BMX 150* SMA wire was mounted through the aperture of the 3D printed element. Finally, male header pins were soldered at the two ends of the SMA wire to retain the easy plug-and-play behaviour of the actuators. With this design, we were also able to maintain the tension of the SMA wire to deliver the maximum force (hence cloth deformation) when actuated.

We used snap fasteners attached to the back of the XRtic actuators to create an easy attachment mechanism. The cap part of the snap fastener is attached to the 3D printed base of the actuators using *steel-enforced epoxy*. The socket is free-hanging, and it can be pressed against the textile and the cap (see *Figure 3*) to make an attachment between the textile and the actuator. In this way, the XR developers can easily attach and detach XRtic actuators on to a dress as shown in *Figure 3*.

4.1.1 Technical Analysis

We examined the behaviour of XRtic actuators to understand the effect on the activation pulse duration, cool-down time, and clothing material. In our experiment set up, we first clipped the actuator on the snap fastener in a horizontal orientation. Then a camera was placed in the same horizontal plane as the actuator to record the actuation behaviour. The recorded video footage was prepossessed and fed into *Tracker 6.0* [71] software to track the actuation angle of the actuator in each condition.

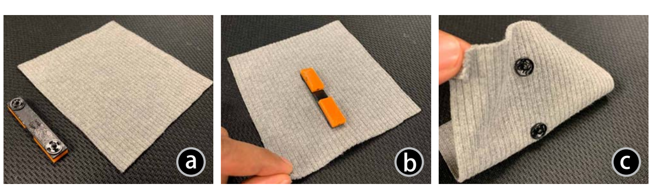


Figure 3: XRtic actuator attachment mechanism is based on snap fasteners. Sandwiching the textile in between the socket and cap of the snap fastener keeps the actuator firmly attached to the clothing.

Effect of the activation pulse duration:

SMAs are activated with the Joule heating generated due to their own resistance, and it requires some time to activate and then return to the inactive idle state. To analysis this behaviour in XRtic actuators, we examined the actuation behaviour of *Tapper* under variable activation pulse durations. We activated *Tapper* for ten different actuation pulse durations from 500*ms* to 5000*ms* with a step size of 500*ms*. Then we plotted the actuation angle of the actuator in each activation pulse duration. With the 500*ms* active pulse duration, the actuated angle of the actuator does not reach the highest value. Activation pulse durations higher than 1000*ms* allowed the actuator to achieve its maximum deformation. Activation pulses longer than 1000*ms*, would hold the maximum deformation for a longer period. Although, we only investigated *Tapper*, we could derive that all other actuators would have the same actuation behaviour as we kept the power-to-length ratio constant for all 4 actuator types.

Effect of the cool-down time:

Our goal was to examine the actuation behaviour with a fixed activation pulse duration and variable cool-down duration. We recorded the behaviour of the actuator with a 1000*ms* active time and variable cool-down times, from 3000*ms* to 500*ms*. We plotted the actuated angle of the actuators in 10-second windows. The actuator went back to its neutral state, given that it had enough time to dissipate the generated heat out of the SMA wire. The cool-down duration that was less than 2000*ms* prevented the actuator from returning to its neutral state, limiting its full range of motion. We did not incorporate the *Compressor* as it is a combination of multiple *Tapper* elements primarily. Based on these findings, we determined that the conceivable frequency of actuation should be considered when interfacing the actuators with the virtual contents.

Effect on different clothing materials:

The cloth actuation varies based on the properties of the attached fabric, such as the thickness, texture, and weight. Therefore, we investigated the actuator behaviour with different types of fabrics. For this, we incorporated seven different fabric materials: *Linen*, *Satin*, *Leather*, *Chiffon*, *Knit*, *Fleece*, and *Cotton*. We used $10 \times 10cm$ fabric pieces from each type and analysed their actuation behaviour with a 1000*ms* activation time. As a baseline, we measured the actuated angle of the actuator, without attaching it to fabric as well. The actuation range was higher for thinner and lighter materials such as *Linen*, *Satin*, and *Chiffon*, as these fabrics do not tend to restrict the cloth deformation. However, thicker or heavier fabrics such as *Knit*, *Fleece*, and *Leather* materials only achieved around 60% of the full range of actuation. Therefore, when installing the actuators, it is essential to consider the properties of the fabrics to achieve an accurate actuation.

4.2 Controller Bus System

We developed custom-made PCB nodes (see *Figure 4a*) connected in a bus architecture to support developers to connect and control XRtic actuators. This consisted of nodes and a controller module as shown in *Figure 4*. Each node can simultaneously activate four different actuators, and can be attached to the clothing using a snap fastener (in the same way as the actuator attachment). Each node includes an *NXP PCA9685*, a 16-channel controller board which can control a PWM output of 12-bit resolution (4096 steps). All the PWM outputs are connected to separate N-channel *MOSFET* drivers connected to a pull-up resistor to control the driving current through the actuators. Each driver can handle a maximum current of 1.4A. All the nodes can be connected to the controller via the

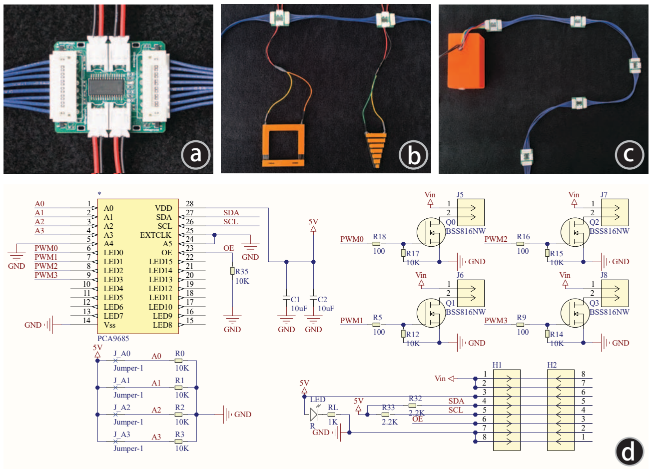


Figure 4: XRtic controller bus system consists of a number of nodes (a) that can control 4 actuators via 4 separate channels. Nodes can be connected together in a bus series (b) and only one node needs to be connected with the controller unit (c). In this way, developers could easily daisy chain actuators on the clothing without creating wire messes. Image (d) illustrates the schematic diagram of the driver PCB.

I^2C protocol (using *SDA* and *SCL* pins of an *Ardunio* board). A maximum of 62 different addresses can be assigned to PCB nodes to share the same bus separately, allowing the designers to connect a maximum of 248 (62×4) actuators in the same bus system. The controller is connected to a *9V* power supply, and based on the required power for each actuator, we control the duty cycle.

4.3 Controller Interface

We used Unity C# scripts to control the actuators with the XR content. With our set up, developers only need to import the *SerialPort* class from the .NET 4.0 C# library to enable USB communication with the actuators. These are activated in Unity by sending a comma separated string with the following parameters: activation duration, the ID of the PCB node, the ID of the channel, and the Actuator type. The developers can follow an iterative workflow to enable cloth actuation in sync with virtual contents, as shown in *Figure 6*. This workflow comprises of five steps that the developers can follow until they are satisfied with the cloth deformation.

5 Applications

Here we present three potential scenarios we developed to highlight the value XRtic could bring into XR applications.

5.1 Body Perception Alternator

The combination of e-textiles and haptic metaphors has been used previously to alter the perception of the user's body [36, 70]. *Tajadura-Jiménez et al.* [68] employed 2D vibrotactile array-based textiles to investigate the effects of multiple vibrotactile patterns on body perceptions (e.g., being heavy, strong). We developed a compressor that can be placed around the torso area of the user's clothing, and the tightness of the clothing around the abdomen can be used as an indicator to emulate binge eating.

In the VR application that we built, the abdomen area would expand when the user takes and eats virtual fruits placed in front of them, depending on the amount of food eaten by the user. At the same time, we wanted to control the compression levels of the user's shirt to simulate tight clothing. This application comprises of *Compressor* elements connected in a series arrangement (see *Figure 5a*) to generate multiple compression levels around the torso area. Maintaining a specific state of an actuator for a more extended period (e.g., greater than 5 seconds) was a challenge as SMAs get heated over time which could damage the SMA wires. To prevent this, we reduced the supplied power of the actuator linearly when it tends to actuate for a longer period.

5.2 Ambience Controller

Wind displays that render wind sensations have often been used in VR applications to improve realism [25]. Most of these systems use multiple wind sources to blow air on different body locations of the users [16].

In contrast, we have created individually controllable apertures on the clothing in different body locations using *Folder* actuators. We used a t-shirt made from a linen material so that the actuators could achieve the highest range of actuation (compared to other materials, as in *subsection 4.1.1*), blocking the airflow when they are closed. During the simulation, the apertures on the user's shirt open up depending on the direction and strength of the wind in a virtual forest. We used a fan as the wind source in this application. Opening up multiple apertures at the same time can significantly increase the airflow over the clothing, and it could simulate hot or cold sensations on the skin of the user (depending on the temperature of the wind blowing through the source) synchronised with the virtual contents. Depending on the driving power, we can control the actuation speed so that we can mimic rapid or gradual ambience changes on the user's skin.

5.3 Micro-tactile Renderer

Rendered touches have been investigated in different research domains such as psychology and neuroscience, and the findings have informed the state-of-the-art research into technology-mediated touches [23]. It has been found that C-tactile afferents of the human skin respond strongly to gentle touches [8].

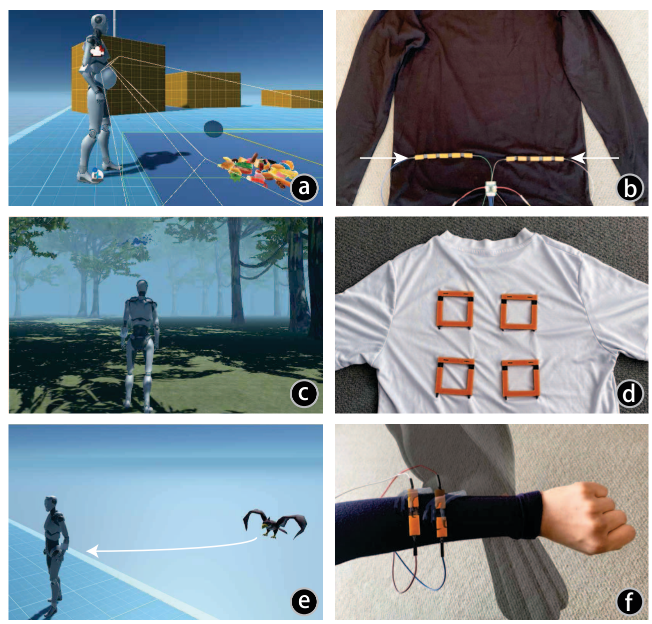


Figure 5: We developed three example use case scenarios that XRtic can enhance the XR experiences: (a, b) *body perception alternator* that compresses the clothing around the user's body to simulate the volume of the body, (c, d) *ambience controller* that controls the connection of the user with environment using the apertures of the clothing, and (e, f) *micro-tactile renderer* that generates micro-tactile sensations on the skin in sync with the virtual contents.

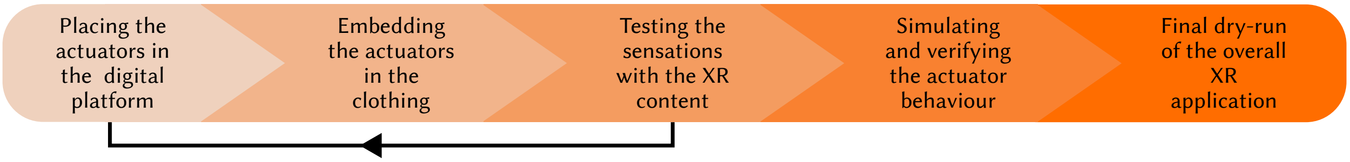


Figure 6: The five main steps of the XR development workflow with XRtic.

Inspired by [22], we simulated the sense of a bird landing on top of a user's forearm. We placed two *Tapper* elements over the forearm area of a shirt sleeve to render a light tapping sensation on the corresponding location of the forearm in synchronisation with the virtual bird's legs. The sensations on the skin would rely on the features such as the orientation, placement (outside or inside the clothing), and type of the actuators. The skin sensitivity of the interested body location also plays a key role when generating micro-tactile touches and the sensations vary depending on the body location.

6 Evaluation

We conducted a user study to gain insights from the XR developers who used our toolkit for application development.

6.1 Participants

We recruited 8 participants aged between 23 and 35 years ($M = 27.6$, $SD = 3.7$), who are familiar with XR application development. They had a range of 1 to 10 years ($M = 4.1$, $SD = 3.22$) of experience in the XR domain, as shown in *Table 2*. Four participants had previous experience developing XR content incorporating feedback mechanisms other than visual modality. None of the participants were familiar with fabrication methods related to shape-changing interfaces.

6.2 Study Setup

We let the participants use their own computers that they used to develop XR applications on, and interface our prototypes. The participants were given a box with all the elements that they needed to incorporate cloth actuation with XR content. This included the four cloth actuators (as mentioned in *Section 4.1*), custom-made nodes to connect the cloth actuators with the controller bus system, snap fasteners to attach the actuators with the clothes, a central control unit which includes an Arduino development board to interface the controller bus system with the computer, connecting cables, 9V power supply, and a USB drive that has example scripts to control the actuators using serial communication.

6.3 Procedure

The experiment procedure consisted of two stages, a 30-minute familiarisation session where participants got hands-on experience with XRtic workflow, and a 45-minute open-ended exploration of application development using the XRtic toolkit.

Table 2: Years of experience and self-identified expertise level of the participants.

Participant	Years of Experience	Self-identified Experience in XR
P1	5	Intermediate
P2	2	Competent
P3	1	Intermediate
P4	5	Proficient
P5	2	Intermediate
P6	1	Intermediate
P7	10	Proficient
P8	7	Competent

Stage 1: Familiarisation with the toolkit

First, we gave each participant an overview of the XR developers workflow (see *Figure* 6). This included a demonstration of the techniques of connecting, attaching, and controlling cloth actuators. They were also given a printed sheet of instructions, with the information needed to connect actuators with nodes, and the commands to control the actuators. We let the participants try all four types of actuators (see *Table* 1) on their own. This session ensured that the participants were familiar with the XRtic and were able to create end-to-end applications.

Stage 2: Open-ended exploration

In stage 2, participants were instructed to brainstorm and develop a potential XR scenario with XRtic integrated. They could select any virtual context and body location as they preferred, and they were allowed to choose any type of cloth actuator. Participants were instructed to follow the workflow (see *Figure 6*) until they were satisfied they had accomplished the task. Initially, they were asked to present three potential XR scenarios they envisioned, verbally or using sketches. Then, they were asked to select one of them and develop it from scratch using the XRtic toolkit. The participants did not have to implement a fully functional XR scenario, and they were asked to interface XRtic with a partially developed XR scenario within the given time period.

6.4 Data Collection and Analysis

Participants were encouraged to follow a think-aloud behaviour throughout the evaluation process. We paused the study after each stage to understand the challenges faced by the participants and to have them fill out a questionnaire to answer specific questions concerning the *Creativity Support Index* (CSI) [13] after completing stage 2 of the study. At the end of stage 2, we conducted a semi-structured interview to understand the feasibility, envisioned concepts, constraints, and limitations of XRtic. Also, participants rated their satisfaction with the outcome and the perceived simplicity of the overall system on a 7-point Likert scale (1-lowest to 7-highest).

6.5 Results and Discussion

6.5.1 Diverse application scenarios

All participants proposed and successfully implemented a practical application. A theme identified by multiple participants was simulating the presence of external objects and persons via cloth deformation was one interesting application for XRtic. For instance, to enable the presence of another person, P1 developed an augmented sleeve with XRtic that simulates a virtual hand-shake (see *Figure 7a*). P7 proposed to render the feeling of holding objects in the hand by restricting the movements of the fingers and palm in a glove according to the type of virtual objects (similar to *Wireality* [15]). Another interesting type of the application was notifying a specific region to the user. For example, VR boundary notifier [P2], detecting when colliding with a wall in VR [P3], and cautioning when the user is in a prohibited region in an XR game [P5]. Providing directional cues was another proposed application-type. This includes DIY haptic suits, haptics in XR games, that can simulate 'moving' items on the body. Some participants developed more serious application-types. For example, P7 developed an arm-sleeve with XRtic actuators (see *Figure 7c*) to simulate the impaired limbs of a stroke survivor during the rehabilitation exercises. Also, he envisioned using this toolkit to enhance perceptual illusions in a virtual context, such as the *rubber hand illusion* [72].

6.5.2 Ease of use

Overall, participants were satisfied with the output generated using our prototyping toolkit. They rated the Likert scale question (1-lowest to 7-highest), *"How satisfied are you with the outcome of your application developed with our toolkit?"* with a higher rating ($M = 5.5$, $SD = 0.76$). Also, almost all participants (7/8) reported that the tool was straightforward to use. After completing all of the intended tasks during the study, they rated *"How easy was the prototyping process?"* with reasonably high scores ($M = 5.75$, $SD = 0.70$). The questions regarding satisfaction and easiness were asked, assuming they were comfortable with developing the chosen XR scenario. P5 identified the ease of use as the most helpful feature of XRtic, by stating, *"Once I knew how to use the toolkit, I was able to produce a result within a short time easily."* Also, P5 initially wanted to actuate a thicker fabric ($> 3mm$), but could not achieve that due to the nature of the snap fasteners we used. These types of minor alterations can be resolved to further improve the usability of the XRtic system in the future.

6.5.3 Iterative and rapid prototyping aspects

On average, a participant spent approximately 18.6 minutes ($SD = 7.72$) on scripting and 14.4 minutes ($SD = 4.31$) installing actuators on clothing during the application development. We observed that almost every participant followed an iterative prototyping approach. Some participants (P4, P6, and P7) commenced the open-ended exploration by placing the cloth actuators on clothing, even before developing the virtual content. They were confident enough about the rapid prototyping aspects of XRtic, hence, if there was any change, they could fix it easily.

Participants tended to follow the iterative workflow shown in *Figure 6* while developing prototypes. For instance, P1, P3, and P8 quickly tested different spatial body locations, body configurations, and actuation frequency from time to time, to understand the sensation generated when the cloth is deformed. P7 highlighted the importance of visualising the actuation in the Unity interface to check the behaviour before deploying to the cloth. That would encourage participants to explore the cloth actuation in the digital space, allowing them to be more efficient in iterative prototyping.

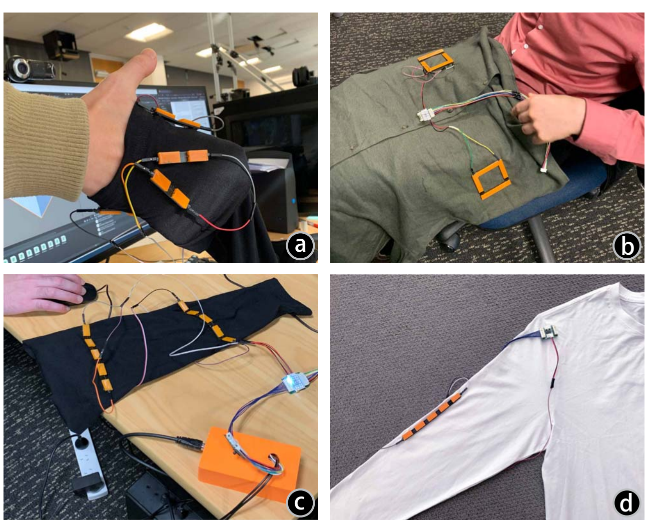


Figure 7: Participants came up with interesting applications using XRtic: (a) virtual handshake enabler, (b) directional cue provider, (c) arm sleeve to simulate stroke patients, and (d) elbow stretch visualiser

Table 3: CSI [13] ratings gathered during the post-study questionnaire. The Average Factor Counts displays the number of times each scale was preferred in the pair-wise factor comparisons. The Average Factor Score shows the independent ratings of the different scales in the range from 0 to 20. The Weighted Factor Score was determined by multiplying each factor subtotal by its factor comparison count, and based on the Average Weighted Factor Scores, the overall CSI score was calculated.

Scale	Avg. Factor Counts (SD)	Avg. Factor Score (SD)	Avg. Weighted Factor Score
Results Worth Effort	4.25 (0.71)	16.12 (2.17)	68.75 (16.58)
Exploration	3.50 (1.19)	15.00 (2.33)	53.12 (21.09)
Collaboration	0.75 (1.03)	13.37 (3.96)	09.25 (14.62)
Immersion	1.25 (0.88)	11.87 (4.42)	15.87 (15.53)
Expressiveness	2.75 (1.67)	15.12 (2.75)	40.50 (22.39)
Enjoyment	2.50 (1.60)	15.25 (1.49)	37.87 (24.77)

The actuation delay caused by the SMAs was a concern for some of the participants while trying to implement quick actuation scenarios, *"the time taken for the actuator to reset is slightly longer than expected, hard to have a quick pulse,"* said P2. Participants made several comments about the iterative and rapid prototyping aspects enabled by XRtic. P4 mentioned, *"The most useful aspect is how easy to add this hardware to my existing application is. If I wanted to add this to my project, it would not take long to integrate, and I would be able to prototype quickly and iteratively."* Also, P7 stated, *"...easy to experiment with different actuator arrangements and rapid prototyping."* These comments and observations reveal XRtic's ability to quickly achieve various prototypes, allowing developers to be involved in an iterative prototyping approach.

6.5.4 Creative exploration

Creativity Support Index (CSI) [13] is a psychometric survey that helps to evaluate the potential of a tool or a system in terms of assisting the users towards creativity. CSI assesses *Exploration*, *Expressiveness*, *Immersion*, *Enjoyment*, *Results Worth Effort*, and *Collaboration* aspects of creativity support. The participants' rated CSI for XRtic was 75.21 (range 0 - 100), and the overall results are summarised in *Table 3*. *Results Worth Effort* (68.75) and *Exploration* (53.12) characteristics were ranked highest above other aspects. This further confirms the ability of XRtic to facilitate quick and easy prototyping. The *Collaboration* aspect was rated the lowest as we did not evaluate the system in collaborative contexts. Overall, it was clear that XRtic's potential is in supporting creativity, especially in four aspects: *Exploration*, *Expressiveness*, *Enjoyment*, and *Results Worth Effort*.

6.5.5 Limitations and Future Work

1. *Actuation Delay in SMAs:* XRtic actuators have a slow response as SMAs need time to dissipate the generated heat to be able to go back to the neutral state. Our technical analysis showed that, ideally, we need a 2 seconds gap between two actuations. P2 stated this limitation as he had challenges when trying to implement an actuator that can perform a quick pulse. However, this could be achieved by having multiple SMA wires in one actuator [46]. With the advancement of smart materials, we also could address this issue in the near future with a faster cool-down mechanism.

2. *Effects on Different Thicknesses of Clothing:* The current version of the setup can be used only on clothing less than 3mm thick as the snap fasteners used can only handle this thickness. P5 wanted to place actuators on a beanie but found it difficult because it had several layers of thick fabric. In a case like this, the developers could use an alternative to snap fasteners (e.g., stronger magnets, or spike rivets) to overcome this constraint.

3. *Previewing the Actuation Behaviour:* P7 asked if there is a way to visualise or simulate the behaviour in the digital platform before deploying the actuators in the clothing. With the new technologies associated with cloth simulations [29], an extended version of this toolkit could have a method of previewing cloth actuation in a digital platform. This will allow developers to iteratively program the desired cloth deformations in a virtual setup.

4. *Improvements in the Evaluation:* We acknowledge that the sample size of the user evaluation is relatively small. However, as we mainly focused on qualitative findings, the negative effect of having a smaller sample size on the user evaluation was minimal. Furthermore, assessing XRtic in a collaborative context would be an interesting future direction as XRtic could potentially be useful for different personnel in design processes. Also, we wanted to demonstrate different examples of how cloth deformation can be helpful, using the proposed application scenarios in *Section 5*. Future researchers could work upon these applications and explore them to address diverse research questions.

5. *Effects of Different Haptic Stimuli:* Our main intention was to develop and explore a prototyping toolkit to allow developers to achieve cloth deformations with XR applications. Providing haptic feedback via different cloth actuators is only one potential application of our toolkit. Evaluating the effects of different actuators could be another exciting research gap that could be investigated in the future by working upon XRtic.

6. *Intelligent Assistance to Developers:* Based on the observations, we learned that the API should actively provide guidance and warning during the development process. For instance, it should warn users from placing the actuators closer than the minimum distances as well as setting up actuation frequency outside of the optimal operating range as shown in *Section 4.1.1*. Also, different actuators have unique properties which could be ideal for different body locations, orientations, or application scenarios. These aspects could be conveyed using an intelligent interface that can make just-in-time recommendations to the user during the development process. Since the required power of XRtic actuators is proportional to the embedded SMA wire length, a future version of XRtic could provide insights on incorporating new actuators based on the SMA wire length. In future, the design space of XRtic can be further expanded by incorporating new actuator types.

7 Conclusion

In this paper, we presented a prototyping toolkit, XRtic, to support XR developers to render cloth deformations synchronised with XR applications. This toolkit comprises plug-and-play modular cloth actuators and a controller interface to control the cloth actuators. The design requirements of the system were derived based on interviews with six expert XR developers. Based on this, we developed the XRtic toolkit, conducted a technical analysis and developed three proof of concept applications. We evaluated the XRtic toolkit with eight expert XR developers. We found that our toolkit was easy-to-use for XR developers and supports iterative prototyping to enable cloth deformation in sync with XR applications. We believe XRtic will provide a strong commencement for the XR community to use cloth deformations in novel ways with XR applications.

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