

Building a Modular Toolkit for Fast Prototyping of SCIs

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Abstract

Shape-changing interfaces (SCIs) are challenging to prototype due to the wide variety of actuators, materials, and fabrication techniques involved. Although numerous SCI toolkits have been proposed to lower this barrier, little is known about their adoption within the research community. We conducted an initial survey of SCI researchers ($n = 73$) and found that toolkit adoption is uncommon: only 15 respondents had used an existing toolkit, and only three had rebuilt one. Participants primarily attributed this to the time required to reproduce toolkits and their application-specific designs. Motivated by these findings, we present *Craftables*, a paper prototyping-inspired toolkit for the early-stage development of SCIs. *Craftables* is designed to be easy to manufacture and supports the rapid construction of actuated interface prototypes for both experts and non-experts. A workshop-based evaluation indicates that participants were able to rapidly assemble the toolkit and create functional actuated prototypes while identifying opportunities for further refinement.

Überblick

Die Entwicklung von Shape-Changing Interfaces (SCIs) ist aufgrund der großen Vielfalt an Aktoren, Materialien und Fertigungstechniken mit hohem Aufwand verbunden. Obwohl zahlreiche SCI-Toolkits entwickelt wurden, um diese Hürde zu senken, ist über deren Verbreitung innerhalb der Forschungsgemeinschaft bislang wenig bekannt. Daher führten wir eine erste Umfrage unter SCI-Forschenden ($n = 73$) durch und stellten fest, dass bestehende Toolkits nur selten genutzt werden: Lediglich 15 Befragte hatten bereits ein bestehendes Toolkit verwendet, und nur drei hatten eines nachgebaut. Als Hauptgründe nannten die Teilnehmenden den hohen Aufwand für den Nachbau sowie die starke Spezialisierung bestehender Toolkits auf bestimmte Anwendungsfälle. Motiviert durch diese Erkenntnisse stellen wir *Craftables* vor, ein an Papierprototyping angelehntes Toolkit für die frühe Entwicklung von SCIs. *Craftables* wurde so konzipiert, dass es einfach herzustellen ist und sowohl Expert:innen als auch Nicht-Expert:innen die schnelle Entwicklung aktiver Interface-Prototypen ermöglicht. Eine workshopbasierte Evaluation zeigt, dass die Teilnehmenden das Toolkit schnell zusammenbauen und damit funktionsfähige aktorische Prototypen erstellen konnten. Gleichzeitig konnten Verbesserungspotenziale für zukünftige Versionen des Toolkits identifiziert werden.

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Conventions & Tools

Throughout this thesis we use the following conventions:

- The thesis is written in American English.
- The first person is written in plural form.

DEFINITION:

A definition is a precise statement of what something is.

DESIGN GOAL:

This thesis should be as comprehensible as possible.

EXCURSUS:

The word excursus comes directly from the Latin excursus, meaning "a running out" . It is derived from: ex-, "out of" and currere, "to run".

KEY TAKEAWAYS:

There are colored boxes, with text in it.

Where appropriate, paragraphs are summarized by one or two sentences that are positioned at the margin of the page.

This is a summary of a paragraph.

Use of Software and AI Tools: In this thesis AI tools were used for writing support, translation and proof reading. Furthermore we used FreeCAD 1.1 to design CAD models.

Chapter 1

Introduction

*“The hands are the instruments of
man’s intelligence.”*

*—Maria Montessori
(referring to all humans)*

Humans interact with and understand the physical world through direct manipulation of three-dimensional objects, yet many everyday interactions with digital systems remain confined to two-dimensional displays.

Despite this mismatch in dimensionality, screen-based interfaces remain the dominant interaction paradigm [Zuckerman and Gal-Oz, 2013]. Their versatility, combined with input devices such as keyboards, mice, and touchscreens, enables users to create, manipulate, and access a wide range of digital content. While screen-based systems can represent a wide range of dynamic states and affordances, they can only simulate material properties such as texture or weight rather than provide direct physical interaction with them.

Displays dominate
Human-Computer-
Interaction (HCI) as
they are versatile and
dynamic.

EXCURSUS | AFFORDANCES:

The term *affordances* in HCI describes perceived action possibilities that an object offers to an actor [Norman, 2013]. For example, a small ball might afford being thrown. Affordances depend not only on the properties of the object, but also on the actor. For instance, a small ball may afford kicking for a soccer player, while it may afford throwing for a baseball player.

Tangible User Interfaces couple digital information with physical artifacts.

To bridge the gap between digital information and the physical world, Ishii and Ullmer [1997] introduced Tangible User Interfaces (TUIs) as an alternative to the Graphical User Interfaces (GUIs). TUIs aim to couple digital information with physical artifacts, enabling interaction through the direct manipulation of physical objects, which was shown to provide cognitive and perceptual benefits [Klemmer et al., 2006] and often be preferred by users [Zuckerman and Gal-Oz, 2013].

Shape-changing interfaces combine the dynamic nature of screens with the haptics of tangible user interfaces through physical shape change.

Shape-changing interfaces (SCIs) extend this line of work by combining the dynamic nature of GUIs with the physical embodiment of TUIs [Rasmussen et al., 2012; Sturdee and Alexander, 2018]. Rather than relying solely on visual output, these interfaces can dynamically alter their shape, texture, orientation, or size to communicate information and provide dynamic physical affordances. Examples include shape-changing displays [Follmer et al., 2013; Leithinger and Ishii, 2010; Yehoshua Wald and Zuckerman, 2021], shape-changing mobile phones [Gomes et al., 2013; Hemmert et al., 2010a,b; Roudaut et al., 2013], and room-sized installations [Oosterhuis and Bitoria, 2008; Suzuki et al., 2020]. Similar to virtual and augmented reality, SCIs broaden the ways in which users can interact with digital information, moving beyond the purely graphical interactions characteristic of traditional WIMP (Windows, Icons, Menus, Pointer) interfaces [Fechter et al., 2022; Rasmussen et al., 2012].

SCIs are challenging to design.

Although SCIs offer significant potential, they remain challenging to design and develop [Alexander et al., 2018]. Unlike GUIs, which benefit from established prototyping workflows ranging from sketches and paper prototypes to

high-fidelity digital mockups, SCIs often require functional physical artifacts even in early design stages. The integration of various actuation technologies such as shape-memory alloys, pneumatic systems, hydraulic systems, and electromechanical actuators makes development time-consuming and technically demanding. To lower this barrier of implementation, researchers have proposed a variety of prototyping toolkits [Coelho et al., 2008; Hardy et al., 2015; Nakagaki et al., 2016; Yehoshua Wald and Zuckerman, 2021; Zhou et al., 2025]. Once acquired, such toolkits enable experts and, in many cases, non-experts to build SCIs more rapidly [Alexander et al., 2018]. Existing approaches range from rapid prototyping toolkits such as *ShapeClip* [2015] to toolkits which enable more sophisticated prototypes like *XStrings* [2025].

Given the diversity of SCIs, no single toolkit can address all application scenarios. Consequently, the development of versatile prototyping tools has been identified as a key challenge for the field [Alexander et al., 2018]. Despite broad agreement on the importance of prototyping toolkits, little is known about their adoption in practice. While these toolkits are intended to reduce the effort required to prototype SCIs, reproducing and implementing the toolkits themselves may present technical and practical challenges. To better understand their role in the design process, we conducted a survey of SCI researchers prior to the development of *Craftables*. Our results indicate that existing toolkits are used only to a very limited extent. Participants reported that many toolkits are highly specialized and require considerable time to implement, suggesting that the replication of the toolkits themselves may constitute a significant barrier to their adoption.

Motivated by these findings, we developed the easy-to-replicate shape-changing toolkit *Craftables*. *Craftables* enables rapid prototyping of SCIs providing the same practical advantages that paper prototyping offers for GUIs: fast, widely available, and low-cost exploration of early-stage design ideas. It enables experts and non-experts to rapidly iterate on and compare different design implementations in a hands-on, crafting-like workflow. Dynamic behavior is realized purely mechanical, enabling interactive prototypes without electronics or specialized technical expertise. The

Shape-changing toolkits lower the barrier of implementation of SCIs.

But the conducted survey indicates that toolkits are rarely used in the SCI community.

Craftables is easy to manufacture and allows crafting of SCIs.

tools and materials needed to build *Craftables* (3D printers, TPU filament, and PTFE Bowden tubes used in 3D printers) are typically available in most research labs or maker spaces, allowing initial trials without the need to order components. Similar to paper prototypes for GUIs, *Craftables* supports quick construction and modification of early designs in a crafting-like workflow. This early-stage exploration also helps define requirements for later systems, such as actuation type, size, speed, and form factor, thereby guiding the selection of appropriate actuation mechanisms in subsequent implementations.

KEY TAKEAWAY | INTRODUCTION:

This thesis contributes (1) *Craftables*, a rapid, widely available, and easily reproducible paper prototyping-like toolkit designed to support early-stage exploration of SCIs and (2) an initial investigation of current toolkit adoption within the SCI community.

1.1 Outline

The remainder of this thesis is structured as follows. Chapter 2 “Related Work”, reviews existing research on SCIs, SCTs, and early-stage prototyping of SCIs. Based on this review, a potential research gap is identified. Chapter 3 “Survey on Use of Toolkits”, presents the results of a survey conducted to further motivate the development of *Craftables* and to investigate the extent to which existing SCIs are adopted by researchers and designers, as well as the barriers that limit their adoption.

Chapter 4 “Presentation of *Craftables*”, introduces the *Craftables* toolkit, describing its components, functionality, workflows, and example applications. Chapter 5 “Design of *Craftables*”, discusses the underlying design principles and concepts that guided the development of the toolkit and may support future extensions by researchers and designers.

Chapter 6 “Evaluation Workshop” evaluates *Craftables* through small workshops involving pairs of participants. The findings are used to assess the toolkit’s strengths and limitations and to identify opportunities for future improvements.

Finally, Chapter 7 “Conclusion” summarizes the contributions and limitations of this work, and discusses future directions for the field, including the potential value of a centralized knowledge base for SCI research and actuation technologies to support researchers and designers.

Chapter 2

Related Work

2.1 Shape-Changing Interfaces

Following the brief introduction of SCIs in Chapter 1 “Introduction”, this chapter provides a clear definition of SCIs, explains the taxonomies used, and illustrates the diversity of interfaces through examples. Furthermore, the current state and challenges of the research field are presented, in particular its complex and slow development and manufacturing processes. In the last two sections, we refer to two complementary solutions to improve and simplify the development process of SCIs: toolkits and *Kintetic SketchUp* [Parkes and Ishii, 2009].

2.1.1 Definition and Characteristics of SCIs

An informal definition of shape-changing interfaces is already given by the name itself: interfaces that are able to change their shape.¹ A more precise definition was formulated by Alexander et al. [2018].

¹ As “naming things” is allegedly one of the hardest things to do in computer science, this is quite an accomplishment.

DEFINITION | SHAPE-CHANGING INTERFACES:

Alexander et al. [2018] define a SCI as:

1. using physical changes in shape or materiality as input and/or output,
2. being interactive and computationally controlled,
3. being self-actuated and/or user-actuated,
4. conveying information, meaning, or affect.

By proposing this definition, Alexander et al. [2018] explicitly expanded earlier definitions. Poupyrev et al. [2007] compiled an overview of actuated tangible interfaces, primarily early shape-changing displays, and used an actuation-based definition corresponding to criterion (3). Rasmussen et al. [2012] understood SCIs mainly as moving, changing input and/or output devices, corresponding to criterion (1). However, it is important to note that prior work before Alexander often implied the remaining criteria. For example, criterion (4) was not explicitly mentioned but was generally assumed.

Several important comprehensive reviews have been published over the past fifteen years.

In addition to Alexander et al. [2018], other important overview work has been conducted. Coelho and Zigelbaum [2011] investigated existing shape-changing materials, such as shape memory alloys, shape memory polymers, and Terfenol-D, and listed their relevant properties, including input stimulus, number of memory states, reversibility, speed, and resolution.

EXCURSUS | SHAPE-CHANGING MATERIALS:

As an alternative to mechanical actuation, smart materials are being investigated for SCIs. Such smart materials change their physical form in response to external stimuli. While these materials enable compact and often silent actuation, they typically require specialized fabrication.

Two years later, Rasmussen et al. (2012) categorized existing SCIs and defined eight different kinds of shape change

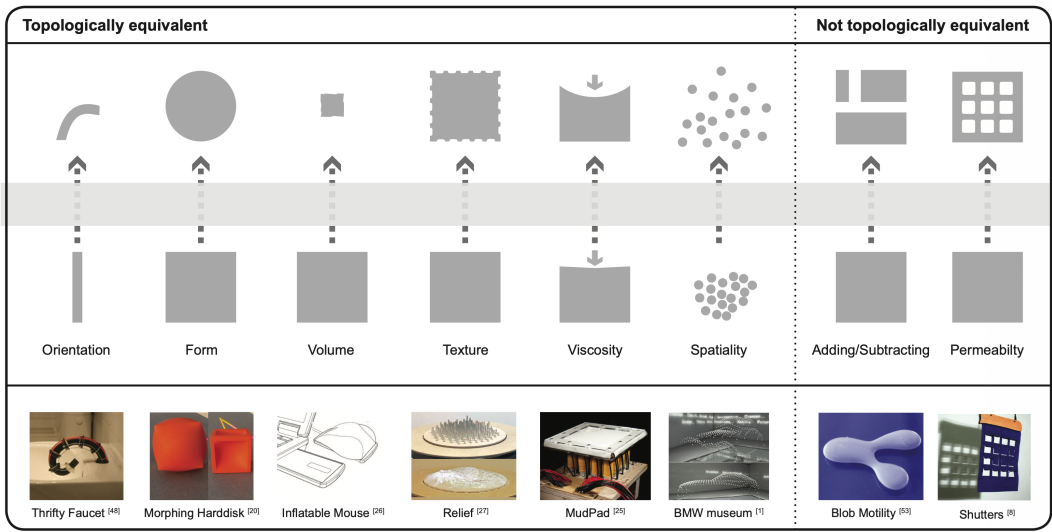


Figure 2.1: Eight types of shape change proposed by Rasmussen et al. [2012]. Later work by Sturdee and Alexander [2018] refined this taxonomy by merging several categories, e.g. *spatiality* and *texture* merged together as *resolution*.

(orientation, form, volume, texture, viscosity, spatiality, adding/subtracting, and permeability), which can be seen in Figure 2.1 (from the original publication).

More recent work by Sturdee and Alexander [2018] analyzed the evolution of taxonomies in SCI research and proposed a convergence of prior work into five kinds of shape-change: spatial, orientation/path, resolution, materiality, and divisibility. Additionally, they listed and categorized existing 84 prototyping as actuated, liquid, malleable, paper & cloth, bendable, elastic & inflatable, and hybrid prototypes, together with characteristics such as input/output capabilities, number of users, control mechanisms, and much more, providing a valuable overview of the current state of the research field.

Recent work slowly converges previous SCI taxonomies.

2.1.2 Diversity of Shape-Changing Interfaces

The breadth of existing taxonomies already suggests the diversity of SCIs. However, the variety of developed systems becomes even more apparent when considering the range

of scales, application domains, and shape-change mechanisms represented in the literature.

Existing prototypes of SCIs are extremely diverse regarding size, application domains and underlying mechanisms.

SCIs span several orders of magnitude in size. At the architectural scale, the *Aegis Hyposurface* [2001] is an interactive wall installation measuring approximately eight by seven meters, capable of dynamically deforming its surface in response to environmental stimuli. *Origami-Walls* [2026] represents shape change at a human scale, exploring robotic partition systems that can physically reconfigure workspaces through large-scale folding transformations. At a smaller scale, systems such as *Relief* [2010] or *inForm* [2013] employ tabletop shape displays consisting of actuated pin arrays that physically represent digital information. At the handheld scale, *Shape-Changing Mobiles* [2010a] explores the use cases of a tilting mobile phone. Examples for unconventional interaction concepts are *Claytric Surfaces* [2012] a malleable interface capable of dynamically controlling stiffness, and *Fl.UIs* [2015] a liquid unpowered touch surface, using computer vision to indicate small changes in the fluid surface to detect touch.

Diversity of SCIs comes with challenges.

These examples represent only a small fraction of the systems explored by the SCI community. Together with the taxonomies presented in the previous section, they illustrate the remarkable breadth of the field, encompassing a wide range of scales, materials, technologies, interaction techniques, and application domains. This breadth makes SCIs powerful as they explore not one new way of interaction; but also comes with some challenges.

2.1.3 Prototyping Challenges in SCI Research

In 2018, 12 grand challenges of SCI research were identified.

The influential works of Rasmussen et al. [2012] and Alexander et al. [2018] summarize several key challenges within the field of SCIs. Some of these challenges can be informally paraphrased as: "What are the applications of SCIs?" [Rasmussen et al., 2012], "How can SCIs be regulated to ensure safety without hindering innovation?" [Alexander et al., 2018], and "How do users experience SCIs?"

As Alexander et al. [2018] identify twelve grand challenges across the four areas of society, user behavior, design, and technology, this thesis focuses on the latter area, which is most relevant to the presented work.

Research in interactive computing typically requires expertise in software development and basic electronics [Alexander et al., 2018]. However, due to the highly technology-driven nature of SCI research, prototyping often becomes considerably more complex and may require knowledge of actuation technologies, materials, fabrication techniques, and embedded systems. Although works such as Taher et al. [2017] provide comprehensive overviews of actuator technologies and their properties, building SCI prototypes remains challenging, time-consuming, and resource-intensive.

Developing SCIs requires skills beyond the typical strengths of HCI researchers.

Two complementary approaches have emerged to address these challenges. The first is the development of toolkits that lower technical barriers and simplify implementation. The second draws on established early-stage design practices from HCI, such as sketching and paper prototyping, to facilitate ideation and concept exploration before investing in fully functional prototypes. Both approaches are discussed in the following sections.

Toolkits and a focus on early-stage development could ease SCI development.

2.1.4 Toolkits for SCIs

For Greenberg [2007], the common and defining feature of a HCI toolkit is that it packages interface design concepts in a way that helps programmers or designers implement their ideas. This broad definition includes software development kits, APIs, widget sets, interface builders, and development environments. A more recent definition by Ledo et al. [2018] incorporates the diverse purposes that toolkits can serve:

DEFINITION | HCI TOOLKIT:

Toolkits are "generative platforms designed to create new interactive artifacts, provide easy access to complex algorithms, enable fast prototyping of software and hardware interfaces, and/or enable creative exploration of design spaces." [Ledo et al., 2018]

Shape-changing toolkits (SCTs) are generative platforms designed to enable fast prototyping and enable exploration of design space.

While this definition was developed for HCI toolkits in general, it also helps understanding toolkits developed specifically for SCIs. As SCI research is inherently hardware-oriented and prototyping remains challenging, shape-changing toolkits (SCTs) aim to facilitate the development process by enabling fast prototyping and/or creative exploration of design spaces. Alexander et al. [2018] summarizes the essence of such toolkits as their ability to "dramatically lower the barrier to implementation".

SCTs are as diverse as SCIs, varying in scale, actuator technology, and other characteristics.

As a consequence of the diversity of SCIs, a similarly diverse ecosystem of SCTs has emerged. Some dimensions of diversity are directly inherited from the interfaces they support. For example, SCTs span a wide range of scales and actuation technologies. At one end of the spectrum, *Robotecture* [2025] provides self-lifting actuated beams that enable the construction of room-scale shape-changing structures using motorized actuation. At the other end, *bioLogic* [2015] employs living *Bacillus subtilis natto* cells as humidity-sensitive nanoactuators to create responsive structures at scales below a few centimeters.

The diversity of SCTs is also reflected in the actuator technologies they employ. *Bosu* [Parkes and Ishii, 2010] explores the use of shape-memory alloys as smart materials for creating SCIs with playback functionality and remote manipulation. Pneumatic actuation is used in systems such as *MorpheusPlug* [Kim et al., 2021], which enables the creation of soft pneumatically actuated SCIs that can be fabricated as a single TPU print on a standard 3D printer.

SCTs differ regarding workflow and fabrication effort.

Beyond scale and actuation technology, SCTs differ along several additional dimensions that are specific to SCTs not SCIs in general. In the following, we identify two comple-

mentary dimensions that characterize SCTs: the workflow paradigm and the fabrication effort required replicate.

Workflow paradigm. We introduce a useful distinction between two common workflow paradigms in SCTs: *physical toolkits* and *digital-to-physical toolkits*. To the best of our knowledge this distinction has not been used explicitly in the existing SCI literature, although related differences are often implicitly present.

This distinction describes where the primary design activity takes place. In physical toolkits, designers construct and modify SCIs directly in the physical world using reusable components. In digital-to-physical toolkits, the design is first created in a digital environment and then realized through fabrication. While both approaches result in physical shape-changing artifacts, they differ in how and where design decisions are made.

WORKFLOW PARADIGMS IN SCTs:

Physical toolkits support SCI design through direct manipulation of reusable physical components in the physical world.

Digital-to-physical toolkits support SCI design in a digital environment, where the final artifact is fabricated as a dedicated physical implementation.

Examples of physical toolkits include *Topobo* [2008], *Robo-itecture* [2025], *Shape-Clip* [2015], *LiftTiles* [2020], and *Bosu* [2010], where modular or semi-modular components are assembled into reconfigurable shape-changing systems. Digital-to-physical toolkits include *MorpheusPlug* [2021], *ElectriPop* [2022], and *X-Strings* [2025], where the design process takes place digitally and results in a fabricated artifact that is not intended for reuse or reconfiguration. Examples are shown in Figure 2.2

It must be noted that this classification is not strict as there exist exceptions. Otaran et al. [2025] presented a toolkit which can be designed digitally and then be printed; but the printed artifacts can then be reconfigured and reused.

We distinguish between *physical* and *digital-to-physical* toolkits, depending on whether the design process takes place in the physical or digital world.

Examples of toolkits categorized under the proposed taxonomy.

The categorization is not strict, as some toolkits span both groups.

Fabrication effort of toolkits differ significantly.

Fabrication effort. A second dimension along which SCTs differ is the effort required to fabricate toolkit. This effort can be understood as a spectrum ranging from low-effort systems, which rely on readily available components and minimal fabrication, to high-effort systems that require custom manufacturing, specialized tools, and technical expertise.

At the high-effort end of the spectrum, *ChainForm* [2016] requires custom PCBs with flexible hinges, LED matrices, multiple conductive surfaces, small servo motors, and 3D-printed parts for each module, in addition to non-trivial modifications of the servo motors themselves. Similarly, *NURBSforms* [2020] depends on the fabrication of custom flexible circuit strips combined with shape memory alloy elements, including circuit etching, soldering, and assembly of thermally active components.

LiftTiles [2020] lowers the fabrication effort but still requires specific components such as springs, motors, and access to tools like a laser cutter and air compressor, despite reported assembly times of approximately 15 to 30 minutes. *ShapeKit* [2025] further reduces complexity, as most structural elements are 3D-printable, although it still requires additional components such as specific Bowden cables, springs, magnets, and a tracking camera.

At the lower end of the physical fabrication spectrum, *ThreadTessel* [2025] requires only standard 3D-printed parts and a motor module, but still involves electrical wiring.

The digital -to-physical toolkit *MorpheusPlug* [2021] represents the lowest fabrication effort, requiring only the ability to 3D print flexible materials such as TPU. Once the de-



Figure 2.2: Examples of physical and digital-to-physical toolkits. Physical: (A) *Robotecture* [2025], (B) *Shape-Clip* [2015], (C) *LiftTiles* [2020]. Digital-to-physical: (D) digital simulation suite of *ElectriPop* [2022], and (E) physical artefact of *ElectriPop*.

sign is completed digitally, fabrication is reduced to a single print process without additional assembly or modification.

Relationship between workflow and fabrication effort.

While workflow paradigm and fabrication effort are conceptually independent dimensions, they are often related in practice. Digital-to-physical toolkits, such as the previously mentioned *MorpheusPlug* [2021], are frequently designed with fabrication as an integral part of the workflow, and therefore tend to reduce or streamline the manufacturing process for the end user. Physical toolkits, in contrast, often prioritize flexibility and recombination of components over minimizing fabrication effort, as their primary focus lies in enabling rapid physical exploration and manipulation of design ideas.

As fabrication is part of the designed workflow of all digital-to-physical toolkits, they tend to be easier to fabricate.

However, this relationship is not strict. Both physical and digital-to-physical toolkits can occupy different positions along the fabrication effort spectrum depending on their design goals and implementation choices. Consequently, SCTs can be understood as existing within a multi-dimensional design space defined by their workflow paradigm and fabrication effort.

2.1.5 Early-Stage Prototyping

Following Buxton's design process in HCI, ideas are initially explored through sketches, which support rapid ideation and low commitment. These sketches can then evolve into paper prototypes that allow early interaction testing and user feedback before progressing to medium- and high-fidelity prototypes for refinement and validation. This iterative development process is widely adopted in HCI research and practice [Buxton, 2007; Snyder, 2003]. Its primary advantage lies in enabling substantial design changes during low-fidelity stages, before significant time and resources have been invested into implementation.

Low-fidelity prototypes in early stages of the HCI development cycle, saves time and resources.

Transferring this process to SCIs is not straightforward. Unlike GUIs, SCIs fundamentally rely on movement and

Low-fidelity prototyping for SCI is difficult as movement is often not easy to implement.

physical transformation, making even low-fidelity prototypes difficult to realize. While sketching remains a common practice during ideation and concept development in SCI research [Jung et al., 2010; Nørgaard et al., 2013], researchers have also investigated how movement itself can be sketched and communicated [Buxton, 2007]. Nevertheless, a gap remains between static sketches and fully functional SCI prototypes.

Some toolkits aim at this low-fidelity gap, but they themselves require non-trivial manufacturing process.

Several approaches have attempted to bridge this gap. *ShapeClip* [2015] supports rapid exploration of shape-changing concepts through modular hardware components, but still requires electronics and physical assembly. *AutoGami* [2013] explores low-fidelity shape-changing artifacts using paper craft structures actuated through inductively powered shape-memory alloys. Similarly, *ClothSurface* [2019] investigates shape-display concepts through a box-based setup covered by a stretchable surface. The system allows users to physically deform and interact with the surface of the box, while the underlying actuation is simulated using a Wizard-of-Oz approach, enabling designers to explore interactions without implementing the underlying technology².

EXCURSUS | WIZARD OF OZ TECHNIQUE:

The Wizard of Oz technique derives its name from the Wizard in *The Wizard of Oz*, who appears powerful and autonomous but is ultimately revealed to be a human operating behind a curtain. Similarly, in a Wizard of Oz study, users interact with what appears to be an autonomous system while key functionality is secretly performed by a human operator [Schlögl et al., 2015].

Ishii and Park also highlight the need for more low-fidelity prototyping in SCI research.

Perhaps the work most closely aligned with this thesis is *Kinetic Sketchup* by Parkes and Ishii [2009] as they identified a similar gap in SCI development then we did and proposed a modular system of playback-capable building blocks intended to support early-stage exploration of movement. In addition, they introduced a design language that combines material, mechanical, and behavioral elements to describe movement capabilities and prototype requirements

² Pay no attention to the man behind the *stretchable surface*.

in a unified manner. An overview of this language can be seen in Figure 2.3. This language can be combined to describe various base modules, for example a rigid, telescope module, which enable high speed movement in both directions.

However, while the conceptual framework was extensively developed, the toolkit itself remained limited and not trivial to reproduce. The publication presents only a single fully realized movement module, whereas additional modules mentioned by the authors were not published in subsequent work to the best of our knowledge.

Ishii and Park's work was limited to the implementation of one module.

All attempts to bridge this gap between sketching SCIs and building them, by introducing toolkits may enable the creation of low-fidelity prototypes, assuming the toolkit is already available. However, the fabrication of the toolkit itself could often remain a barrier, as it may require custom components, electrical wiring, or other technical expertise. When this initial manufacturing effort is taken into account, the overall effort is no longer low and becomes comparable to other technically demanding prototyping approaches, unlike paper prototyping in GUIs. However, once a toolkit is available, systems such as *ShapeClip* enable rapid, low-fidelity prototyping comparable to paper prototyping in GUI development. This observation motivates the survey presented in 3 "Survey on Use of Toolkits", in which we investigate the extent to which existing SCI toolkits are adopted, reused, and rebuilt within the research community.

Using toolkits to create low-fidelity artifacts is only valid if toolkit are easy-to-manufacture or already available.

Craftables is conceptually aligned with aspects of *Kinetic sketchup*, although this relationship was not an explicit design influence and was recognized only after development. Similar to paper prototypes in traditional HCI, *Craftables* aims to provide a low-fidelity, modular prototyping system for SCIs, but taking its manufacturing process into account. The toolkit can be combined with common prototyping materials such as paper, cardboard, or textiles to support early-stage exploration of movement and interaction concepts before committing to specific actuator technologies, movement mechanisms, scales, force requirements, or manufacturing processes.

Craftables aims to enable low-fidelity prototypes including its own manufacturing process.

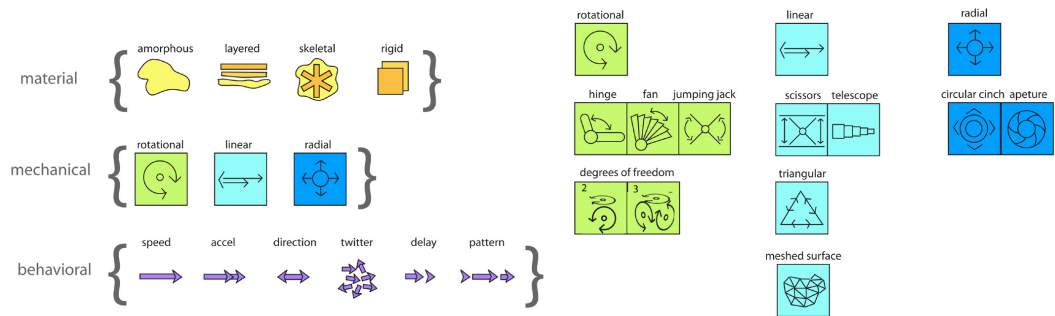


Figure 2.3: Parkes and Ishii [2009] introduced the kinetic deconstruction into material, mechanical, and behavioral properties. For each mechanical category, descriptive properties are defined by the authors, which can be combined to create base modules.

Craftables adopts a fully mechanical approach to minimize fabrication effort and enable easy fabrication.

Unlike Kinetic Sketchup [2009], *Craftables* does not aim to provide playback functionality or electronically actuated movement. Instead, it prioritizes ease of fabrication and hands-on exploration over functional fidelity, reducing technical barriers typically associated with existing physical toolkits. As discussed in the previous section, this enables a more paper prototyping-like experience for SCIs, allowing rapid assembly and exploration of concepts before committing to specific actuator technologies or manufacturing constraints.

KEY TAKEAWAY | RELATED WORK:

We identify a need for toolkits that support early-stage low-fidelity prototyping of SCIs, similar to paper prototyping in GUI development. While some existing toolkits aim to enable low-fidelity prototyping, most do not adequately consider their own fabrication process. Under the assumption that toolkits are not readily available and must first be built, they do not fully enable low-fidelity prototyping in practice. *Craftables* is designed to minimize fabrication effort, enabling truly low-fidelity prototyping closer to what HCI researchers are familiar with from GUI development.

Chapter 3

Survey on Use of Toolkits

Within the scientific community working on SCIs, there appears to be a broad consensus that toolkits are essential for advancing the field. This consensus is reflected implicitly in the large number of SCTs that have been published over the past years. In a recent literature review conducted at our chair by a thesis student, we found that since 2012, at least one SCT has been published every year, with local peaks of 5 publications in 2015 and 9 in 2022 [Gunchev, 2026]. Overall, at least 47 toolkits were published between 2008 and 2026 [Gunchev, 2026]. The importance of toolkits is also explicitly emphasized in the influential work by Alexander et al. [2018], who "see the need to develop toolkits that help prototype [...] shape-changing interfaces" and identified this as one of the grand challenges of the field.

Toolkits are widely recognized as essential for SCI research.

Despite this apparent consensus, there are indications that SCTs are rarely rebuilt or adopted by other research groups. First, Alexander et al. [2018] note that prototype replications of SCI are uncommon, although their scientific value is widely acknowledged. Since this observation applies to shape-changing prototypes in general, it may also extend to SCT. Second, follow-up developments of existing toolkits are rare. Notable exceptions include *ShapeCanvas* [2016] and *PolySurface* [2017], which build on *Shape-Clip* [2015], *ChainFORM* [2016] as an extension of *LineFORM* [2015],

Despite widespread recognition of their importance, there are indications that suggest only limited adoption of SCTs.

and *jamSheets* [2014] as a derivative of *Jamming UI* [2012]. However, in all of these cases, at least one researcher was involved in both projects. Consequently, these examples do not represent independent adoption or further development of toolkits by external research groups.

We conduct a survey on SCT adoption in the research community.

These observations motivated us to conduct a comprehensive survey to investigate whether SCTs are rebuilt by other researchers and, if not, to understand the reasons behind this lack of adoption.

3.1 Survey Design

Online survey chosen to reach the most researchers, even though the number of participants will be limited.

As our goal was to identify the consensus within a research community, the number of researchers we needed to reach was substantial. Consequently, an online survey was the only feasible method of data collection. Potential participants were contacted via email, and the survey was administered using SoSci Survey¹, an open-source and free online survey platform developed in Germany. From the outset, we were aware that surveying a majority of all researchers working on SCTs would be impossible for three reasons.

830 authors were extracted via CHI/TEI publications, but this approach may not fully represent the SCT research community.

First, identifying relevant researchers posed a significant challenge. We classified a researcher as relevant if they had published a paper related to SCIs at *CHI*² or *TEI*³ since 2020. We did not scrape the ACM Digital Library⁴, as this would violate its terms of use. Instead, we downloaded all papers returned by our search query (provided in Appendix A) and automatically extracted author email addresses from the PDF files. This process yielded 830 authors with identifiable email addresses. Determining precisely which authors were relevant to our survey would have required an extensive manual review and was therefore beyond the scope of this work. Furthermore, this approach inevitably

¹ www.sosicisurvey.de

² CHI: ACM International Conference on Human Factors in Computing Systems

³ TEI: ACM International Conference on Tangible, Embedded and Embodied Interaction

⁴ <https://dl.acm.org/>

excluded PhD candidates and other researchers working in the field who had not yet published at either venue.

Second, achieving a high response rate was considered unrealistic due to the large volume of unsolicited emails academic researchers receive on a daily basis [Behdinan et al., 2025; Grey et al., 2016; Wood and Krasowski, 2020]. Sending individually crafted emails to 830 researchers was beyond the scope of this work. Consequently, an automated approach was required that would still appear personal and legitimate rather than spam-like. To better understand how researchers distinguish legitimate emails from spam, we asked multiple PhD candidates which characteristics they used to identify spam messages and what should be avoided. Based on this feedback, recipients were addressed by their full name rather than with a formal salutation (e.g., "Dr."), and one of their publications was referenced in the email. In most cases, publication titles were shortened to make the message appear more natural (e.g. "Craftables: a SCI toolkit" to "Craftables"). For approximately 200 recipients, we manually created a more personalized wording, as this often appeared even more authentic (e.g. "Craftables" to "your paper about your crafting-like toolkit."). To remain transparent, the email also included a disclaimer stating that it had been sent using SoSci Survey. The complete bulk email format can be found in Appendix B.

High response rates were unlikely due to email overload in academia. Spam-avoidance strategies were used to ensure messages appeared legitimate.

Third, even if our emails were not misidentified as spam by either filters or recipients, we assumed that the likelihood of participation would still be low due to the required time investment. We therefore designed the survey to be completable in 2 to 4 minutes by limiting it to ten questions. This decision was also motivated by feedback from PhD candidates.

Short survey design to reduce drop-off and improve participation rates.

All questions and shortened, paraphrased versions of the possible answers are listed below. The complete questionnaire can be found in the Appendix C. Indented questions were displayed only if participants provided a positive response to the preceding question. The numbers and letters indicate the page and position of each question in the questionnaire (page 1 was a consent form).

Paraphrased version of questionnaire, original printed in appendix.

- 2A** At which university or research institute are you currently employed?
- 2B** Are you developing any kind of hardware prototype in your research group?
(Yes / No)
- 2C** Are you aware of any SC toolkits that could be useful for your research that you have not yet rebuilt?
(Yes / No / Already rebuilt all)
- 6A** Earlier, you mentioned useful SC toolkits that you have not rebuilt. What are the reasons?
(Time constraints / Too specific / Cost / Insufficient documentation / Lack of tools or skills / Unavailable parts)
- 3A** Have you ever used an SC toolkit developed by another research group?
(Yes / No)
- 4A** What was the name of the SC toolkit?
- 4B** How did you acquire the SC toolkit?
(Purchased / Rebuilt / Gifted / Loaned)
- 4C** At which university or research institute did you use the toolkit developed by someone else?
- 5A** Which of the following tools and capabilities are available within your research group (i.e., someone in your group can use them upon request)?
(3D printing / Soldering / CAD / Vector design / Laser cutting / Microcontrollers / Textile fabrication / Silicone casting)
- 5B** Which of the following tools do you personally have access to and can operate yourself?
(Same options as Question 5A)

Single background variable collected; duplicate toolkit reports controlled via institution + toolkit name, assuming one SCT group per university.

To minimize the survey completion time, we collected only a single background variable: the participant's current institutional affiliation. A potential issue when surveying members of the same research group is that a single toolkit adoption may be reported by multiple participants. To

avoid counting the same adoption multiple times, we identified responses referring to the same toolkit usage instance based on the reported toolkit name and the participant's encoded institutional affiliation. This approach relies on the assumption that only one research group working on SCIs exists within a given university.

University affiliations were encoded using a predefined list of 10,224 universities worldwide obtained from a GitHub project⁵. Participants could search for and select their university from this list. Because university domains were included as searchable keywords, abbreviations were often supported in addition to official institution names. For example, RWTH Aachen University could be found both by searching for its official name ("Rheinisch-Westfälische Technische Hochschule Aachen") and by searching for "RWTH", which is reflected in its domain name, "rwth-aachen.de". If an institution was not included in the list, participants could manually enter the name of their institute. Participants were explicitly informed that manually entered institute names would not be anonymized and could therefore be associated with their institution.

Affiliations encoded using a global university list with search support; manual entries were possible but not anonymized.

3.2 Survey Results

3.2.1 Survey Participants and Potential Nonresponse Bias

EXCURSUS | NONRESPONSE BIAS:

Nonresponse bias occurs when individuals who choose not to participate differ systematically from those who do. For example, in a customer satisfaction survey, highly satisfied or highly dissatisfied customers may be more likely to respond than those with neutral experiences, leading to a distorted view of overall customer satisfaction.

⁵ List of universities and domains: <https://github.com/Hipo/university-domains-list>

The response rate of 8.8% (73 of 830) means the results should be interpreted as an exploratory view rather than a consensus of the community.

A total of 830 researchers were invited to participate in the survey. Of these, 73 completed at least part of the questionnaire, corresponding to a response rate of 8.8%. Given this relatively low response rate, the survey should not be interpreted as a consensus study of the research community. Instead, the results provide an exploratory perspective on current experiences and practices among a subset of researchers. Furthermore, five respondents terminated the survey before completion. Consequently, the number of responses varies slightly between questions.

Due to anonymization and limited available data, nonresponse bias cannot be systematically assessed. The only plausible source is email wording, for which no clear indications of bias were observed.

Because the survey was fully anonymized and intentionally collected only limited background information, assessing potential nonresponse bias is challenging. The available data does not allow for a systematic comparison between respondents and non-respondents. One possible source of nonresponse bias concerns how the recruitment email referenced the recipient's prior work. To explain how a participant's contact information had been obtained, the email mentioned one of their publications. Depending on the mailing list, this reference appeared either as the full paper title, a shortened version of the title, or a manually written, more informal description of the work (e.g., "I found your email through your paper on tangible learning studies from TEI"). This information was not recorded within the survey data and therefore cannot be linked to individual responses. However, 25 researchers contacted the authors directly via email. Based on these interactions, no obvious differences in engagement were observed between researchers whose work had been referenced using different title formats. Nevertheless, the available evidence is insufficient to determine whether the wording used in the recruitment email influenced participation or response behavior.

3.2.2 Participant Demographics

The respondents represented at least 18 countries and 51 research institutions (Q2A). The largest groups originated

from Germany (10 participants)⁶, the United States (7), the United Kingdom (6), China (5), and Denmark (5). Additional participants came from Japan, Sweden, Canada, the Netherlands, France, Australia, Türkiye, Finland, Israel, India, Hong Kong, New Zealand, and South Korea. One participant did not provide sufficient information to determine their country of affiliation. Most institutions were represented by a single participant. Ten institutions were represented by multiple respondents, with a maximum of four participants from the same institution. Two respondents were affiliated with companies rather than academic institutions. One of these organizations operates internationally and could not be assigned to a single country. Twelve participants chose not to disclose their institutional affiliation.

Participants were internationally distributed across 18 countries and 51 institutions, with most institutions represented by a single respondent and only a few contributing multiple participants.

Fifteen respondents reported that their current research group does not actively develop hardware prototypes (Q2B). These participants were retained in the analysis because they may possess relevant experience from previous institutions or may have used externally developed prototypes without rebuilding them.

3.2.3 Use and Acquisition of Research Toolkits

Fifteen of the 73 respondents reported having used at least one toolkit developed by another research group (Q3A). Figure 3.1 summarizes how these toolkits were acquired (Q4B).

Only 15 participants had used a toolkit from other researchers, and only 3 of those had rebuilt one.

The total number of acquisition instances exceeds the number of respondents because some participants reported using multiple toolkits obtained through different channels. Purchasing was the most common acquisition method. Four toolkits had been received as gifts and two had been borrowed from other groups. Only three respondents reported rebuilding a toolkit developed elsewhere. Two par-

⁶ This may indicate a small but likely negligible source of bias. Researchers affiliated with German institutions may be more likely to recognize RWTH and therefore be more inclined to respond. However, as there is no reason to assume that German researchers differ systematically from the broader SCI research community with respect to the survey topic, no substantial bias is expected.

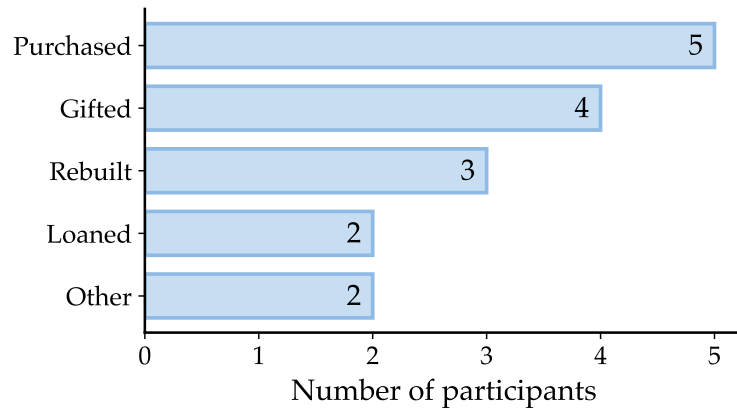


Figure 3.1: Only participants who had affirmed to have used a toolkit in the past were asked how they had acquired it. From this already small portion of participants, only three had ever rebuild a toolkit.

ticipants selected the category "Other", although no further details were collected.

Reported SCT usage was low, but highly diverse, with only two toolkits recurring and some non-standard or unclassifiable entries.

Question 4A asked the fifteen respondents who had used an SCT developed by another research group to identify the toolkit. Reported examples included *ShapeKit* [2025], *Shape-Clip* [2015], *PneuDuino* [2016], *FlowIO* [2021], *Programmable Air* [2018], *Morphees* [2013], *MorpheesPlug* [2021], and *Shape-Changing Clay-Dough* [2024]. The only toolkits mentioned more than once was *Programmable Air* and *Shape-Clip*.

Furthermore, two mentioned tools are not standard SCTs but may support SCI research, namely *Vuforia*⁷ (AR toolkit) and *Toio*⁸ (swarm robotics platform). Three further entries could not be clearly linked to any specific system, including *Decocrome*, *custom Rhino/Grasshopper plugins*, and *compliant metamaterial structures from Thingiverse*.

Overall, these findings suggest that the adoption of externally developed toolkits is relatively uncommon. Rebuilding existing toolkits appears to be even less common.

⁷ Vuforia: <https://developer.vuforia.com> [Accessed: 2026-07-02]

⁸ Toio: <https://toio.io/> [Accessed: 2026-07-02]

3.2.4 Awareness of Existing Toolkits

Participants were asked whether they were aware of any existing toolkit that could have been useful for their research (Q2C). Thirty-three respondents reported that they were not aware of any such toolkit, while 32 indicated that they knew at least one potentially useful toolkit. Interestingly, eight respondents stated that they had rebuilt all toolkits they considered relevant. This response appears inconsistent with the earlier finding that only three respondents reported rebuilding an existing toolkit. Even under a broader interpretation, namely that respondents had acquired rather than rebuilt all relevant toolkits, the responses remain difficult to reconcile because seven of these eight participants also reported never having used a toolkit developed by another research group. This discrepancy suggests that some participants may have interpreted the questions differently. Consequently, these responses should be interpreted with caution.

Awareness of relevant SCTs was split, but responses show inconsistencies that suggest differing interpretations of the survey questions and should therefore be treated with caution.

3.2.5 Reasons for Not Rebuilding Existing Toolkits

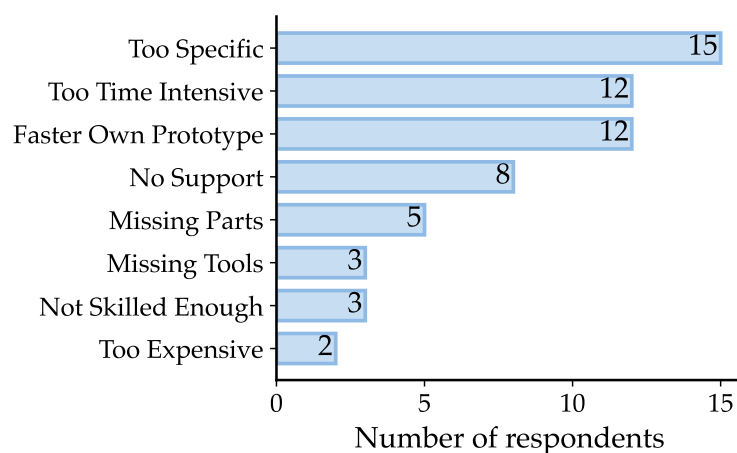


Figure 3.2: Only participants who had affirmed to be aware of a potential useful toolkit (Q2C), which they had not yet rebuilt, were asked why not (Q6A).

Existing SCTs were mainly not rebuilt because they were too specialized and too time-consuming to rebuild.

Respondents who were aware of potentially useful toolkits ($n = 32$) were asked why they had not rebuilt them (Q6A). Figure 3.2 presents the distribution of responses. The most frequently cited reason was that existing toolkits were too specific to the original research context (15 responses, 47%). Two additional reasons were reported almost as often. Twelve respondents stated that rebuilding a toolkit would be too time intensive (38%), while another twelve believed that developing a new prototype from scratch would be faster than adapting an existing toolkit. Less common barriers included a lack of support or documentation (8 responses, 25%), missing parts (5 responses, 16%), insufficient technical skills (3 responses, 9%), missing tools or equipment (3 responses, 9%), and excessive costs (2 responses, 6%). One participant additionally contacted the authors via email and highlighted a factor that was not captured by the predefined response options:

"Since I work at a corporate research lab, there may also be additional factors, such as the time required to carefully investigate and understand the rights, costs, and potential intellectual property issues."

Main barriers are time, rebuilding effort, and contextual fit rather than cost or resources.

Taken together, the responses indicate that practical concerns related to time, adaptation effort, and contextual fit are substantially more important barriers than cost, technical expertise, or access to equipment.

3.2.6 Technical Capabilities of Research Groups

Most technical capabilities are widely available in research groups, suggesting that tools or skills are unlikely to be a major barrier to SCT rebuilding.

To better understand whether infrastructure limitations might contribute to the low rate of toolkit adoption, participants were asked about the technical capabilities available to them personally and within their research groups (Q5A, Q5B). Figure 3.3 summarizes the results.

Across all categories, capabilities available within the research group were reported more frequently than capabilities available to individual researchers. This pattern is expected as the research group always include the respondent themselves. Capabilities such as 3D printing, microcontroller development, laser cutting, soldering, CAD design,

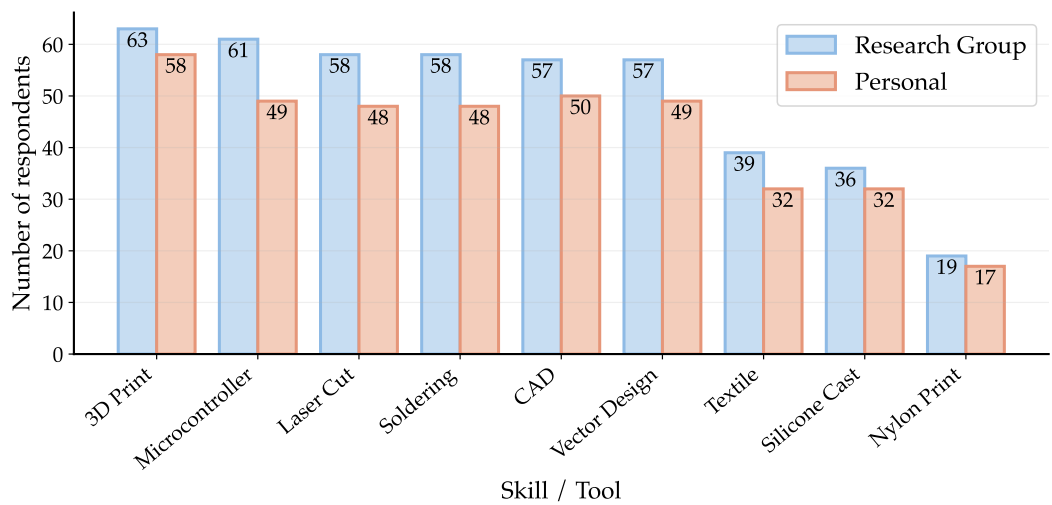


Figure 3.3: To better understand the resources of the SCI community, we asked researchers which tools they and skills have access to. At this point of the survey the highest possible number of positive answers is 68.

and vector graphic design were available in the vast majority of research groups. More specialized fabrication techniques, including textile fabrication, silicone casting, and nylon printing, were considerably less common. More generally, the results suggest that a lack of technical infrastructure or skill is unlikely to be a major factor limiting toolkit rebuilding. This interpretation is consistent with the finding that only three respondents identified missing tools as a barrier.

3.2.7 Summary of Findings

Several consistent patterns emerge despite the limited response rate.

First, the use of toolkits developed by other research groups appears to be relatively uncommon, and rebuilding such toolkits is even rarer. Only a small proportion of respondents reported having rebuilt an existing toolkit.

Toolkits are rarely used.

Second, the primary barriers to rebuilding are related to effort and applicability. Existing toolkits are often perceived

Toolkits are too specific and rebuilding them is too time intensive.

as too specific to the original research context, and many respondents believe that adapting a toolkit would require more time than developing a new prototype independently.

Fabrication capabilities are not a barrier, as most research labs are well-equipped.

Third, the survey provides little evidence that a lack of fabrication infrastructure is a major obstacle. Most research groups reported access to a wide range of prototyping capabilities, while only a small number of respondents identified missing tools as a reason for not rebuilding existing toolkits.

There might be a discoverability issue, as many participants were not aware of any useful toolkits.

Finally, more than half of the respondents were unable to identify a toolkit that would have been useful for their research. This may partly reflect the survey reaching some non-relevant researchers, but it may also indicate a broader discoverability issue, where relevant toolkits are difficult to identify within the growing body of published systems and prototypes.

KEY TAKEAWAY | SURVEY:

In total, the survey collected responses from 73 international researchers across 18 countries, providing an exploratory snapshot of current SCT-related practices and adoption. The survey strengthens the assumption that SCTs are rarely used in practice beyond their original development context, as adoption and rebuilding are uncommon and mainly hindered by effort and the perceived specificity of existing toolkits rather than by resource constraints.

Chapter 4

Presentation of *Craftables*

In Chapter 2.1.4 “Toolkits for SCIs”, we defined the term physical toolkits to describe SCTs consisting of reconfigurable physical modules, for which the design process takes place in the physical world. This enables rapid iteration, as artifacts do not need to be re-fabricated from scratch, when modified.

Furthermore, we presented the work of Parkes and Ishii [2009], who highlighted the advantages of low-fidelity prototyping in SCI research drawing a parallel to paper prototyping in GUI development, and developed a design language for this purpose.

In 3 “Survey on Use of Toolkits”, we found that toolkits are rarely rebuilt. Participants identified limited generalizability and the time required for fabrication as the primary reasons.

Combining these findings, we identify the need for an **easy-to-manufacture physical** toolkit that serves as a **paper prototyping-like, early-stage development** tool for creating SCIs. To address this need, we present *Craftables*, which enables the creation of early-stage actuated interfaces through a **generalizable**, crafting-like process¹.

We motivate the creation *Craftables* by combining the findings of the previous chapters.

Design vision of *Craftables*.

¹ Strictly speaking, *Craftables* does not enable the construction of SCIs, but rather simulates them. As it relies on the Wizard-of-Oz technique to realize movement, it does not satisfy Condition 2 (interactivity or

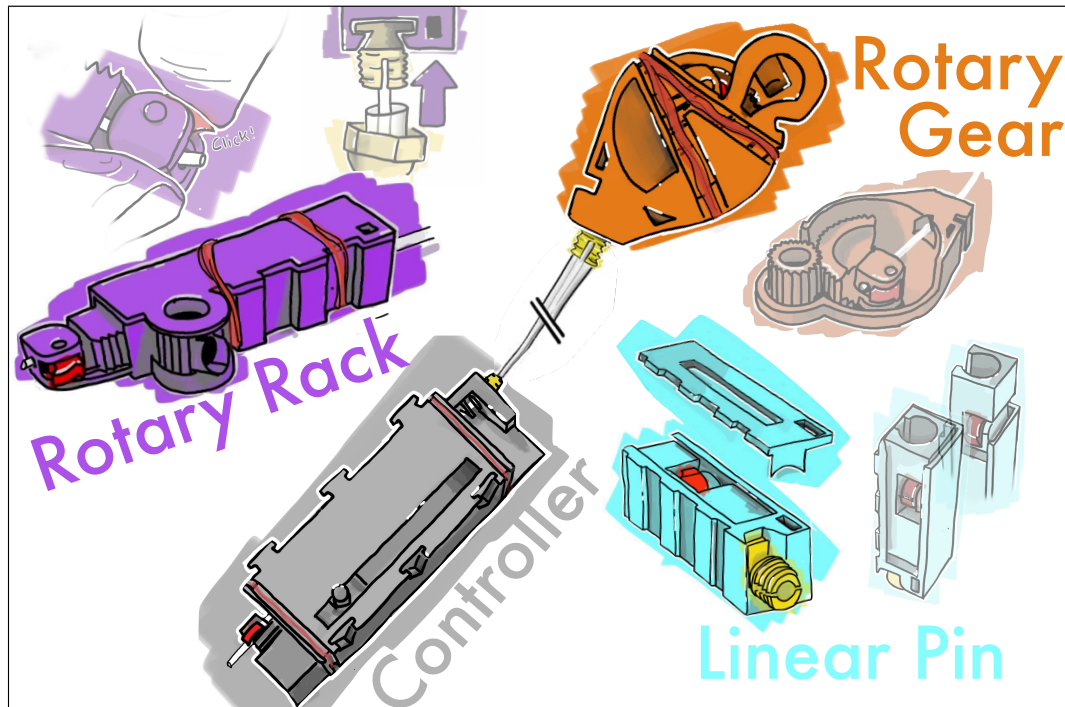


Figure 4.1: Three movement modules and one controller module.

Craftables is almost entirely 3D-printable, significantly lowering the barrier of rebuilding the toolkit.

This chapter introduces the toolkit and its application; the next chapter presents its design rationale.

This chapter presents the components of *Craftables* and describes how SCIs can be created using a crafting-like workflow. In addition, it presents examples of both existing and novel prototypes developed with *Craftables*. While this chapter focuses on the functionality of the individual modules and the range of possible applications, the following chapter discusses the design goals and decisions underlying *Craftables* in detail. The former enables the use of the toolkit, while the latter provides the design rationale needed to understand, modify, and extend it.

4.1 Concept of Craftables

Craftables consists of three movement modules, control modules, and Bowden cables. By moving the slider of a control module, a linear force is transmitted through the Bowden cables to the movement modules, generating different types of motion.

Movement Modules are controller via a Bowden cable connected to a Controller Module.

Figure 4.1 provides illustrations of each module, and an example of a connected system. The Controller Module, shown on the left, is connected to one of the three movement modules via a Bowden cable. When the slider is actuated, the orange Rotary Gear Module moves accordingly. In addition to the Movement and Controller modules, *Craftables* includes structural components and so-called attachments, which further increase the versatility of the toolkit. Using these components, users can craft SCIs containing movement modules that are actuated through Bowden cables connected to an externally positioned Controller Module.

Movement Modules of *Craftables* are then embedded in your crafted structure, creating SCIs.

Examples of prototypes Figure 4.2 presents an overview of prototypes created with *Craftables*, including both novel and reference systems. The examples demonstrate different application areas of SCIs, ranging from expressive objects such as interactive flowers and an owl to functional applications such as texture-changing surfaces and low-resolution shape displays. Established systems such as Shuttters (E) [2009] and ShapeKit (D) [2025] are included to illustrate the broader design space and adaptability of the approach. Notably, Shuttters (E) does not use Movement Modules, while ShapeKit does not use Controller Modules, demonstrating that *Craftables* can also be applied beyond its originally intended use case. The examples vary in complexity and highlight the flexibility of *Craftables* across decorative and functional applications.

computational control) of the SCI definition proposed by Alexander et al. [2018].

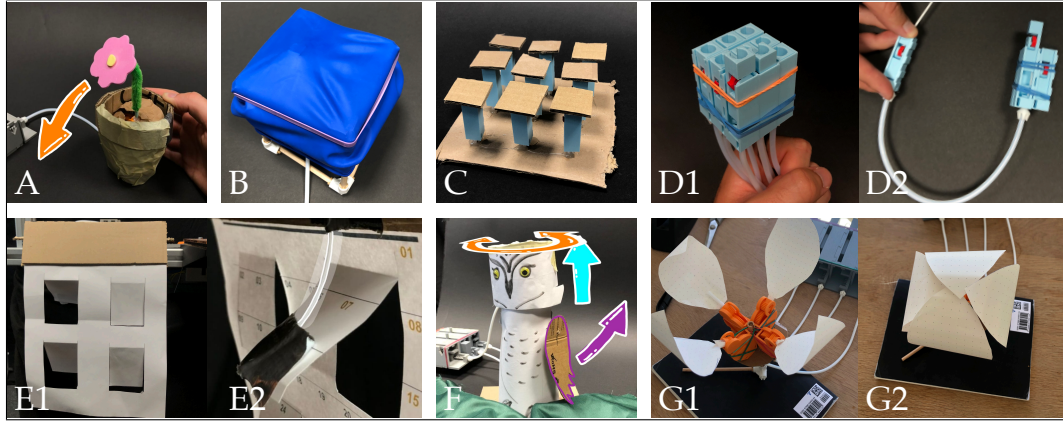


Figure 4.2: Overview of prototypes created with *Craftables*. (A) Interactive flower, (B) texture-changing surface, (C) low-resolution shape display, (D) Early-stage version of ShapeKit [2025], (E) Early-stage version of Shutters [2009], (F) interactive owl, (G) second flower prototype.

4.2 Components of *Craftables*

Movement Modules. The three movement modules provide either linear or rotational motion. For the rotational motion two different form factors and mechanisms are available. Figure 4.1 depicts all movement modules. For the purpose of this thesis we will reference the color of the module, even though it is of course arbitrary.

Many design elements
are shared across all
modules.

All movement modules share a common mechanical interface: a cable-driven actuation system with a red **Locking Lever**, an **8 mm Connector** hole for attachments, and a top cover secured via rubber bands. The housing also provides small notches and holes for additional fixation using rubber bands or zip ties. Additionally, they share the same yellow **Tube Coupling (V2)**, which connects the Bowden cable tube to the module. It is important to note that the original white Tube Coupling (V1) was replaced by the completely redesigned yellow Tube Coupling (V2) only after the workshop evaluation. As a result, many of the figures in this thesis show the original white Tube Coupling (V1).

Craftables provides
three movement
module: 1× linear and
2× rotary movement

The three movement modules differ in their underlying mechanisms, resulting motion patterns, and form factors.

- **Blue Linear Pin Module** is the simplest movement module, providing linear motion. It can be used to modify form, size, and texture, and to prototype a low-resolution 3D display (see Figure 4.1 B,C).
- **Orange Rotary Gear Module** transforms the linear motion of the Controller Module into rotational motion via a master gear driven by the cable. It supports attachments along and perpendicular to the rotation axis (see Figure 4.1 F, G1).
- **Violet Rotary Rack Module** uses a rack-driven mechanism to generate rotational motion. This enables a more compact footprint, but with axial extension during actuation. This gives the users flexibility when designing flatter prototypes.

Gray Controller Module. Inspired by mixing consoles from the music industry, the gray Controller Module allows the user to control their prototype. Using the slider, users can actuate the connected movement module.

As the movement modules often provide only a limited range of motion (typically less than 4 cm), the Controller Modules incorporate a built-in transmission based on a rack-and-pinion mechanism, visible in Appendix G. By exchanging the gear and rack components, different transmission ratios can be achieved. We provide print files for transmission ratios of 2:1 and 3:1. This enables users to develop custom movement modules while maintaining compatibility with the *Craftables* framework. To move the slider, it must first be pressed down to unlock it. This locking mechanism prevents unintended movement caused by external forces or movement of the prototype. To facilitate marking specific positions or the maximum range of motion, a piece of masking tape can be attached next to the slider and used as a writable label. Multiple controller modules can be mechanically connected by snapping them together. Additional rubber bands can be added to further increase structural stability.

Each Movement Module can be controlled by a Controller Module.

As Bowden cable we use widely available 3D-printer tubes and TPU filament.

Tube, cable and Tube Coupling As the toolkit is almost entirely 3D-printable, with the exception of the tube and cable, standard components commonly used in 3D printers were selected for these functions. Specifically, a standard PTFE Bowden tube is used as the guiding tube, while TPU filament (Shore hardness 68D) serves as the cable that transmits force from the controller to the movement module. For proper operation, the ends of the PTFE tube must be securely fixed. This is achieved using the Tube Coupling (V2) component, which is partly based on a design from MakerWorld². The coupling can be used in two different modes, depending on the expected workload. In many cases, it is sufficient to simply insert the tube into the coupling. However, if higher forces are expected, a cap can be screwed on to secure the tube more tightly. An illustration of the yellow Tube Coupling (V2) and its cap can be found at the top of Figure 4.1.

A standardized connector enables a wide range of interchangeable attachments

8 mm Connector and Attachments. To support a wide range of shape-changing prototypes, all movement modules feature a standardized 8 mm Connector. By inserting interchangeable **Inlays** (white and brown), the connector accommodates PTFE tubes, wooden dowel rods, or custom attachments. This common interface simplifies attaching moving elements while enabling application-specific end effectors. We provide several example attachments that demonstrate the connector's flexibility, including an 8×8 cm texture plate for creating texture changes with Linear Pin Modules (Figure 4.3), paper clip pins for securing paper elements (Figure 4.3), and circular plates for attaching cardboard or connecting additional modules using hot glue. Two inlay variants support 4,mm PTFE tubes and 5,mm wooden dowel rods, paper clips, and circular plates. Since the inlays are generated from parameterized OpenSCAD³ models, they can be easily adapted to different rod diameters, enabling custom attachments.

² Phi: <https://makerworld.com/de/models/2172876-pc4-m10-and-pc4-m6-bambu-ptfe-tube-connector> [Accessed: 2026-07-03]

³ OpenSCAD is a free and open-source script-based CAD modeller that enables easy modification of design parameters, even for users with little CAD experience.

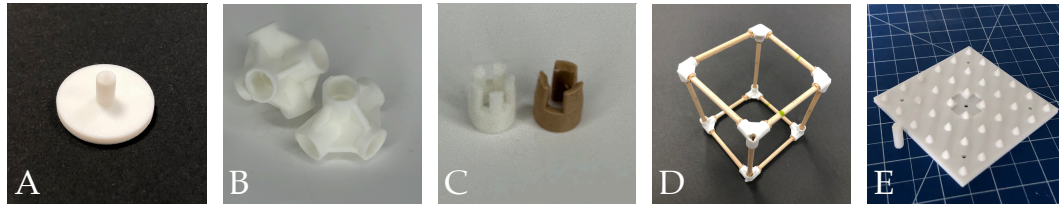


Figure 4.3: More components of *Craftables*. (A) Circular plate, (B) Structural joints, (C) Inlays, (D) Structure, and (E) Texture plate and paper pin.

Structural System. While the movement modules can be integrated into structures made from a wide range of materials, including cardboard and LEGO bricks, we also propose a lightweight structural system that is almost entirely 3D-printable. The system consists of joint elements, the same PTFE tube used as the Bowden guide, and 5 mm wooden dowel rods. The joint elements are based on a model found on MakerWorld⁴ and was then modified.

The PTFE tube can be manually bent to create curves with different radii. The joint elements are available with different numbers of connection arms and connection angles. In addition, we provide fully parameterized OpenSCAD models that allow users to generate custom joint geometries.

The joints use the same interchangeable 8 mm Connector as the movement modules. By inserting the appropriate Inlay, either PTFE tubes or wooden dowel rods can be securely connected.

As structure we provide a 3D printed solution but also point to cardboard or building bricks (LEGO).

4.3 Workflow with *Craftables*

Figure 4.3 illustrates the workflow for creating an interactive prototype with *Craftables*. While simplified, it covers all essential steps of the prototyping process. Throughout this section, a running example, a plant that reminds the user to water their real plants, is used to demonstrate each step.

⁴ Koolm: <https://makerworld.com/de/models/1166433-connector-generator-parametric-connectors> [Accessed: 2026-07-03]

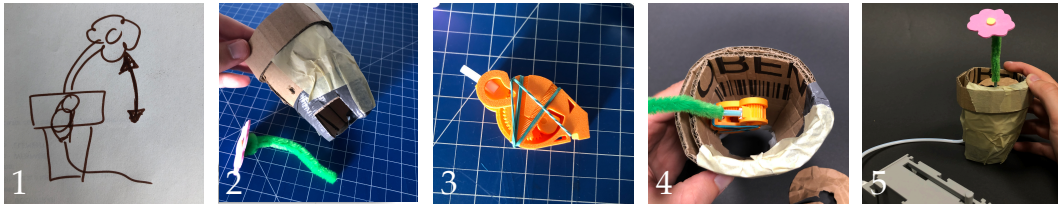


Figure 4.4: Example workflow for building the plant reminder prototype with *Craftables*. From left to right: (1) concept sketch, (2) construction of the physical prototype, (3) preparation of the Movement Module, (4) mounting the module inside the plant pot, and (5) connecting the Movement Module to the Controller Module.

1. **Develop your idea.** Sketch your concept and the intended movement. It is often helpful to draw multiple positions of the moving parts, create a small storyboard, or use arrows to indicate the motion. Decide which Movement Module(s) will be required and include them in your sketch.

Example: Our example is an artificial plant that gently reminds the user to water their real plants. Rather than displaying a notification on a screen, the flower itself moves, providing a subtle reminder that could be triggered by a calendar or smart-home system.

2. **Build the physical prototype / structure.** Construct the static structure and decide where the Movement Modules will be mounted. Plan how the moving parts will be attached and how the cables will be routed to the Controller Module.

Example: The prototype consists of a flower and a plant pot. It is built using cardboard, hot glue, adhesive tape, pipe cleaners, and craft foam. The Movement Module will be mounted inside the pot such that its secondary gear is centred. The flower stem will be inserted into a short PTFE tube connected via the 8 mm connector, while the cable exits through a small hole in the back of the pot.

3. **Prepare the Movement Modules.** Insert and secure the cable in each Movement Module. Ensure that the cable is long enough to reach the Controller Module, allowing some extra length as a safety margin. Finally, close the module and temporarily secure the cover with rubber bands.

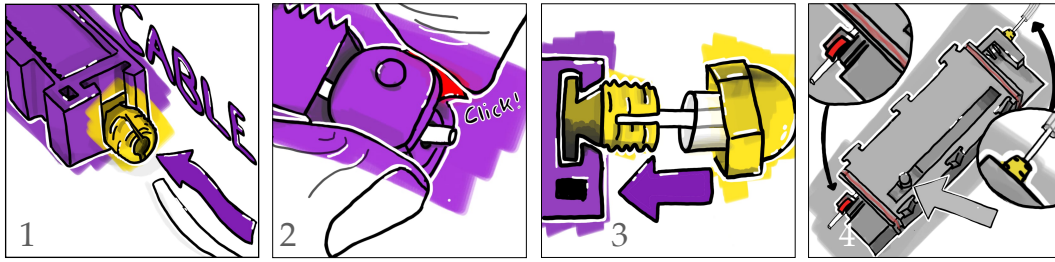


Figure 4.5: Connecting a Movement Module to the Controller Module. The sequence shows cable insertion, locking, tube connection, and final connection to the Controller. The full process is described more detailed in Section 4.3 “Connecting Modules”.

4. **Mount the Movement Modules.** Fix the modules securely to the prototype using hot glue, cable ties, rubber bands, or other suitable fastening methods.

Example: In this prototype, cable ties are threaded through the sides of the plant pot to securely hold the Movement Module in place. This provides a robust and reliable attachment.

5. **Connect the Movement Module to the Controller Module.** Cut a PTFE tube to the required length so that it reaches comfortably from the Movement Module to the Controller Module. A detailed illustration of this connection is provided in Figure 4.5 along with a description in the next paragraph.

Connecting Modules. The connection process between a Movement Module and the Controller Module is illustrated in Figure 4.5 and consists of the following steps:

1. Insert the cable through the yellow Tube Coupling (V2) into the Movement Module until it is visible through the inspection hole (near the red Locking Lever)
2. Secure the cable by pressing down the red Locking Lever.

3. Insert the PTFE tube into the yellow Tube Coupling (V2) of the Movement Module. If heavier loads are expected, screw on the yellow cap to hold the tube in place.
4. Move the Controller slider to its lowest position, insert the cable into the Controller Module, and push it through completely until the PTFE tube reaches the Controller Module.
5. Insert the PTFE tube into the Controller's yellow Tube Coupling (V2) and secure the cable by pressing down the red Locking Lever.

The Movement Module and the Controller Module are now fully connected and ready for operation. **Note:** The movement range of each Movement Module is limited and may be smaller than the travel range of the Controller slider. The valid end positions should therefore be determined after assembly and marked on the Controller using masking tape.

KEY TAKEAWAY | PRESENTATION OF *Craftables*:

We present *Craftables*, which supports the design of early-stage, low-fidelity shape-changing prototypes. In a craft-like process, users construct a structure from materials such as cardboard and paper, into which one of three movement modules can be embedded. Connecting these modules to the Controller Module enables actuation of the crafted artifact.

Chapter 5

Design of *Craftables*

While the previous chapter described the functionality of *Craftables*, this chapter will dive deeper into the design goals and rules followed during the development of *Craftables*. Understanding those allows motivated users to expand the kit to fit their needs while maintaining consistency with the original design philosophy. Sharing specific design decisions and the reasoning behind them will prevent unnecessary iteration when expanding the toolkit.

This chapter explains the design goals and reasoning to enable users to expand *Craftables*.

In Chapter 2 “Related Work”, we identified the need for toolkits that enable early-stage, low-fidelity shape-changing prototyping. Within this overarching purpose of *Craftables*, we define two design goals, directly informed by the results of our survey, which highlight a significant gap between the development of SCTs and their adoption by other researchers. Participants identified the time and effort required to rebuild toolkits, as well as the specificity of existing systems, as the primary barriers to rebuilding. Based on these findings, we derive the main and secondary design goals of *Craftables*.

We define two design goals as direct consequences of the results of the survey.

DESIGN GOAL 1 | REPRODUCIBLE EVERYWHERE WITH MINIMAL EFFORT:

Craftables should be reproducible with minimal effort using equipment and materials commonly available to research labs and makerspaces worldwide.

DESIGN GOAL 2 | TRANSPARENCY AND MODIFIABILITY TO ENSURE BROAD APPLICABILITY:

Craftables should be easy to understand, modify, repair, and extend without requiring specialized knowledge or proprietary components, ensuring their applicability beyond the specific requirements of the original use case.

To achieve these design goals, we formulate a set of design rules derived directly from Design Goal 1 and 2. These rules operationalize the goals and serve as concrete mechanisms to ensure that they are reflected in the design of *Craftables*. The following paragraphs describe these rules and explicitly show how they influenced the development of the system.

5.1 Design Goal 1: Reproducible Everywhere with Minimal Effort

We chose 3D printing as manufacturing process as its widely available and requires little effort.

The primary goal of *Craftables* is to lower the barriers to replication for researchers around the world. By this, we primarily mean reducing the effort required to rebuild *Craftables*, as our survey indicated that neither access to equipment nor technical skills are the factors that most strongly hinder toolkit adoption. While participants reported access to a broad range of fabrication equipment, extending well beyond 3D printers, we nevertheless chose 3D printing as the primary manufacturing method for *Craftables*. Compared to many alternative fabrication techniques, it typically requires little effort beyond obtaining and printing the necessary files.

The goal of worldwide effortless reproducibility motivates the following design rules.

- I. Components should be fully 3D-printable whenever possible.
- II. Designs should be compatible with standard printing settings (e.g., a 0.4 mm nozzle and a 0.2 mm layer

height) to maximize compatibility across printers and minimize the need for customization.

- III. The need for support structures should be avoided whenever possible to reduce printing time and post-processing effort. If supports are required, they should be integrated into the model to ensure independence from the slicer software used.
- IV. The use of printer-dependent features, such as snap-fits, should be minimized.
- V. Standard printing materials should be used whenever possible, and specialized filaments should be avoided. The survey showed that only 28% of research labs have access to nylon printing. Furthermore, the use of standard PLA enables researchers to create an initial implementation without requiring additional material purchases.
- VI. If non-printed components are required, they should be standardized and globally available.

These design rules guided the development of *Craftables*, as illustrated by the following examples.

Bowden Cables. Since Bowden cables cannot be 3D printed, we chose to use TPU 3D-printing filament as the cable and standard PTFE tubing as the guide tube. Both materials are readily available to users of 3D printers, meaning that, in many cases, no additional components need to be ordered before testing parts of the kit. This lowers the barrier to replicating and experimenting with the toolkit. Another reason for choosing TPU filament over steel cable is its smaller minimum bending radius enabling more compact module designs.

As bowden cables materials were chosen which are already available at most research labs.

Screws and Springs. The use of screws could have enabled a more compact module design. In earlier iterations, filament securing was achieved using screws instead of the current locking lever mechanism, which requires more

No springs or screws are used as they might not be globally available.

space. Since a locking mechanism is necessary in every module, its size determines the minimum module dimensions. Despite this potential advantage, the use of screws and springs in the locking mechanism was ultimately rejected. These components follow either metric or imperial standards, and their availability may vary by region, potentially limiting accessibility and compliance with Rule VI.

Rubber bands are used to secure the covers of the modules to avoid a snap-fit.

Rubber Bands. In accordance with the guideline to minimize printer-dependent features (Rule IV.), the module lids were designed without snap-fit mechanisms. Instead, commonly available household rubber bands (Rule VI.) are used to secure the lids while still allowing rapid access and reconfiguration.

Connectors with Inlays. Although snap-fit mechanisms were generally avoided in the design, they were necessary for the structural joints and connector interfaces of the modules. To address the variability in printer tolerances, we introduced interchangeable inlays: small components that can be printed quickly and whose dimensions can be easily adjusted through its OpenSCAD model. By printing and testing a few inlay variants, users can identify the optimal fit for their specific printer with minimal material and time investment. Additionally, the inlay system enables the components to be printed in their optimal orientation without support structures (Rule III.), as the orientation of the inlays is independent of the main module geometry.

Assembly and Print-in-Place. Without supports and brims the 3D printed the components can be assembled directly in only a few intuitive steps without the use of tools. Each module consists of no more than nine parts, enabling straightforward assembly. Furthermore, the larger gear of the waver module is implemented as print-in-place component, therefore requiring no additional post-print assembly.

5.2 Design Goal 2: Transparency and Modifiability to Ensure Broad Applicability

Craftables is designed to be easy to understand, modify, and extend. Users should be able to inspect a module, understand its functionality, and adapt it to their own requirements with minimal effort. Examples of this design goal are shown below.

Connector opening. The standardized 8 mm connector opening allows users to easily extend the toolkit. New components can be attached using simple custom connectors without modifying existing modules.

Proposed Structure. Although we provide a fully 3D-printable structural system, modules can also be attached to alternative structures such as cardboard, laser-cut wood, or LEGO bricks. As attachments zip ties, tape or even hot glue can be used.

Movement Modules. All movement modules partially expose their internal mechanisms or can be opened within seconds, making their functionality easy to inspect, modify, and repair.

KEY TAKEAWAY | DESIGN OF *Craftables*:

The main design goal of *Craftables* was to minimize fabrication effort and enable easy reproduction across different contexts. This was achieved by relying primarily on support-free 3D-printed components that require no post-processing after printing.

Chapter 6

Evaluation Workshop

Before presenting the evaluation strategy, we briefly reiterate the purpose of *Craftables*. *Craftables* is a toolkit designed to support the rapid prototyping of actuated SCIs in early-stage development. It follows a craft-oriented, paper prototype-inspired approach intended to make the creation process accessible to both experts and non-experts.

To evaluate the toolkit, we conducted three small crafting workshops, each with two participants. In addition, we used the toolkit ourselves to construct example SCIs (Figure 4.2), which provided further iterative insights into its design and usability. The evaluation focused on two aspects. First, we examined how easily the modules can be assembled without extensive prior instruction. Since all components are fully 3D-printable, most of the manufacturing process is straightforward and external to the user. We therefore focused specifically on the assembly process, as it represents the primary remaining barrier between fabrication and use of the toolkit. Second, each participant group was asked to build a single actuated interface using the toolkit. During this process, the experimenter observed potential limitations in the components and the overall workflow.

Workshop evaluation focused on assembling and using the toolkit to create a prototype.

6.1 Workshop Design

After a brief introduction to SCIs and toolkits, the workshop consisted of two parts: **Assembly** and **Crafting**. In addition, participants completed a demographics questionnaire at the beginning of the workshop and a feedback questionnaire at the end (Appendix D, E).

Participants A total of six participants took part in the workshop (ages: 20, 24, 24, 30, 30, 33; gender: three male, three female). Four participants had a background in HCI, three of whom also had experience with SCIs. The remaining two participants had a physics background and were therefore considered non-experts.

Participants had only one image to guide the assembling process.

Part I: Assembly Participants were instructed to assemble each module using only a single printed instruction image (Appendix F). The order of the modules was randomized. After assembling the individual modules, participants were instructed to connect a Controller Module to a movement module using the Bowden cable. For this task, they were provided with an additional instruction image and a short explanatory text (Appendix F).

Participants were instructed to create a shape-changing prototypes using the toolkit.

Part II: Crafting In the second part of the workshop, participants were presented with a selection of 10 sketches as inspiration for their prototype (Appendix F). They were free to decide what they wanted to build. The experimenter helped to define an appropriate scope for the prototype. Before starting the implementation, participants sketched their prototype and considered the placement of the movement modules. The workshop had no time limit, and participants were free to stop at any point, even if the prototype was not yet completed, as the goal was to observe the workflow rather than the final result. All required tools and materials were provided, including paper, cardboard, foam paper, a hot glue gun, super glue, tape, zip ties, scissors, utility knives, pliers, and tweezers.

6.2 Constructed Prototypes

During the workshops, participants created three interactive artifacts (Figure 6.1): a penguin, a maritime-themed carousel, and a slug.

The penguin is a two-dimensional cardboard prototype that can move its arms and extend its tongue. The carousel rotates by approximately 200° while simultaneously moving two figures, a seahorse and an octopus, up and down. The slug can move its eyes independently while rotating its shell. All of them could be used as non-intrusive notification system at home.

The carousel did not function reliably during the workshop because the Tube Coupling (V1) repeatedly detached under the weight of the rotating structure. After the workshop, the Tube Coupling was replaced with pneumatic fittings, which provide higher resistance. With this modification, the carousel operated as intended. This demonstrates that *Craftables* can be extended with commercially available components when required.

Craftables can also be combined with commercially available pneumatic tube connectors.

The slug further demonstrates that *Craftables* is not limited to cardboard and paper, but can be readily combined with other materials, such as laser-cut wood. In this example, the slug's shell was fabricated from laser-cut wood. The experimenter assisted with the fabrication using a laser cutter.

Craftables is not limited to cardboard and paper.

The penguin illustrates how a prototype constructed within approximately one hour can already provide valuable design feedback. Colleagues described the penguin as visually appealing but found the human-like tongue unsettling in combination with the absence of a beak. This suggests that this particular design would not be well suited as a non-intrusive notification device.

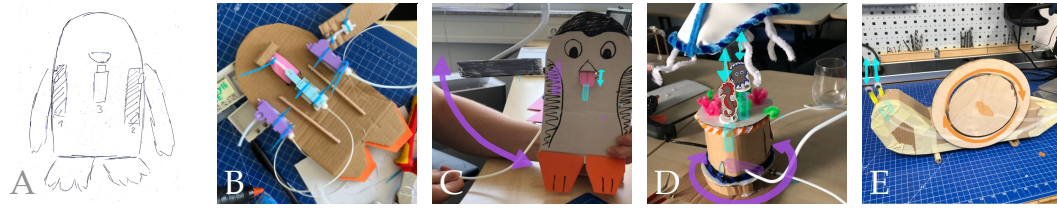


Figure 6.1: In three workshops, three artifacts were created. (A)-(C) showing the creation of the moving penguin, (D) the maritime carousel, and (E) the spinning slug. The images are digitally enriched, illustrating movement and the position of the movement modules inside the prototypes.

6.3 Participants Feedback and Analysis

The feedback presented in this section was collected either through observations and notes taken during the workshops or through the post-study questionnaire (Appendix E). The findings are grouped thematically and provide an overview of the participants' experiences with the toolkit.

Crafting-like Workflow Overall, participants responded positively to the crafting-oriented workflow. They reported enjoying the workshop (e.g., *"I had a lot of fun."*) and were generally satisfied with the prototypes they created. This is reflected in the questionnaire, where all participants agreed or strongly agreed with the statement *"I am satisfied with my prototype."* (2 × Agree, 4 × Strongly Agree), see Figure 6.2.

Participants responded positively to the crafting-like workflow, reported increasing familiarity over time, and were able to make meaningful design decisions with the toolkit, despite some added complexity from actuation.

Participants also reported that the movement modules substantially simplified the creation of movement within their prototypes. At the same time, one participant remarked that the workflow *"felt much more clunky than just crafting"* (German: *"hat sich mehr 'hacky' angefühlt"*), indicating that the integration of the actuated components introduced additional complexity compared to traditional crafting.

A recurring observation was that working with the toolkit became easier over time. All participants agreed that they became more comfortable using the toolkit as the workshop

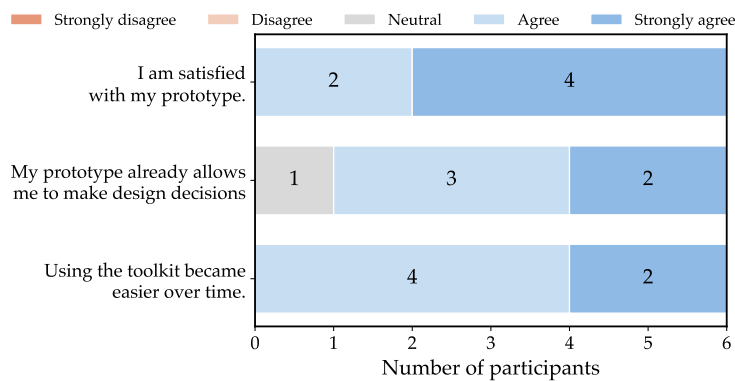


Figure 6.2: Results of post-hoc questionnaire about crafting experiences.

progressed (4 × Agree, 2 × Strongly Agree), see Figure 6.2. Since *Craftables* is intended as a paper prototyping-like toolkit for actuated interfaces, it was encouraging that participants generally felt their prototypes already enabled them to make design decisions. One participant responded neutrally to this statement, while the remaining participants agreed (3 × Agree) or strongly agreed (2 × Strongly Agree). A summary of the questionnaire responses is shown in Figure 6.2.

Weaknesses of Components Several weaknesses of individual components were identified, often by multiple participants. The white Tube Coupling (V1, redesigned afterwards), which connects the Bowden tube to the module, was the most frequently criticized component. Participants reported that the tube disengaged under higher loads, while the bayonet connector on the opposite end often failed to remain attached, disconnecting under its own weight or due to the stiffness of the Bowden tube. The stiffness of the tube itself was also perceived as cumbersome during prototyping, as it tended to move components out of position until permanently fixed.

Another frequently mentioned issue was inserting the cable into the modules, particularly the gray Controller Module. One participant commented, "Inserting the cable into the module makes me aggressive." Participants reported

Multiple usability issues were reported for individual components, particularly the Tube Coupling (V1) and assembly of the Controller Module.

that the cable frequently became caught on small edges within the locking mechanism, making insertion unnecessarily difficult.

Several participants also encountered difficulties during assembly of the Controller Module. The push-down mechanism was often assembled in the wrong orientation because its asymmetry was not sufficiently apparent. Similarly, the correct orientation of the red Locking Lever and its cover was not always obvious.

Finally, several participants suggested improving the color coding of the modules by matching the color of the white circular plates to the corresponding brown 5 mm inlay.

Assembly was generally perceived as easy, but varied across modules, with the Controller rated as most difficult.

Assembly of Modules Overall, participants perceived the assembly of the modules as relatively easy, although the perceived difficulty differed between modules. As expected, the blue Linear Pin and violet Rotary Rack modules were rated as the easiest to assemble. All six participants strongly agreed that the blue Linear Pin was easy to assemble, while the violet Rotary Rack received five *Strongly Agree* and one *Agree* rating. The orange Rotary Gear was perceived as moderately difficult (3 $\times$ Neutral, 2 $\times$ Agree, 1 $\times$ Strongly Agree), whereas the gray Controller was considered the most challenging module to assemble (1 $\times$ Strongly Disagree, 3 $\times$ Disagree, 2 $\times$ Agree), see Figure 6.3.

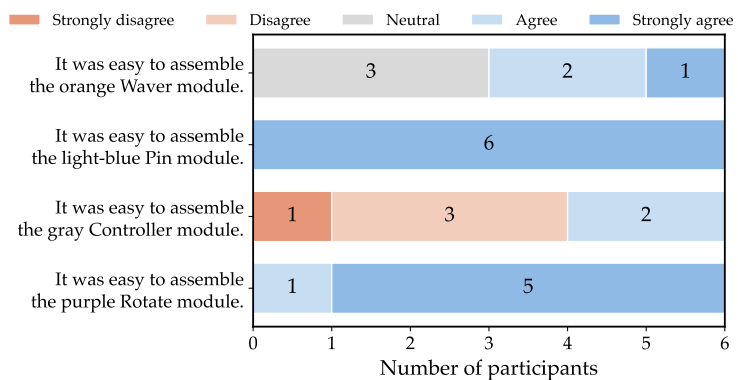


Figure 6.3: Results of post-hoc questionnaire about assembling each of the four modules.

Participants frequently commented that the quality of the instruction images presented the main barrier during assembly. In particular, the orientation of the red lever was difficult to recognize, and some parts were either occluded or not shown at all (e.g., the rubber bands and the second gear). When information was missing from the instructions, participants reported relying on a trial-and-error approach to determine the correct placement of parts. Since most parts fit in only one position, the correct configuration was eventually found, although this process was described as “frustrating” by one participant.

Several participants also noted the lack of clear feedback when parts had been positioned correctly, as many components remained slightly loose after insertion. Consequently, participants were often uncertain whether a part had been assembled correctly. One participant with long fingernails additionally needed to use tweezers to assemble some of the smaller components. Despite these difficulties, all participants stated that they would be able to assemble the modules significantly faster the second time. This observation is also reflected in the post-study questionnaire, where all participants agreed that using the toolkit became easier over time (4 × Agree, 2 × Strongly Agree), see Figure 6.2.

Participants reported unclear and incomplete instructions as the main barrier during assembly, leading to trial-and-error, but also noted a clear learning effect over time.

6.4 Improvements of Craftables

Due to the scope of this thesis, it was not possible to address all issues identified by the workshop participants. However, we were able to improve one of the two main concerns, as well as several smaller issues.

As described previously, the workshop evaluated an earlier implementation of the Tube Coupling, which exhibited two main problems: (1) the tube disengaged under higher loads, and (2) the bayonet connector could disengage from the movement module. Although the latter issue could be mitigated using hot glue, participants still perceived it as “annoying”. Figure 6.4 compares Version 1 and Version 2 of the Tube Coupling.

Workshop feedback led to a partial redesign of key components, improving robustness, assembly feedback, and instruction clarity.

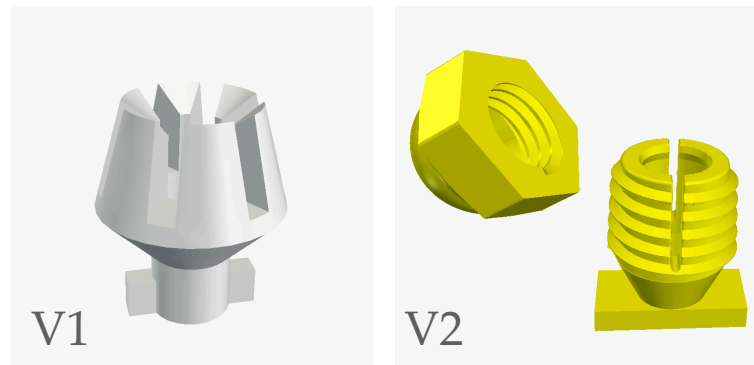


Figure 6.4: The Tube Coupling was redesigned after the workshop evaluation increasing the strength of the connection both to the modules, and to the tube.

The Tube Coupling was redesigned to improve load resistance and prevent unintended disconnection, with trade-offs in print settings and fabrication constraints.

To address these issues, we completely redesigned both the Tube Coupling and the movement modules. The resulting second version of the Tube Coupling (presented in 4 “Presentation of *Craftables*”) was inspired by an early design exploration that had previously been discarded because of its larger size and the requirement for a printing layer height of 0.12 mm instead of 0.2 mm. We were able to reduce its size; however, the threaded component still requires researchers reproducing the toolkit to adjust the printing settings when printing this component. Although this is not ideal, the additional printing requirement is limited to this single part.

Similar to the previous design, the new Coupling grips the tube using teeth. For applications requiring higher load resistance, a threaded cap can be screwed onto the connector, significantly increasing its holding strength. In addition, the bayonet connector was replaced by a fixed T-bar connector, which is permanently assembled as part of each movement module and held in place by the redesigned tops/covers.

The redesign of the covers also improved the tactile feedback of the assembled parts. Workshop participants reported that the original covers could still move after being attached to the movement module, resulting in an unsatisfactory feel. This issue has been significantly reduced.

Since the printing colors are arbitrary, researchers can choose any desired color coding. To maximize versatility, all parts can also be printed in the same color, as several components share identical parts, including the secondary gears, locking levers, Tube Coupling (V2), and the lever cover.

We also addressed feedback regarding instructions and illustrations by replacing them with hand-drawn illustrations. These provide a clearer view of the relevant components and are complemented by exploded views of all parts in the appendix.

The second major issue identified during the workshop, namely that the cable does not pass through the mechanism easily, can also be addressed. However, doing so would require extensive iteration, as the clicking mechanism depends on very precise dimensions to securely fixate the cable. Consequently, even small modifications would require repeated design iterations. While this is entirely feasible, it was beyond the scope of this thesis.

Instruction improvements focused on clearer visual representations using hand-drawn and exploded-view illustrations.

KEY TAKEAWAY | EVALUATION WORKSHOPS:

The workshops demonstrated that the toolkit can be easily assembled and therefore easily manufactured. The craft-like process was perceived as engaging and also enabled non-experts to prototype SCIs. Participants provided feedback on specific components and their usability, informing potential improvements for future iterations.

Chapter 7

Conclusion

7.1 Limitations

7.1.1 Limitations of Survey

This thesis provides an initial investigation into the current adoption of toolkits within the SCI community. Its results reinforce the suspicion that the actual adoption of toolkits is considerably lower than the number of published toolkits might suggest. However, the findings of this survey should not be interpreted as conclusive evidence due to two important limitations.

First, the exact composition of the participant pool is unknown. We contacted 830 researchers who had published papers at CHI or TEI related to SCI. However, we do not know how many contacted researchers were not part of the intended target group (i.e., false positives) or how many relevant researchers were not reached (i.e. false negatives). Additionally, some responses indicate that participants may not have belonged to the intended audience. For example, several participants reported having rebuilt toolkits with which we are unfamiliar or that are not directly related to SCIs. Furthermore some survey responses were internally inconsistent. Eight participants stated that they had rebuilt all toolkits they found interesting. However,

The survey results should be interpreted with caution, as the composition of the participant pool could not be fully verified.

when asked whether they had ever used a toolkit, seven of these participants answered negatively. From our perspective, these responses are contradictory and further suggest that the survey includes false positives.

The survey results are limited also by the small sample size and unknown nonresponse bias.

Second, the sample size of the study is limited to 73 responses, which is too small to support robust generalizations. In principle, if no nonresponse bias was present, the sample could potentially be a representative subgroup of the target population, and there is no a priori reason to assume systematic nonresponse bias. However, because we do not have information about who responded and who did not, nonresponse bias cannot be assessed. The results must therefore be interpreted with caution.

7.1.2 Limitations of *Craftables*

Craftables remains limited by deliberate design trade-offs and the scope of this thesis, not allowing another design iteration.

The evaluation workshops highlighted several limitations of *Craftables*. One consequence of the design goal of enabling worldwide manufacturability was the decision to avoid snap-fit mechanisms. As a result, assembled parts do not provide the satisfying tactile feedback typically associated with snap-fit designs. While this was perceived negatively by participants, introducing snap-fits would reduce printer compatibility and therefore conflict with the primary design goal.

Furthermore, redesigning all components based on the usability feedback collected during the workshops was beyond the scope of this thesis. Although the Tube Coupling was redesigned and its force resistance significantly improved, the achievable force and precision remain limited.

These limitations also affected the development of a fourth movement module, the *Linear Lift*, based on a scissor mechanism. Compared to the Linear Pin, it would have provided a substantially larger range of motion while maintaining a flatter profile. However, its development was discontinued because the original Tube Coupling could not withstand the required forces. Although the redesigned Tube Coupling addresses this issue to a large extent, con-

tinuing the development of the *Linear Lift* was beyond the scope of this thesis.

Finally, although workshop participants did not express a need for additional movement modules, *Craftables* is currently limited to three movement modules. Using the movement language proposed by Parkes and Ishii [2009], these modules cover only a subset of the possible combinations of movement, material, and rigidity.

Craftables is currently limited to three movement modules.

7.2 Future Work

To address the limitations of this thesis, we outline future work for both the survey and the *Craftables* toolkit.

7.2.1 Follow-up Survey

We propose a comprehensive follow-up study within the SCI community as a continuation of this initial investigation. The 830 contacted authors would need to be manually screened to ensure their relevance to the field. Additionally, further SCI researchers should be identified, including those who may have published in other venues or not published at all.

A follow-up survey should improve participant identification, recruitment, and response tracking to obtain more representative results.

Furthermore, it would be necessary to establish direct participant tracking to determine who responded and who did not, in order to assess nonresponse bias and gain a more accurate understanding of the participant pool. In addition, stronger measures would be required to reduce the likelihood of survey responses being classified as spam, for example by distributing the survey via a university server rather than SoSci Survey's infrastructure. It may also be beneficial to collaborate with established researchers in the field to reduce the risk of survey invitations being ignored or discarded.

Our initial investigation provides a starting point for such efforts, offering a list of potentially relevant researchers to-

gether with preliminary results that may help motivate collaboration and increase participation.

7.2.2 Expanding *Craftables*

Craftables can be extended with additional movement modules and electronic actuation while preserving its modular architecture.

Craftables itself can be further developed by adding additional attachment and movement modules, following the terminology of Parkes and Ishii [2009] with respect to kind of motion, material, and rigidity.

Furthermore, electronic Controller Modules could be developed. 3d printing filament as cable was partly chosen because mechanisms already exist that can precisely handle filament transport through PTFE tubes, as used in many 3D printer systems. Such electronic modules could therefore potentially be implemented with relatively limited effort, for example by using a Bowden extruder¹ and connecting it to a stepper motor accordingly.

7.2.3 Community-wide Knowledge Platform

Craftables was designed with paper prototyping in mind, as commonly used in GUI development cycles. It enables designers to iterate quickly with relatively little effort while still obtaining useful information.

A shared knowledge base would allow faster development of SCIs by utilizing the variety of toolkits, fabrication methods and prototypes already published.

The next step after prototyping with *Craftables* is to consider which actuation types may be appropriate, as well as suitable fabrication methods. At this stage, a shared platform could support researchers and designers by providing a comprehensive database of prior work in SCI research, categorised by properties such as size, actuation type, speed, force, and other relevant dimensions.

Alexander et al. [2018] already emphasised the need for “a platform that enables the sharing of knowledge and code across the whole community,” while also noting that

¹ <https://www.roboter-bausatz.de/p/mk8-bowden-extruder-links>
[Accessed 20026-06-29]

it was still too early for such an effort. First, a better understanding of requirements based on existing prototypes and taxonomy work would be necessary. Since then, several relevant contributions have been made, for example, by Sturdee and Alexander [2018], who classified 83 prototypes and their properties, and by Taher et al. [2017], who provided a comprehensive overview of actuators and materials and their associated properties for SCI research.

Eight years after the proposal by Alexander et al. [2018], it may now be appropriate to revisit this idea in light of the accumulated body of work, and to explore the feasibility of developing such a platform to better connect the SCI community and support the reuse of existing toolkits and fabrication methods, potentially making the field more accessible to designers.

Such a knowledge base was already proposed eight years ago; it might be time.

However, this would likely not fundamentally change the fact that SCI research remains strongly technology-driven, as also suggested by our survey. One main reason for not rebuilding toolkits is that they are considered too specific. This may also indicate that researchers continue to develop entirely new materials and systems that cannot easily be represented or simulated within existing toolkit frameworks.

7.3 Closing Remarks

We presented *Craftables*, an easy-to-manufacture toolkit that supports both expert and non-expert users in creating low-fidelity SCIs. Inspired by paper prototyping in HCI, it is designed to enable rapid iteration in the early stages of SCI development.

The workshop evaluation suggests that this approach can support iterative exploration of design ideas in SCI. In particular, participants were able to engage with the system in a lightweight crafting-like process.

A survey conducted in this thesis indicates that toolkit adoption within the SCI research community remains lim-

ited, despite toolkits being considered an important challenge in the field. A key barrier appears to be the time and effort required to rebuild existing systems. *Craftables* addresses this by prioritising manufacturability, being almost entirely 3D-printable and requiring no post-processing.

Overall, *Craftables* extends the landscape of SCI toolkits by directly addressing one of their main challenges: their replicability.

Appendix A

Search Query of the ACM Digital Library

This appendix provides the search query [Gunchev, 2026] used to retrieve relevant publications from the ACM Digital Library.

As described in 3.1 “Survey Design”, we identified and extracted email addresses of 830 researchers relevant to the field of SCI by querying the ACM Digital Library for papers published since 2020 in the CHI and TEI venues. The corresponding search was conducted using the following query:

```
AllField:(("shape-changing interface*" OR "shape
changing interface*" OR "shape-change interface*"
OR "shape-changing display*" OR "shape changing
display*" OR "shape display*" OR "deformable
display*" OR "morphing interface*" OR "morphable
interface*" OR "organic user interface*" OR
"kinetic interface*" OR "actuated interface*" OR
"tangible user interface*" OR "graphical-tangible
user interface*" OR GTUI OR "shape-changing
surface*" OR "shape changing surface*))
```

The query was originally designed by Gunchev [2026] as part of his master’s thesis.

Appendix B

Bulk Email Format

In 3.1 “Survey Design”, we explained how we reduced the risk of a spam-like appearance in our outreach emails. This included avoiding overly formal salutations (e.g., “Dr.”) and using shortened publication titles or more informal, personalized descriptions.

Examples of personalization: full title “Craftables: A modular toolkit for rapid prototyping of SCIs”, short title “Craftables”, custom description “about your crafting-like toolkit”.

Email:

From: Paul Gilles <mailer@soscisurvey.de>
To: %mail%
Subject: Outreach from RWTH Aachen - About using
Shape Changing Toolkits

Hello %firstname% %lastname%,

I am from the Human-Computer Interaction
chair (i10, Media Computing Group) at RWTH
Aachen (Germany). My name is Paul, and I am
doing research on shape-changing interfaces.
I found your email through your paper

%papertitle_or_description%.

I am currently conducting a quick survey about shape-changing toolkits: even though there already exist many toolkits, we don't really know whether those toolkits are actually rebuilt and used-and if not, why.

The survey only takes 2-4 minutes (depending on how long you think about the questions :)). You can click the link below or copy it (clicking on random links in emails is not always a great idea) or visit sosci and type /sctoolkits/ after the web address.

<https://www.soscisurvey.de/sctoolkits/>

I would really appreciate it if you participate. Even though there are no incentives :(hopefully we get some insight into how toolkits are actually used. If you have any questions, feel free to reach out.

Best,
Paul Gilles

Disclaimer: This email was sent via SoSci Survey, which helps us organize the survey. You do not get a personalized link, so everything is anonymous. This also means you can forward the email if you like. We found you by looking at papers published at CHI or TEI in recent years.

Appendix C

Survey

The survey was conducted using SoSci Survey and consisted of six pages. A paraphrased version of all questions and answer options has already been provided in 3.1 “Survey Design”. The following five full-size pages present a comprehensive export of the questionnaire generated by SoSci Survey.

How are Shape Changing (SC) Toolkits used and rebuild?

Welcome, and thank you for participating in our survey.

This survey takes **approximately 2 to 4 minutes** and focuses on the use of shape-changing toolkits in research. All responses are collected anonymously and will be used solely for scientific purposes. Your participation is voluntary, and you may stop the survey at any time without providing a reason.

We appreciate your participation.

I consent to the use of my anonymous data for research purposes.

☐ Ok

Throughout the survey, we use **SC toolkits** as abbreviation of **shape-changing toolkits**, meaning toolkits that can be used to develop shape changing interfaces.

At which university or research institute are you currently employed?

This information will be encoded and only used for identifying multiple submissions from the same research groups. If your institute is not automatically shown, you can still just type it in, but then it will not be encoded.

☐ Prefer not to answer

Are you developing any kind of hardware prototype in your research group?

- ☐ Yes
☐ No

Are you aware of any SC toolkits that could be useful for your research, which you have not yet rebuild?

- ☐ Yes, there are useful SC toolkits which we did not rebuild
☐ No, there are no useful SC toolkits for us
☐ No, we rebuild all useful SC toolkits

1 Active Filter(s)

Filter T006/F1

If any of the following options is selected: **3**

Then display question/text **T005** placed later in the questionnaire (otherwise hide)

Throughout the survey, we use **SC toolkits** as abbreviation of **shape-changing toolkits**, meaning toolkits that can be used to develop shape changing interfaces.

Have you ever used a SC toolkit developed by another research group?

- ☐ Yes
☐ No

3 Active Filter(s)

Filter T001/F1

If any of the following options is selected: **1**

Then display question/text **T002** placed later in the questionnaire (otherwise hide)

Filter T001/F2

If any of the following options is selected: **1**

Then display question/text **T003** placed later in the questionnaire (otherwise hide)

Filter T001/F3

If any of the following options is selected: **1**

Then display question/text **T004** placed later in the questionnaire (otherwise hide)

What was the name of the SC toolkit?

Please type in the names of the toolkits you used, separated by a semicolon, e.g. ShapeKit; XStrings.

How did you acquire the SC toolkit?

(Multiple selections possible)

- ☐ Rebuilt it yourself
☐ Purchased it
☐ Received it as a gift
☐ Received it as a loan

☐ Other

At which university or research institute did you use the toolkit developed by someone else?

This information will be encoded and only used for identifying multiple submissions from the same research groups. If your institute is not automatically shown, you can still just type it in, but then it will not be encoded.

☐ Prefer not to answer

Which of the following tools and capabilities are available within your research group (i.e., someone in your group can use them upon request)?

- ☐ 3D printing (standard materials, e.g., PLA, PETG, TPU)
- ☐ 3D printing nylon
- ☐ Laser cutting
- ☐ Silicone casting
- ☐ Soldering
- ☐ Textile fabrication (e.g., sewing, embroidering)
- ☐ CAD modelling (e.g., FreeCAD, Fusion360)
- ☐ Microcontroller prototyping and wiring
- ☐ Vector-based design and editing

☐ None

Which of the following tools do you personally have access to and can operate yourself?

- ☐ 3D printing (standard materials, e.g., PLA, PETG, TPU)
- ☐ 3D printing nylon
- ☐ Laser cutting
- ☐ Silicone casting
- ☐ Soldering
- ☐ Textile fabrication (e.g., sewing, embroidering)
- ☐ CAD modelling (e.g., FreeCAD, Fusion360)
- ☐ Microcontroller prototyping and wiring
- ☐ Vector-based design and editing

☐ None

Page 06

Earlier you said that useful SC toolkits exist, which you did not rebuild. What are the reasons why you did not rebuild the toolkit?

(Multiple selections possible)

- ☐ Not all needed tools are available (e.g., missing 3D printer, laser cutter)
- ☐ Not skilled enough (e.g., soldering, 3D modeling)
- ☐ Specific parts were not available (e.g., specific screws, rods, ...)
- ☐ Toolkit seemed useful but still too specific for our use case
- ☐ Toolkit does not provide sufficient support (e.g., no instructions, no software)
- ☐ Rebuilding seemed too time intensive
- ☐ Rebuilding was too expensive
- ☐ It seemed faster to just develop our own prototype

☐ None of the above

Last Page

Thank you for completing this questionnaire!

We would like to thank you very much for helping us.

Your answers were submitted, you may close the browser window or tab now.

Paul Gilles, RWTH Aachen – 2026

Appendix D

Workshop Questionnaire I

Demographics

Participant ID: _____

Date: _____

D1. Age: _____ years

D2. Gender:

- ☐ Female
- ☐ Male
- ☐ Diverse
- ☐ Prefer not to say

D3. Highest Educational Qualification:

- ☐ Secondary School

- ☐ Vocational Training
- ☐ Bachelor's Degree
- ☐ Master's Degree
- ☐ Doctorate (PhD)
- ☐ Other: _____

D4. Academic/Professional Background (optional):

Experience and Interests

Please rate the following statements.

Scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly agree

No.	Statement	1	2	3	4	5
E1	Experience with maker projects.	☐	☐	☐	☐	☐
E2	I enjoy crafting and creative making.	☐	☐	☐	☐	☐
E3	Experience with hardware prototyping.	☐	☐	☐	☐	☐
E4	Worked with Shape-Changing Interfaces before.	☐	☐	☐	☐	☐
E5	Familiar with research on Shape-Changing Interfaces.	☐	☐	☐	☐	☐
E6	Confident using new technical tools.	☐	☐	☐	☐	☐

Appendix E

Workshop Questionnaire II

Questionnaire – Evaluation of the Modular Prototyping Toolkit

Participant ID: _____

Date: _____

Use of the Modules

Scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly agree

Statement	1	2	3	4	5
Easy to assemble orange Waver module.	☐	☐	☐	☐	☐
Easy to assemble light-blue Pin module.	☐	☐	☐	☐	☐
Easy to assemble gray Controller module.	☐	☐	☐	☐	☐
Easy to assemble purple Rotate module.	☐	☐	☐	☐	☐
Easy to connect orange Waver module.	☐	☐	☐	☐	☐
Easy to connect light-blue Pin module.	☐	☐	☐	☐	☐
Easy to connect gray Controller module.	☐	☐	☐	☐	☐
Easy to connect purple Rotate module.	☐	☐	☐	☐	☐

Crafting your Prototype

Statement	1	2	3	4	5
Satisfied with my prototype.	☐	☐	☐	☐	☐
Prototype allows design decisions (size, speed, motion).	☐	☐	☐	☐	☐
Toolkit became easier over time.	☐	☐	☐	☐	☐

Weaknesses

Did any components perform poorly?

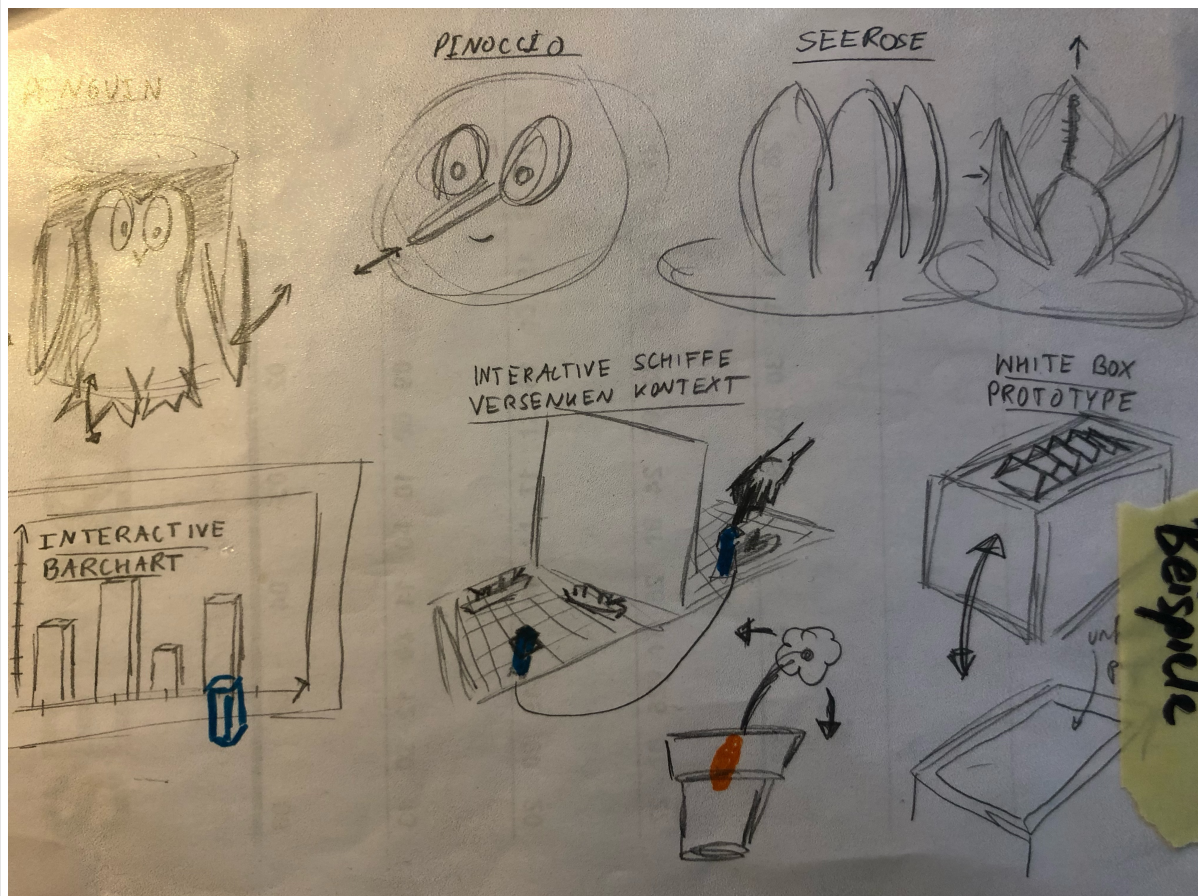
(orange Waver, purple Rotate, light-blue Pin, gray Controller, white structural parts, inlays, bayonet connector)

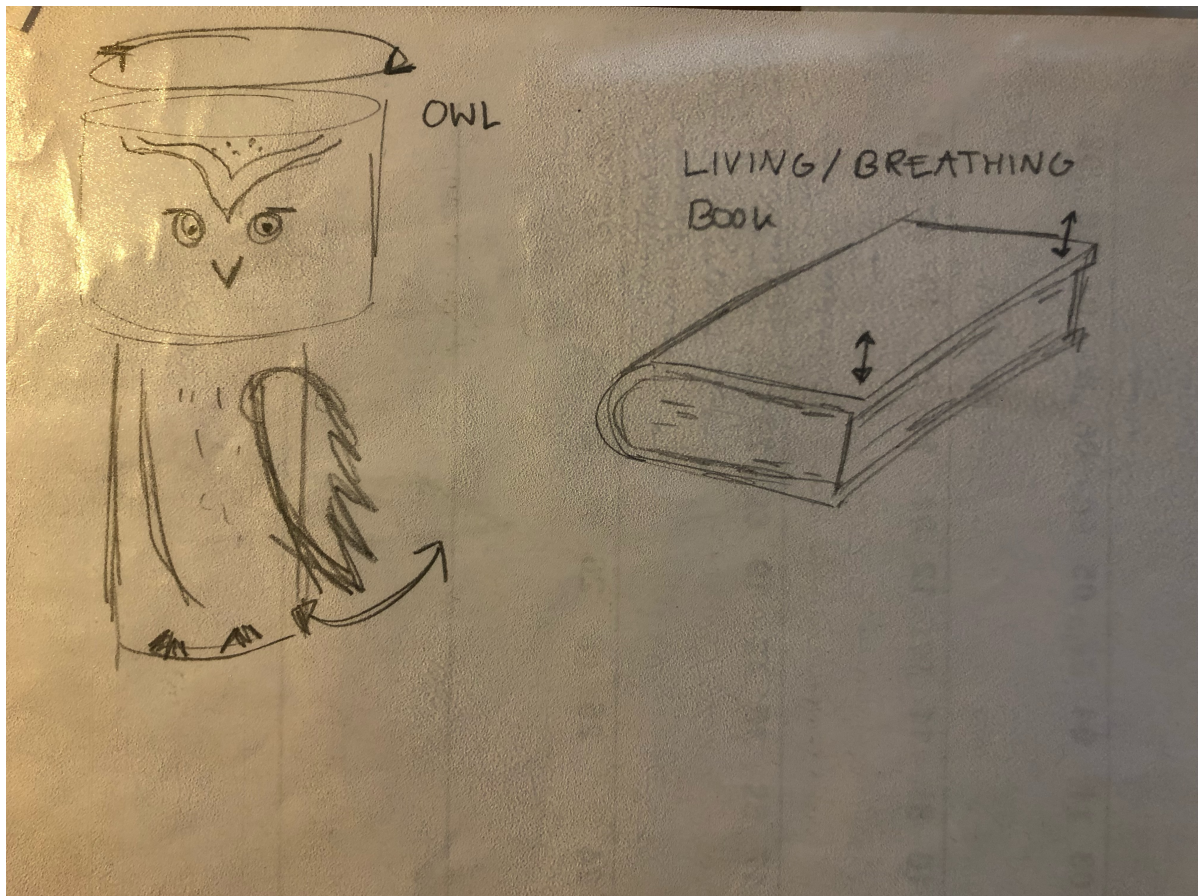
Anything else?

Appendix F

Workshop Instructions

The instruction text was: "First, connect the cable to the module by inserting it into the cable clip and pressing down the locking lever. The inspection hole in the cable clip can be used to verify that the cable has been inserted sufficiently. Next, prepare the tube by attaching a tube coupler to each end. Slide the tube over the cable, insert the tube coupler into the module, and rotate it by 45° to secure the connection. Before connecting the control module, move its slider fully backward to provide easy access to the cable clip. Insert the cable into the control module and pull it through completely; any excess cable can remain inside the control module. Adjust the module position by gently pulling on the cable, then secure the cable by pressing down the locking lever. Finally, connect the remaining end of the tube to the control module. The module is now fully connected and ready for operation."





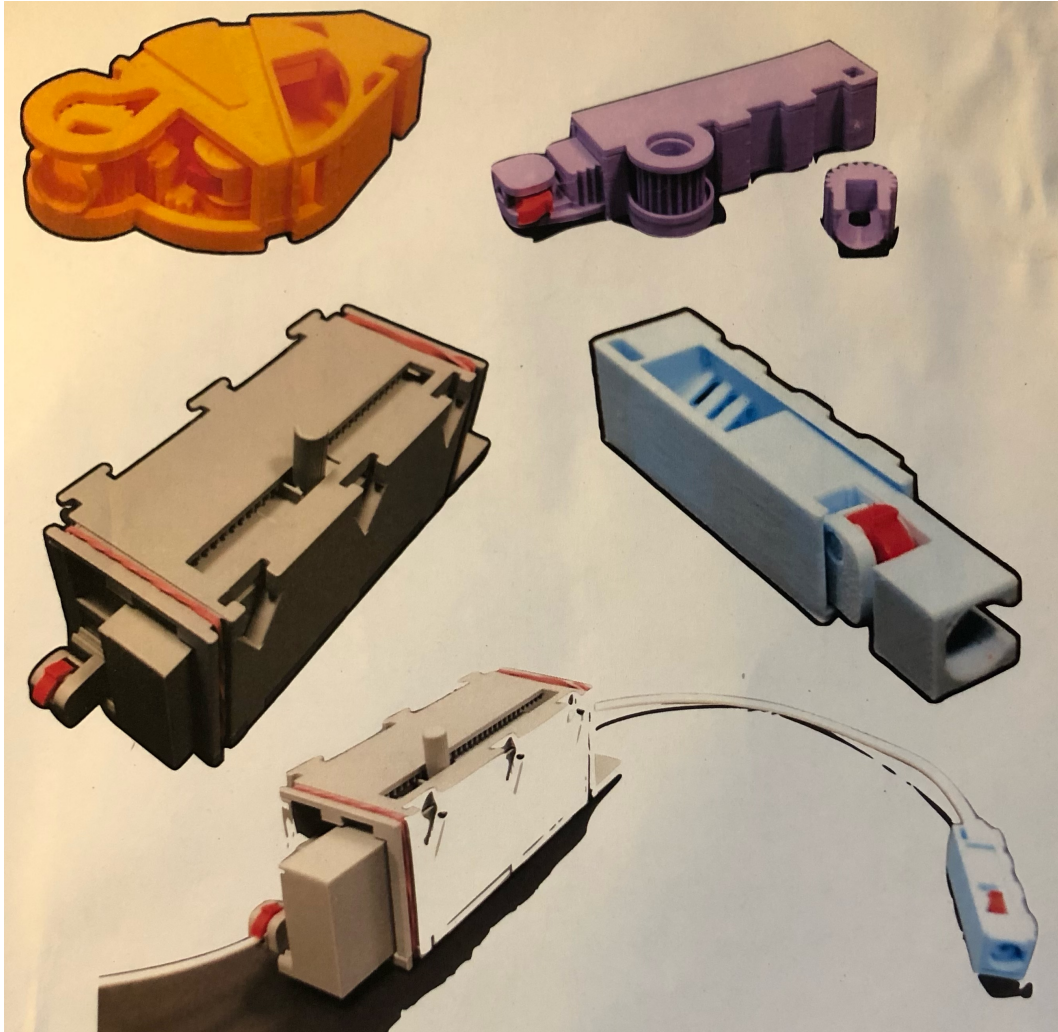


Figure F.1: Instructions workshop participants used to assemble the modules

Appendix G

Instructions

All files are uploaded to RWTH Gitlab: <https://git.rwth-aachen.de/i10/thesis/thesis-paul-gilles-craftables>
Assembling instructions are given on the next page.

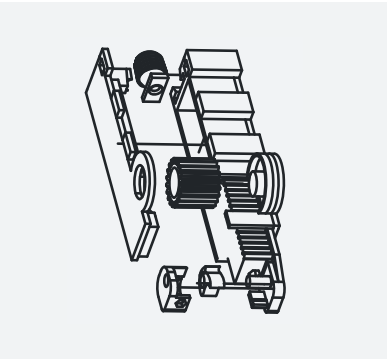
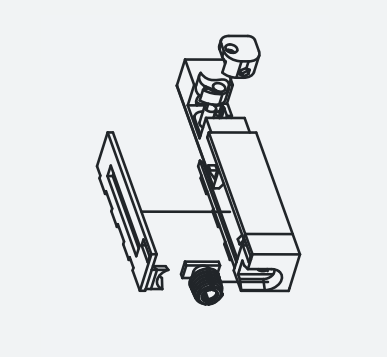
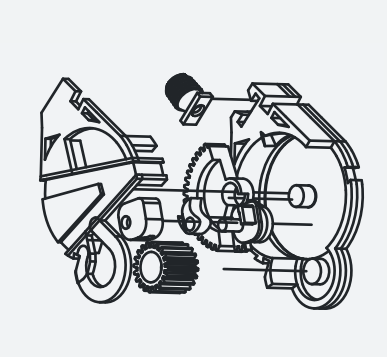
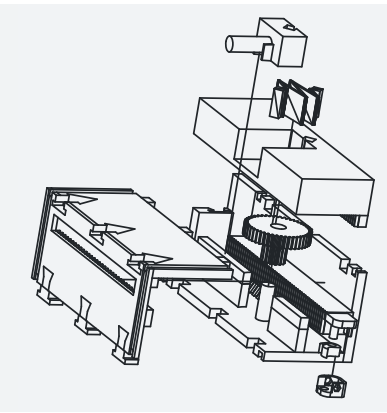
Rotary Rack		To Print 1x RR_Top 1x RR_Rack 1x RR_Hull 1x Small Gear Up or 1x Small Gear Side 1x Tube Coupling V2 1x Lever 1x Lever Cover
Linear Pin		To Print 1x LP_Top 1x LP_Pin 1x LP_Hull 1x Tube Coupling V2 1x Lever 1x Lever Cover
Rotary Gear		To Print 1x RG_Top 1x RG_MasterGear 1x RG_Hull 1x Small Gear Up or 1x Small Gear Side 1x Tube Coupling V2 1x Lever 1x Lever Cover
Controller		To Print 1x C_Top 1x C_Bottom 1x C_Gear 1x C_PushDown 1x C_Wave 1x C_Sted (print on right side) 1x C_Rack 1x Tube Coupling V2 1x Lever 1x Lever Cover

Figure G.1: List of print files and instruction.

Bibliography

- [1] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. Grand Challenges in Shape-Changing Interface Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, page 1–14, Montreal QC Canada, April 2018. ACM. doi.org/10.1145/3173574.3173873.
- [2] Asha Behdinan, Naomi Eisenberg, and Graham Roche-Nagle. The extent of academic spam within academic medicine. *JVS-Vascular Insights*, 3:100237, 2025. doi.org/10.1016/j.jvsvi.2025.100237.
- [3] Fiona Bell, Erin McClure, Camila Friedman-Gerlicz, Ruby Ta, and Leah Buechley. Shape-Changing Clay-Dough: Taking a Material-Oriented Approach to 3D Printing Ceramic Forms. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, CHI '24, New York, NY, USA, 2024. Association for Computing Machinery. doi.org/10.1145/3613904.3642246.
- [4] Bill Buxton. *Sketching User Experiences: Getting the Design Right and the Right Design*. Interactive Technologies. Morgan Kaufmann, Amsterdam; Boston, 2007. ISBN 9780123740373. doi.org/10.1016/B978-0-12-374037-3.X5043-3.
- [5] Tim Campbell, Cesar Torres, and Eric Paulos. FLUIs: Liquid-Mediated Vision Based Touch Surfaces. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, page 85–88, New York, NY, USA, 2015. Association for Computing Machinery. doi.org/10.1145/2677199.2680604.
- [6] Marcelo Coelho and Pattie Maes. Shutters: a permeable surface for environmental control and communication. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, TEI '09, page 13–18, New York, NY, USA, 2009. Association for Computing Machinery. doi.org/10.1145/1517664.1517671.
- [7] Marcelo Coelho and Jamie Zigelbaum. Shape-changing interfaces. *Personal and Ubiquitous Computing*, 15(2):161–173, February 2011. doi.org/10.1007/s00779-010-0311-y.

-
- [8] Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. Surfex: a programmable surface for the design of tangible interfaces. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems*, page 3429–3434, Florence Italy, April 2008. ACM. doi.org/10.1145/1358628.1358869.
- [9] Aluna Everitt and Jason Alexander. PolySurface: A Design Approach for Rapid Prototyping of Shape-Changing Displays Using Semi-Solid Surfaces. In *Proceedings of the 2017 Conference on Designing Interactive Systems*, page 1283–1294, Edinburgh United Kingdom, 2017. ACM. doi.org/10.1145/3064663.3064677.
- [10] Aluna Everitt, Faisal Taher, and Jason Alexander. ShapeCanvas: An Exploration of Shape-Changing Content Generation by Members of the Public. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, page 2778–2782, San Jose California USA, May 2016. ACM. doi.org/10.1145/2858036.2858316.
- [11] Cathy Mengying Fang, Jianzhe Gu, Lining Yao, and Chris Harrison. ElectriPop: Low-Cost, Shape-Changing Displays Using Electrostatically Inflated Mylar Sheets. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22, New York, NY, USA, 2022. Association for Computing Machinery. doi.org/10.1145/3491102.3501837.
- [12] Marius Fechter, Benjamin Schleich, and Sandro Wartzack. Comparative evaluation of WIMP and immersive natural finger interaction: a user study on CAD assembly modeling. *Virtual Reality*, 26, 03 2022. doi.org/10.1007/s10055-021-00543-0.
- [13] Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. Jamming user interfaces: programmable particle stiffness and sensing for malleable and shape-changing devices. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*, UIST '12, page 519–528, New York, NY, USA, 2012. Association for Computing Machinery. doi.org/10.1145/2380116.2380181.
- [14] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. inFORM: dynamic physical affordances and constraints through shape and object actuation. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, page 417–426, St. Andrews Scotland, United Kingdom, October 2013. ACM. doi.org/10.1145/2501988.2502032.
- [15] Antonio Gomes, Andrea Nesbitt, and Roel Vertegaal. MorePhone: an actuated shape changing flexible smartphone. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, page 2879–2880, Paris France, April 2013. ACM. doi.org/10.1145/2468356.2479558.

- [16] Mark Goulthorpe, Mark Burry, and Grant Dunlop. Aegis Hyposurface©: The Bordering of University and Practice. In *Proceedings of ACADIA 2001: Reinventing the Discourse*, pages 344–349, 2001. doi.org/10.52842/CONF.ACADIA.2001.344.
- [17] Saul Greenberg. Toolkits and interface creativity. *Multimedia Tools and Applications*, 32(2):139–159, January 2007. doi.org/10.1007/s11042-006-0062-y.
- [18] Andrew Grey, Mark J Bolland, Nicola Dalbeth, Greg Gamble, and Lynn Sadler. We read spam a lot: prospective cohort study of unsolicited and unwanted academic invitations. *BMJ*, page i5383, December 2016. doi.org/10.1136/bmj.i5383.
- [19] Vladislav Gunchev. Prototyping Toolkits for Shape-Changing User Interfaces. Bachelor’s thesis, RWTH Aachen University, Aachen, March 2026.
- [20] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, page 19–28, Seoul Republic of Korea, April 2015. ACM. doi.org/10.1145/2702123.2702599.
- [21] Fabian Hemmert, Susann Hamann, Matthias Löwe, Anne Wohlauf, and Gesche Joost. Shape-changing mobiles: tapering in one-dimensional deformational displays in mobile phones. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*, page 249–252, Cambridge Massachusetts USA, January 2010a. ACM. doi.org/10.1145/1709886.1709936.
- [22] Fabian Hemmert, Susann Hamann, Matthias Löwe, Anne Wohlauf, Josefine Zeipelt, and Gesche Joost. Take me by the hand: haptic compasses in mobile devices through shape change and weight shift. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*, page 671–674, Reykjavik Iceland, October 2010b. ACM. doi.org/10.1145/1868914.1869001.
- [23] Jeffrey C. F. Ho. ClothSurface: Exploring a Low-Cost Prototyping Tool to Support Ideation for Shape Displays. *Multimodal Technologies and Interaction*, 3(3): 64, 2019. doi.org/10.3390/mti3030064.
- [24] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, page 234–241, Atlanta Georgia USA, March 1997. ACM. doi.org/10.1145/258549.258715.
- [25] Heekyoung Jung, Youngsuk L. Altieri, and Jeffrey Bardzell. Computational objects and expressive forms: a design exploration. In *CHI ’10 Extended Abstracts on Human Factors in Computing Systems*, CHI EA ’10, page 3433–3438,

- New York, NY, USA, 2010. Association for Computing Machinery. doi.org/10.1145/1753846.1753997.
- [26] Hyunyoung Kim, Aluna Everitt, Carlos Tejada, Mengyu Zhong, and Daniel Ashbrook. MorpheesPlug: A Toolkit for Prototyping Shape-Changing Interfaces. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, page 1–13, Yokohama Japan, May 2021. ACM. doi.org/10.1145/3411764.3445786.
- [27] Scott R. Klemmer, Björn Hartmann, and Leila Takayama. How bodies matter: five themes for interaction design. In *Proceedings of the 6th conference on Designing Interactive systems*, page 140–149, University Park PA USA, 2006. ACM. doi.org/10.1145/1142405.1142429.
- [28] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. Evaluation Strategies for HCI Toolkit Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, page 1–17, Montreal QC Canada, April 2018. ACM. doi.org/10.1145/3173574.3173610.
- [29] Daniel Leithinger and Hiroshi Ishii. Relief: a scalable actuated shape display. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*, page 221–222, Cambridge Massachusetts USA, January 2010. ACM. doi.org/10.1145/1709886.1709928.
- [30] Jiaji Li, Shuyue Feng, Maxine Perroni-Scharf, Yujia Liu, Emily Guan, Guanyun Wang, and Stefanie Mueller. Xstrings: 3D Printing Cable-Driven Mechanism for Actuation, Deformation, and Manipulation. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, page 1–17, Yokohama Japan, April 2025. ACM. doi.org/10.1145/3706598.3714282.
- [31] Yasushi Matoba, Toshiki Sato, Nobuhiro Takahashi, and Hideki Koike. ClaytricSurface: an interactive surface with dynamic softness control capability. In *ACM SIGGRAPH 2012 Emerging Technologies*, SIGGRAPH '12, New York, NY, USA, 2012. Association for Computing Machinery. doi.org/10.1145/2343456.2343462.
- [32] Akira Murakami, Kazuyuki Fujita, Yuki Onishi, and Yoshifumi Kitamura. OrigamiWalls: A Shape-Changing Robotic Partitioning System for Diverse Spatial Reconfigurations. In *Proceedings of the 2026 Designing Interactive Systems Conference*, page 4559–4576, Singapore, Singapore, 2026. ACM. doi.org/10.1145/3800645.3812904.
- [33] Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, page

- 333–339, New York, NY, USA, 2015. Association for Computing Machinery. doi.org/10.1145/2807442.2807452.
- [34] Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, and Hiroshi Ishii. ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, page 87–96, Tokyo Japan, October 2016. ACM. doi.org/10.1145/2984511.2984587.
- [35] Mie Nørgaard, Tim Merritt, Majken Kirkegaard Rasmussen, and Marianne Graves Petersen. Exploring the design space of shape-changing objects: imagined physics. In *Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces, DPPI '13*, page 251–260, New York, NY, USA, 2013. Association for Computing Machinery. doi.org/10.1145/2513506.2513533.
- [36] Donald A. Norman. *The Design of Everyday Things: Revised and Expanded Edition*. Basic Books, New York, 2013.
- [37] Kas Oosterhuis and Nimish Bitoria. Interactions with proactive architectural spaces: the muscle projects. *Communications of the ACM*, 51(6):70–78, 2008. doi.org/10.1145/1349026.1349041.
- [38] Ata Otaran, Yu Jiang, and Jürgen Steimle. Sparsely actuated modular metamaterials for shape changing interfaces. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*, page 1–12, Bordeaux/Talence France, March 2025. ACM. doi.org/10.1145/3689050.3704942.
- [39] Jifei Ou, Lining Yao, Daniel Tauber, Jürgen Steimle, Ryuma Niiyama, and Hiroshi Ishii. jamSheets: thin interfaces with tunable stiffness enabled by layer jamming. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction, TEI '14*, page 65–72, New York, NY, USA, 2014. Association for Computing Machinery. doi.org/10.1145/2540930.2540971.
- [40] Jifei Ou, Felix Heibeck, and Hiroshi Ishii. TEI 2016 Studio: Inflated Curiosity. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction, TEI '16*, page 766–769, New York, NY, USA, 2016. Association for Computing Machinery. doi.org/10.1145/2839462.2854119.
- [41] Amanda Parkes and Hiroshi Ishii. Kinetic sketchup: motion prototyping in the tangible design process. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, page 367–372, Cambridge United Kingdom, February 2009. ACM. doi.org/10.1145/1517664.1517738.
- [42] Amanda Parkes and Hiroshi Ishii. Bosu: a physical programmable design tool for transformability with soft mechanics. In *Proceedings of the 8th ACM*

- Conference on Designing Interactive Systems*, page 189–198, Aarhus Denmark, August 2010. ACM. doi.org/10.1145/1858171.1858205.
- [43] Amanda J. Parkes, Hayes Solos Raffle, and Hiroshi Ishii. Topobo in the wild: longitudinal evaluations of educators appropriating a tangible interface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, page 1129–1138, Florence Italy, April 2008. ACM. doi.org/10.1145/1357054.1357232.
- [44] Ivan Poupyrev, Tatsushi Nashida, and Makoto Okabe. Actuation and tangible user interfaces: the Vaucanson duck, robots, and shape displays. In *Proceedings of the 1st international conference on Tangible and embedded interaction*, page 205–212, Baton Rouge Louisiana, February 2007. ACM. doi.org/10.1145/1226969.1227012.
- [45] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, page 735–744, Austin Texas USA, May 2012. ACM. doi.org/10.1145/2207676.2207781.
- [46] Anne Roudaut, Abhijit Karnik, Markus Löchtfeld, and Sriram Subramanian. Morphees: toward high “shape resolution” in self-actuated flexible mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, page 593–602, Paris France, April 2013. ACM. doi.org/10.1145/2470654.2470738.
- [47] Stephan Schlögl, Gavin Doherty, and Saturnino Luz. Wizard of Oz Experimentation for Language Technology Applications: Challenges and Tools. *Interacting with Computers*, 27(6):592–615, November 2015. doi.org/10.1093/iwc/iwu016.
- [48] Amitabh Shrivastava. Programmable-Air, 2018. URL <https://programmableair.com/>. Accessed: 2026-06-20.
- [49] Ali Shtarbanov. FlowIO Development Platform – the Pneumatic “Raspberry Pi” for Soft Robotics. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, page 1–6, Yokohama Japan, May 2021. ACM. doi.org/10.1145/3411763.3451513.
- [50] Carolyn Snyder. *Paper Prototyping: The Fast and Easy Way to Design and Refine User Interfaces*. Interactive Technologies. Morgan Kaufmann, San Francisco, CA, 2003. ISBN 9781558608702. doi.org/10.1016/B978-1-55860-870-2.X5023-2.

- [51] Miriam Sturdee and Jason Alexander. Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research. *ACM Computing Surveys*, 51(1):1–32, January 2018. doi.org/10.1145/3143559.
- [52] Ryo Suzuki, Ryosuke Nakayama, Dan Liu, Yasuaki Kakehi, Mark D. Gross, and Daniel Leithinger. LiftTiles: Constructive Building Blocks for Prototyping Room-scale Shape-changing Interfaces. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '20, page 143–151, New York, NY, USA, 2020. Association for Computing Machinery. doi.org/10.1145/3374920.3374941.
- [53] Faisal Taher, John Vidler, and Jason Alexander. A Characterization of Actuation Techniques for Generating Movement in Shape-Changing Interfaces. *International Journal of Human–Computer Interaction*, 33(5):385–398, May 2017. doi.org/10.1080/10447318.2016.1250372.
- [54] Yasaman Tahouni, Isabel P. S. Qamar, and Stefanie Mueller. NURBSforms: A Modular Shape-Changing Interface for Prototyping Curved Surfaces. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*, page 403–409, Sydney NSW Australia, February 2020. ACM. doi.org/10.1145/3374920.3374927.
- [55] Yuhan Wang, Keru Wang, Zhu Wang, and Ken Perlin. Robotecture: A Modular Shape-changing Interface Using Actuated Support Beams. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*, page 1–11, Bordeaux/Talence France, March 2025. ACM. doi.org/10.1145/3689050.3704925.
- [56] Kelly E. Wood and Matthew D. Krasowski. Academic E-Mail Overload and the Burden of “Academic Spam”. *Academic Pathology*, 7:2374289519898858, January 2020. doi.org/10.1177/2374289519898858.
- [57] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, page 1–10, Seoul Republic of Korea, April 2015. ACM. doi.org/10.1145/2702123.2702611.
- [58] Iddo Yehoshua Wald and Oren Zuckerman. Magnetform: a Shape-change Display Toolkit for Material-oriented Designers. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*, page 1–14, Salzburg Austria, February 2021. ACM. doi.org/10.1145/3430524.3446066.
- [59] Lina Zhang, Yibin Huai, Zhian Hu, Jiayi Wu, Alvaro Cassinelli, and Kening Zhu. ThreadTessel: A Modularized Tangible Toolkit Leveraging Origami Tes-

- sellation for Designing Thread-actuated Shape-changing Structures. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*, page 1–15, Bordeaux/Talence France, March 2025. ACM. doi.org/10.1145/3689050.3704929.
- [60] Ran Zhou, Jianru Ding, Chenfeng Gao, Wanli Qian, Benjamin Erickson, Madeleine Balaam, Daniel Leithinger, and Ken Nakagaki. Shape-Kit: A Design Toolkit for Crafting On-Body Expressive Haptics. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, page 1–26, April 2025. doi.org/10.1145/3706598.3713981.
- [61] Kening Zhu and Shengdong Zhao. AutoGami: a low-cost rapid prototyping toolkit for automated movable paper craft. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, page 661–670, New York, NY, USA, 2013. Association for Computing Machinery. doi.org/10.1145/2470654.2470748.
- [62] Oren Zuckerman and Ayelet Gal-Oz. To TUI or not to TUI: Evaluating performance and preference in tangible vs. graphical user interfaces. *International Journal of Human-Computer Studies*, 71(7–8):803–820, 2013. doi.org/10.1016/j.ijhcs.2013.04.003.

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