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Prototyping Toolkits for Shape-Changing User Interfaces

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Abstract

In recent years, a growing number of toolkits, frameworks, and platforms have been proposed to support the prototyping process of shape-changing interfaces. However, there is still no clear overview of how these prototyping approaches are structured, which parts of the workflow they support, and where important gaps remain. This thesis, therefore, reviews the literature on prototyping toolkits for shape-changing interfaces.

To address this problem, a systematic literature review was conducted following the PRISMA approach. The review combined backward and forward snowballing from four seed papers with a structured database search in the ACM Digital Library. The final reviewed corpus of 47 publications was then analyzed using a qualitative coding scheme developed around three research questions: how SCI prototyping toolkits can be categorized, how they support the design-to-fabrication workflow, and how they are evaluated.

The review shows that SCI prototyping toolkits are primarily focused on three actuation approaches: smart materials, electromechanical systems, and pneumatic systems. Most toolkits are designed for desktop-scale prototyping, whereas body-scale and spatial systems are less common. The corpus also shows a strong orientation toward designers and researchers, although some more recent work increasingly addresses non-experts. In terms of workflow support, many toolkits provide useful support for early-stage design exploration through CAD tools, graphical user interfaces, or simulations, but fewer offer integrated workflows that connect design, fabrication, and implementation seamlessly. Evaluation practices also remain uneven. Demonstrations are the most common strategy, while usage-based and technical evaluations appear less consistently, and long-term studies are seldom.

Overall, this thesis provides a structured overview of research on SCI prototyping toolkits and identifies remaining challenges for future work, particularly regarding workflow integration, broader accessibility, and stronger evaluation practices.

Überblick

In den letzten Jahren wurde eine wachsende Zahl von Toolkits, Frameworks und Plattformen vorgeschlagen, um den Prototyping-Prozess für Shape-changing Interfaces zu unterstützen. Dennoch gibt es bisher keinen klaren Überblick darüber, wie diese Prototyping-Ansätze strukturiert sind, welche Etappen des Workflows sie unterstützen und wo weiterhin wichtige Lücken bestehen.

Um dieses Problem zu adressieren, wurde eine systematische Literaturrecherche gemäß den PRISMA-Leitlinien durchgeführt. Das Review kombinierte rückwärts- und vorwärtsgerichtetes Snowballing, ausgehend von vier Seed Papers, mit einer strukturierten Datenbanksuche in der ACM Digital Library. Der finale untersuchte Datensatz mit 47 Publikationen wurde anschließend mithilfe eines qualitativen Kodierschemas analysiert, das sich an drei Forschungsfragen orientierte: wie sich SCI-Prototyping-Toolkits kategorisieren lassen, wie sie den Design-to-Fabrication-Workflow unterstützen und wie sie evaluiert werden.

Das Review zeigt, dass SCI-Prototyping-Toolkits vor allem auf drei Aktuierungsansätze ausgerichtet sind: Smart Materials, elektromechanische Systeme und pneumatische Systeme. Die meisten Toolkits sind für Desktop-Scale-Prototyping ausgelegt, während Body-Scale- und räumliche Systeme seltener vorkommen. Der Datensatz zeigt außerdem eine starke Ausrichtung auf Designer und Forschende, auch wenn einige neuere Arbeiten zunehmend Nicht-Expert:innen adressieren. Im Hinblick auf den Workflow bieten viele Toolkits nützliche Unterstützung für die frühe Designexploration durch CAD-Werkzeuge, grafische Benutzeroberflächen oder Simulationen, doch nur wenige integrieren Workflows, die Design, Fertigung und Implementierung nahtlos miteinander verbinden. Auch die Evaluationspraktiken bleiben uneinheitlich. Demonstrationen sind die häufigste Strategie, während nutzungsbasierte und technische Evaluationen weniger konsistent angewendet werden. Insgesamt liefert diese Arbeit einen strukturierten Überblick über die Forschung zu SCI-Prototyping-Toolkits und identifiziert verbleibende Herausforderungen für zukünftige Arbeiten.

Acknowledgments

First, I would like to thank Prof. Dr. Jan Borchers and Prof. Dr.-Ing. Ulrik Schroeder for examining my thesis.

Many thanks to Sarah Sahabi for the supervision of my work, for your feedback and guidance over the last months. Thank you for giving me the opportunity to work on such an interesting and creative topic. I have enjoyed it a lot and am excited to conduct further research in the field of shape-changing interfaces in the future.

Thank you so much to my family and friends for supporting and motivating me, both locally and online, during my studies, and for checking in on me. Thank you for always being by my side.

Also, special thanks to my partner for your constant love and support throughout this thesis, especially in stressful times.

Finally, I am really happy that my little sister, Bella, can see my work and be proud of me!

Conventions

Throughout this thesis, we use the following conventions:

- The thesis is written in American English.
- The first person is written in plural form.
- Unidentified third persons are described in female form.

Short excursuses are set off in colored boxes.

> **EXCURSUS:**
> Excursuses are set off in orange boxes.

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.

Fill in whatever other text conventions you might have here.

Chapter 1

Introduction

> *"Shape-changing user interfaces represent a potential future direction for human-computer interaction, aiming to bring the sense of touch and physical manipulation back into the forefront."*
>
> *—Daniel Leithinger* [1]

Shape change in nature and how it helps animals and plants.

Shape change can be observed across biological systems as a response to environmental conditions and adaptive pressures. For instance, animals can adjust their posture or body volume to regulate their temperature, while certain plants can modify their form to match surrounding plants for camouflage. These examples demonstrate that shape change is rarely just cosmetic but often serves clear functional applications [Ryding et al., 2021].

Shape change in everyday life and how it helps humans.

Humans also have a long history of interacting with shape-changing materials. Activities like pottery, sculpting, or playing with soft materials like plasticine require physical contact. These interactions are intuitive and embodied, and can be continuously adjusted with the hands. In such contexts, shape change supports learning, creativity, and expression, often without the need for explicit instructions or abstract representations [Bell et al., 2024; Ishii et al., 2004; Liang et al., 2021].

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[1] https://www.youtube.com/watch?v=Hw1qUn2wri4, *last accessed 20.01.2026*

Connecting nature and technology.

Inspired by the adaptive qualities of nature, researchers have been exploring in the last years how computational systems could similarly transform their physical form [Rasmussen et al., 2012]. Early papers on *tangible and embodied interaction* emphasized the integration of digital information with physical materials, which aims to "bridge the gap between bits and atoms" [Ishii and Ullmer, 1997].

Development of material science "opened the door" for SCIs.

At the same time, advances in *digital fabrication*, *actuation technologies*, and *smart materials* have made it increasingly practical to experiment with physical transformation in interactive systems [Qamar et al., 2018]. These technological developments have contributed to the emergence of *shape-changing interfaces* (SCIs) as a distinct research area within the field of *Human-Computer Interaction* (HCI) [Rasmussen et al., 2012].

Rather than relying just on screens or static physical controls, these interfaces communicate information and afford interaction through movement, deformation, or changes in texture. A commonly used definition describes SCIs as physically tangible, interactive devices, surfaces, or spaces that enable rich and organic experiences with computational systems [Sturdee and Alexander, 2018].

One of the grand challenges of SCIs.

While several reviews have examined the design space of SCIs [Rasmussen et al., 2012; Sturdee and Alexander, 2018], researchers have also identified grand challenges within this space. One of them is related to prototyping [Alexander et al., 2018]. Many SCI prototypes remain one-off research artifacts that are difficult to reproduce, extend, or transfer into other contexts. This implies that designers without strong technical backgrounds may struggle to explore shape-changing interaction concepts, and it may be challenging for them to use their knowledge from one project to another [Qamar et al., 2018; Sturdee and Alexander, 2018].

SCI development requires multidisciplinary expertise across hardware and software.

Prototyping toolkits have been proposed to address these limitations and to build a bridge among designers, non-experts, and researchers [Dai et al., 2024; Kim et al., 2021]. The development of SCIs requires the integration of software programming, complex electronics, actuation mechanisms, and mechanical design [Alexander et al., 2018; Qamar et al., 2018]. This is a complex combination of competencies that differs from what is typically required in other areas of interactive computing. The diversity of these technologies and the lack of standardized platforms make it difficult to prototype and reproduce shape-changing systems efficiently. However, existing toolkits vary widely in terms of their goals, supported technologies, and intended users. Moreover, many toolkit papers provide limited evaluation, making it difficult to assess their practical usefulness [Alexander et al., 2018; Ledo et al., 2018].

Existing literature often discusses technical innovation or interaction concepts, while questions related to workflow support, usability, and reproducibility remain neglected [Qamar et al., 2018; Sturdee and Alexander, 2018].

Although several toolkits have been introduced to address prototyping challenges, they differ considerably in terms of technical scope, abstraction level, and intended user groups. In addition, evaluation approaches for toolkits are inconsistent, ranging from informal demonstrations to small user studies, with little agreement on appropriate metrics [Alexander et al., 2018; Ledo et al., 2018].

Existing SCI toolkits lack systematic comparison and evaluation.

Thus, it remains unclear how effectively current prototyping toolkits support the full design-to-fabrication process and how transferable their solutions are beyond specific research contexts. Despite the growing number of toolkits, there is a lack of structured comparison regarding their design principles and methodological foundations. This gap motivates this thesis, which offers a systematic examination focused specifically on SCI prototyping toolkits. The unique contribution of this research is a comprehensive analysis of the tools and frameworks that facilitate the creation of SCIs, thereby identifying both existing gaps and ongoing challenges in the field. By clarifying the scope to emphasize toolkit development and evaluation, this thesis aims to advance understanding of how such resources support the multidisciplinary process of SCI prototyping.

We address these gaps by systematically reviewing prototyping toolkits for SCIs. For the literature review, we used the *Preferred Reporting Items for Systematic reviews and Meta-Analyses* (PRISMA) Guideline as a base [Page et al., 2021].

Research questions of the thesis.

The paper is guided by the following research questions (RQs):

RQ1: What toolkits and frameworks have been proposed for prototyping shape-changing interfaces, and how can they be systematically categorized?

RQ2: How do prototyping toolkits for shape-changing interfaces support the design-to-fabrication workflow, and what aspects of this workflow are emphasized or constrained by existing tools?

RQ3: How are shape-changing interface prototyping toolkits evaluated in the literature, and what methodological gaps and remaining challenges can be identified for their future development?

This thesis investigates existing SCI prototyping toolkits through a systematic literature review.

Our goal is to explore and reflect on the current field of prototyping toolkits for shape-changing user interfaces via a structured literature review, through which we would try to provide clarity and structure to this area.

1.1 Outline

The thesis is structured in five chapters. Following this Introduction, Chapter 2 "Theoretical Background" introduces relevant background concepts related to SCIs and prototyping. Chapter 3 "Methodology" presents the methodological approach and explains the process of selecting and analyzing the literature. Chapter 4 "Results" gives a summary of the outcome from the conducted literature review. Chapter 5 "Discussion" addresses the three research questions by categorizing existing toolkits, analyzing workflow support, and examining evaluation practices. Finally, Chapter 6 "Summary and Future Work" discusses the identified challenges, implications for future research, and potential directions for developing more accessible and reproducible SCI prototyping frameworks.

Chapter 2

Theoretical Background

This chapter provides the theoretical background necessary to understand the prototyping of shape-changing interfaces. It begins by introducing key definitions, taxonomies, and the design space that structures the field. It then examines the material and actuation mechanisms that make physical transformation possible, emphasizing the multidisciplinary nature of SCI development. The chapter also discusses prototyping within HCI and highlights the specific challenges that arise when material properties, mechanical actuation, sensing, and software control must work together. Finally, it briefly introduces the concept of toolkits.

2.1 Shape-Changing Interfaces

DEFINITION:
Shape-changing interfaces are physically tangible, interactive devices, surfaces or spaces which allow for rich, organic and novel experiences with computational devices [Sturdee and Alexander, 2018].

The design space of shape change.

Rasmussen et al. [2012] provided an early and influential overview of shape-changing interfaces, demonstrating the

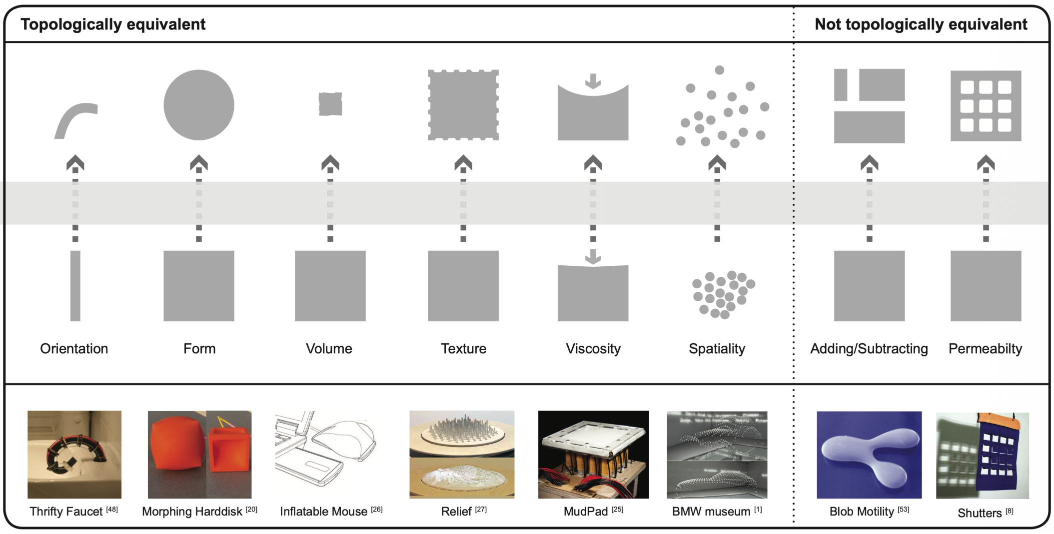


Figure 2.1: The figure shows the taxonomy that categorizes the different types of shape change. Image taken from Rasmussen et al. [2012]. The examples in the figure are from the following sources (from left to right): Togler et al. [2009]; Horev [2006], Kim et al. [2008]; Leithinger and Ishii [2010]; Jansen [2010]; BMW Museum; Blob Motility; Coelho and Maes [2009].

wide range of possible physical transformations and interaction purposes. Their work mapped different types of deformation and interaction characteristics, while also highlighting open challenges and research gaps within the field.

Different deformation types imply different prototyping requirements.

One important aspect of this taxonomy is the identification of distinct deformation types. These include *orientation*, *form*, *volume*, *texture*, *viscosity* and *spatiality*. These types of shape change are illustrated in Figure 2.1.

Such distinctions are not only descriptive categories. Each type of transformation implies different mechanical requirements, material properties, and actuation strategies. A system designed to change curvature requires flexible substrates and distributed force application, whereas a system for volumetric expansion may rely on pneumatic or inflatable mechanisms. In this sense, design taxonomies already reveal technical implications that directly influence implementation and prototyping decisions.

Figure 2.2: The figure shows the 8 suggested categories of shape-changing prototypes. Image taken from Sturdee and Alexander [2018].

SCIs can also be classified by research focus and application context.

While Rasmussen et al. [2012] structured the field mainly through deformation dimensions, later analyses expanded on this perspective. Sturdee and Alexander [2018] examined the literature to classify shape-changing interfaces according to research focus, distinguishing between technology-driven contributions, interaction-driven explorations, and application-oriented systems. There were suggested 8 categories of SCIs, as shown in Figure 2.2.

This classification demonstrates that SCIs operate simultaneously as material systems, interaction systems, and research artifacts. Some projects emphasize novel actuation techniques or fabrication processes, while others explore experiential qualities, affordances, or use cases.

SCIs emerge from the interaction of physical transformation, computation, and user interaction.

Taken together, these taxonomies show that SCIs cannot be reduced to a single defining characteristic such as resolution, responsiveness, or fidelity. Instead, they are characterized by the connection between physical transformation, computational control, and human interaction. Before addressing prototyping, it is important to understand these conceptual structures, because each dimension of the design space introduces specific technical and methodological considerations.

Unlike traditional graphical interfaces, where visual layout can be modified independently from the physical device, SCIs bind form and function together. A modification in shape does not only change appearance, but it also alters interaction affordances and user expectations. This tight coupling between physical structure and interaction logic is one of the fundamental reasons why prototyping in this domain differs from more conventional interface design.

2.1.1 Affordances of SCIs

Affordances describe how users perceive possible interactions with an artifact.

While Ishii and Ullmer [1997] emphasize making digital information graspable through physical form, SCIs extend this approach by enabling the physical form itself to change dynamically in response to computational processes or user actions.

In HCI, this is often discussed in terms of affordances . Affordance is the action possibility that an artifact offers, as it is perceived by a user in a particular context [Norman, 2013].

Transformability through material, structure, and visible mechanisms.

For SCIs, affordances are not only about pressing, dragging, or rotating, but also about whether and how an object might physically transform. Petersen et al. [2020] analyze shape-changing interfaces from this perspective and ask how SCIs communicate their transformability potential, including when the interface is not currently moving. They argue that users pick up cues about possible transformations from several aspects of the artifact, such as its structure, material, visible mechanisms, and overall form. These cues help users anticipate whether an object might bend, fold, stretch, inflate, rotate, or otherwise change shape and whether this change is user-driven or actuated.

Based on a review of existing prototypes, Petersen et al. [2020] identify four recurring design strategies that designers use to communicate transformability, namely *structure, material, actuation mechanisms* and *form*.

These strategies illustrate that the static appearance of an SCI is already part of its interaction design. Users rarely see an object in its animated state alone. If transformability is not legible, users may either fail to discover key interactions or feel unsafe when unexpected motion occurs.

2.1.2 Applications

SCIs have been proposed for diverse application domains.

Shape-changing interfaces have the potential to be applied across a wide range of domains. By enabling physical transformation as part of interaction, these systems can support new forms of communication between users and digital systems [Rasmussen et al., 2012]. Possible application ideas have been suggested across multiple domains, including entertainment, augmented living, medical devices, tools and utensils, architecture, and wearables. Sturdee et al. [2015] conducted a public ideation study that grouped 336 ideas into 11 application themes, illustrating the breadth of possible use cases for shape-change. Some of the SCIs are shown in Figure 2.3.

2.2 Materials and Actuation Mechanisms

Actuation technologies determine how shape change can be physically realized.

The physical transformation of shape-changing interfaces is enabled through a combination of materials, mechanical structures, and actuation technologies. While taxonomies describe what kind of transformations are possible, material and actuation systems determine how these transformations can be realized in practice [Alexander et al., 2018; Qamar et al., 2018].

Several categories of actuation approaches appear repeatedly in the literature.A practical distinction can be made between *electromechanical actuation*, *pneumatic actuation*, and *smart-material-based actuation*, each with characteristic strengths and prototyping trade-offs [Alexander et al., 2018; Qamar et al., 2018]. In the following subsections, an overview of the different actuation types is provided.

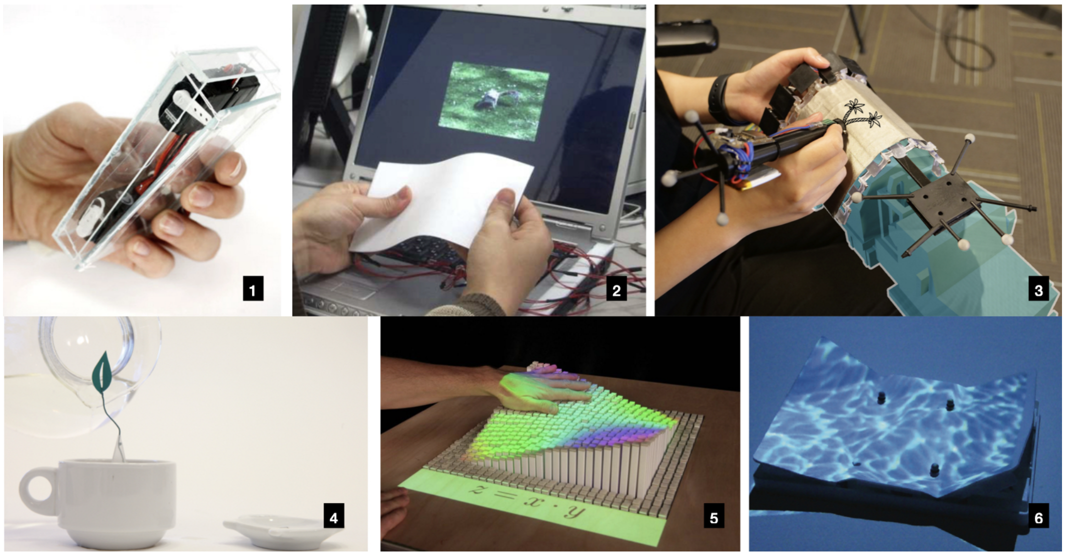


Figure 2.3: The figure shows SCI prototypes in different application fields. The examples are from the following sources (from left to right): 1. Shape-changing mobiles, Hemmert et al. [2010]; 2. Bookisheet, Watanabe et al. [2008]; 3. VRScroll and Sketching Pen, Ying et al. [2024]; 4. Living teabags, Yao et al. [2015]; 5. inFORM, Follmer et al. [2013]; 6. Shape-Changing Tablet combined with Augmented Reality, Coelho and Maes [2009].

2.2.1 Electromechanical Actuation

Electromechanical systems provide precise control but require complex hardware.

Electromechanical actuation typically relies on motors and mechanically driven elements, for example, in *pin-based shape displays*. Shape display systems such as inFORM [Follmer et al., 2013] are built around dense arrays of motorized linear actuators, where each actuator functions as a controllable "physical pixel". This approach offers controllability and repeatability but often leads to large, heavy setups, and increasing resolution further complicates the technical implementation [Alexander et al., 2018; Follmer et al., 2013].

2.2.2 Pneumatic Actuation

Pneumatics enable soft deformation but increase system complexity.

In contrast to electromechanical actuation, pneumatic actuation uses air pressure to inflate, contract, or de-form flexible structures and is strongly connected to developments in soft robotics and inflatable interfaces [Ou et al., 2016; Qamar et al., 2018]. A good example is aeroMorph [Ou et al., 2016], which presents a design and fabrication pipeline for programmable inflatables and shows how pneumatic interfaces can generate multiple shape-changing behaviors. From a prototyping perspective, pneumatics can enable slim and varied geometries but frequently introduces additional system dependencies, such as air routing and pressure control, which raise the engineering overhead for iteration [Alexander et al., 2018; Ou et al., 2016].

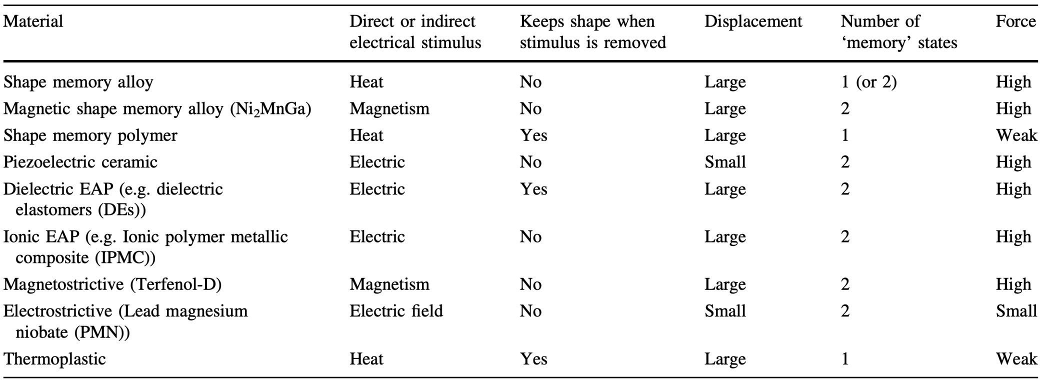
2.2.3 Smart Materials

Smart materials enable shape change through intrinsic material properties.

Beyond traditional electromechanical and pneumatic systems, smart materials offer additional possibilities for creating dynamic physical transformation. Smart materials and morphing structures (e.g., *shape memory alloys* (SMAs), *dielectric elastomers* and *structurally programmed materials*) enable controlled changes in form through intrinsic material properties [Coelho and Zigelbaum, 2011; Qamar et al., 2018].

Classification of Shape-changing mechanisms.

Coelho and Zigelbaum [2011] provide a comparative overview of such materials, highlighting key trade-offs between displacement range, generated force, energy consumption, and the ability to hold its shape without continuous power. For example, as shown in Figure 2.4, SMAs can produce relatively large forces but typically switch between one or two memorized shapes and require heating to actuate. Nevertheless, dielectric elastomers can undergo large, muscle-like deformations but demand high voltages and careful encapsulation.Qamar et al. [2018] extend this view from a material science perspective, grouping shape-changing mechanisms into classes such as *stretchable structures, deployable structures, variable-stiffness materials* and *shape-memory systems*, and discussing their applicability to interactive devices.



Material	Direct or indirect electrical stimulus	Keeps shape when stimulus is removed	Displacement	Number of 'memory' states	Force
Shape memory alloy	Heat	No	Large	1 (or 2)	High
Magnetic shape memory alloy (Ni_2MnGa)	Magnetism	No	Large	2	High
Shape memory polymer	Heat	Yes	Large	1	Weak
Piezoelectric ceramic	Electric	No	Small	2	High
Dielectric EAP (e.g. dielectric elastomers (DEs))	Electric	Yes	Large	2	High
Ionic EAP (e.g. Ionic polymer metallic composite (IPMC))	Electric	No	Large	2	High
Magnetostrictive (Terfenol-D)	Magnetism	No	Large	2	High
Electrostrictive (Lead magnesium niobate (PMN))	Electric field	No	Small	2	Small
Thermoplastic	Heat	Yes	Large	1	Weak

Figure 2.4: The figure shows a comparative table of smart materials and their properties from year 2011. Image taken from Coelho and Zigelbaum [2011]. It helps designers with choosing the right materials.

These materials are often discussed as a pathway to slimmer and more integrated form factors compared to conventional electromechanics. However, they also introduce constraints such as energy requirements, response time, durability, and material-specific limitations that can affect prototyping reliability. Qamar et al. [2018] frame this as a multidisciplinary challenge, arguing that advancing shape-changing interfaces requires both progress in accessible material technologies and a deeper HCI understanding of how material properties shape interaction affordances.

2.2.4 Fabrication Methods

Digital fabrication enables rapid prototyping of deformable structures.

Fabrication methods shape what is feasible to prototype. Digital fabrication workflows such as *laser cutting* and *3D printing* are frequently used to create deformable surfaces, linkages, or semi-flexible structures [Everitt and Alexander, 2019]. For example, Living Hinges [Jensen et al., 2017] have been explored as a low-cost way to create flexible surfaces that can support repeatable prototypes for studying shape-change experiences.

In a similar way, Everitt and Alexander [2019] demonstrate how interlinked 3D-printed panels can be fabricated into deformable surfaces for shape-changing displays, including discussions of actuation trade-offs and scaling considerations.

Crucially, in the SCI field, the choice of actuation and fabrication is not separate from interaction design. Material stiffness, elasticity, actuator distribution, and output resolution directly influence what users can perceive and do, which makes “form” part of the interface logic rather than a passive container [Qamar et al., 2018].

Normal prototyping vs SCI prototyping.

As a result, prototyping shape-changing interfaces often becomes a coupled process in which changes to physical construction may require changes to sensing and control, and vice versa. That is one of the core reasons why SCI prototyping differs from more conventional interface prototyping [Qamar et al., 2018; Sturdee and Alexander, 2018].

2.3 Prototyping in HCI

Prototypes allow designers to explore and refine interaction concepts.

Prototyping is a central practice in Human–Computer Interaction, serving both as a design method and as a research approach. In HCI, building interactive systems is not only engineering but a kind of constructive research in which knowledge is embodied in artifacts [Hudson and Mankoff, 2014]. Prototypes make interaction concepts tangible, allowing researchers to explore, test, and refine ideas through iterative development.

Prototypes differ in both fidelity and purpose. Rather than representing complete systems, they selectively emphasize particular aspects of a design, such as interaction flow, technical feasibility, or user experience [Lim et al., 2008]. Iterative cycles of building and refinement help identify usability issues and technical constraints early in the design process. In traditional graphical interfaces, iteration primarily concerns software behavior and visual layout, while hardware infrastructure remains relatively stable.

2.4 Prototyping Challenges of SCI

SCI prototyping requires integrating materials, mechanics, and software.

Prototyping shape-changing interfaces introduces challenges that extend beyond those encountered in traditional graphical or even tangible interface design [Alexander et al., 2018]. While conventional prototyping often focuses primarily on software behavior and interaction flow, SCIs require the coordinated integration of material properties, mechanical actuation, sensing technologies, and software control. This tight coupling between physical transformation and computational logic significantly increases the complexity of design and implementation.

Prototyping cannot be separated from material and mechanisms.

First, SCIs rely on diverse actuation mechanisms, including electromechanical systems, pneumatic structures, and smart materials. A review by Qamar et al. [2018] of material and actuation approaches highlights the technical diversity and multidisciplinary knowledge required to implement such systems. Each actuation class introduces specific constraints related to force distribution, response time, scalability, energy consumption, and fabrication feasibility. As Rasmussen et al. [2012] emphasize, the physical characteristics of shape transformation directly influence interaction possibilities and design decisions. Consequently, prototyping cannot be separated from material and mechanical considerations.

Second, fabrication processes add an additional layer of complexity.SCIs frequently require digital fabrication methods such as 3D printing, laser cutting, or custom mechanical assemblies. Research prototypes such as inFORM [Follmer et al., 2013] or aeroMorph [Ou et al., 2016] demonstrate how tightly integrated hardware infrastructures are necessary to enable dynamic physical transformation. Iterative refinement, therefore, becomes slower and more resource-intensive compared to purely software-based systems.

Custom hardware makes SCI prototypes difficult to reproduce.

Third, reproducibility and scalability present methodological challenges. Unlike graphical interfaces, whose states can be replicated through code alone, SCIs often rely on custom-built hardware configurations, making replication across research groups more difficult and increasing barriers to entry. Alexander et al. [2018] identify the need for more accessible prototyping infrastructures as one of the grand challenges in shape-changing interface research.

Challenges in evaluation and testing.

Finally, the evaluation of SCI prototypes is inherently complex. Because physical transformation influences perception, affordances, and embodied interaction, evaluation must account for both technical performance and experiential qualities. The integration of material behavior and interaction logic complicates controlled experimentation and makes it more difficult to isolate variables during testing [Sturdee and Alexander, 2018].

This combination of requirements creates a significant barrier to experimentation and iteration. Addressing this complexity motivates the development of structured prototyping support that can encapsulate recurring technical patterns and lower the threshold for creating shape-changing systems. In the following section, we turn to the concept of toolkits as a means of overcoming these challenges and facilitating more accessible and effective prototyping within the SCI domain.

2.5 Toolkits

Toolkits provide reusable components that support rapid prototyping.

In HCI research, toolkits are commonly understood as generative platforms that encapsulate reusable components, abstractions, or workflows to support the creation of interactive systems [Greenberg, 2007; Myers et al., 2000]. Unlike single-purpose systems, toolkits are designed to enable others to build new artifacts within a structured design space.

They may include software libraries, hardware modules, or integrated development environments that reduce implementation effort and lower technical barriers [Ledo et al., 2018]. Toolkits differ from broader platforms or frameworks in that they explicitly aim to support prototyping and experimentation by providing predefined building blocks and guiding design pathways.

Chapter 3

Methodology

This chapter describes the methodological approach used in the literature review. Rather than strictly adhering to a single review protocol, the methodology was adapted to the exploratory, mapping-oriented nature of this research. The following sections describe the search strategy, selection process, and data extraction procedure in detail to ensure clarity and reproducibility.

3.1 Rationale for the Literature Review

The need of literature review.

The field of shape-changing interfaces is interdisciplinary and terminologically diverse. Rasmussen et al. [2012] and Alexander et al. [2018] highlight both the complexity of the design space and the need for structured prototyping support. Given the fragmented terminology and the overlap with related fields such as tangible interaction and digital fabrication, it is essential to systematically map and structure the existing literature. The RQs introduced in Chapter 1 "Introduction" guide this literature review and aim to provide a clearer overview of prototyping tools that support the development of SCIs. The goal of the review is therefore to identify relevant toolkit categories, examine how they support the design-to-fabrication workflow, and analyze how these toolkits are evaluated in the literature.

PRISMA-based approach.

To structure this process, the review follows selected principles from *Preferred Reporting Items for Systematic reviews and Meta-Analyses* (PRISMA) Statement [Page et al., 2021]. The PRISMA guidelines were initially created with the field of medical science in mind, as it was essential for clinicians to stay up to date with the research. In HCI research, PRISMA-based approaches are increasingly adopted to structure literature reviews [Stefanidi et al., 2023]. Between 2020 and 2023, there was a 30% increase in reviews using the PRISMA Statement compared to the five years from 2015 to 2019.

Methodology inspired by those publications.

Several prior studies informed the methodological section of this review. Rasmussen et al. [2012] reviewed the literature and analyzed different types of shape change and transformation. This literature review resulted in a detailed explanation of how researchers define SCIs. Coelho and Zigelbaum [2011] provide on the other hand, an overview of the shape-changing materials and their properties, while also describing how users interact with such systems. Sturdee and Alexander [2018] created a database of shape-changing prototypes and categorized the SCIs into 8 types. Their work provides a helpful guide for each one of the identified interface types and their applications. Alexander et al. [2018] highlights the challenges in the field of SCIs and discusses potential ideas for future research.

For better analysis, the literature will be coded.

In addition, Ledo et al. [2018] evaluated a corpus of 68 toolkit papers, which resulted in deriving 4 toolkit evaluation strategies. Following their approach, *coding* was used to help us connect the collected data to its analysis, as shown later in Section 3.5 “Data Extraction and Coding” (p. 25). Charmaz [2006] explains in their book further how coding should be done and what the types are. Therefore, we performed a PRISMA-inspired literature review that combined seed paper snowballing and database search [Wohlin, 2014].

The following sections will discuss our review process. It combined seed paper snowballing with a structured database search to capture both foundational and recent work in the field.

3.2 Identification of the Literature

3.2.1 Initial Step

We start with 4 key papers and then do backward/forward snowballing.

As an initial step, a set of 4 foundational papers Rasmussen et al. [2012], Alexander et al. [2018], Coelho and Zigelbaum [2011], and Sturdee and Alexander [2018] was selected as seed papers to identify relevant literature. These papers were chosen because they provide key contributions to the SCI field and provide a strong connection to prototyping and toolkit discussions. The selected key papers and the number of references and citing publications associated with each of them are shown in Table 3.1.

Paper	References	Cited by
Coelho and Zigelbaum [2011]	20	224
Rasmussen et al. [2012]	62	530
Alexander et al. [2018]	126	245
Sturdee and Alexander [2018]	113	85

Table 3.1: Identifying the corpus through the first step

Establishing initial dataset of publications

Their references were examined through backward snowballing, and their "Cited by" records were inspected through forward snowballing using the literature-mapping web tool *ResearchRabbit* [1] to identify later work building on these papers. This step was intended to establish an initial dataset of candidate publications and to gain a better understanding of the terminology, venues, and publication types used in this field.

The dataset identified in this initial step was then merged with the dataset from the next step and screened according to the process described later in Section 3.4 “Screening Process”.

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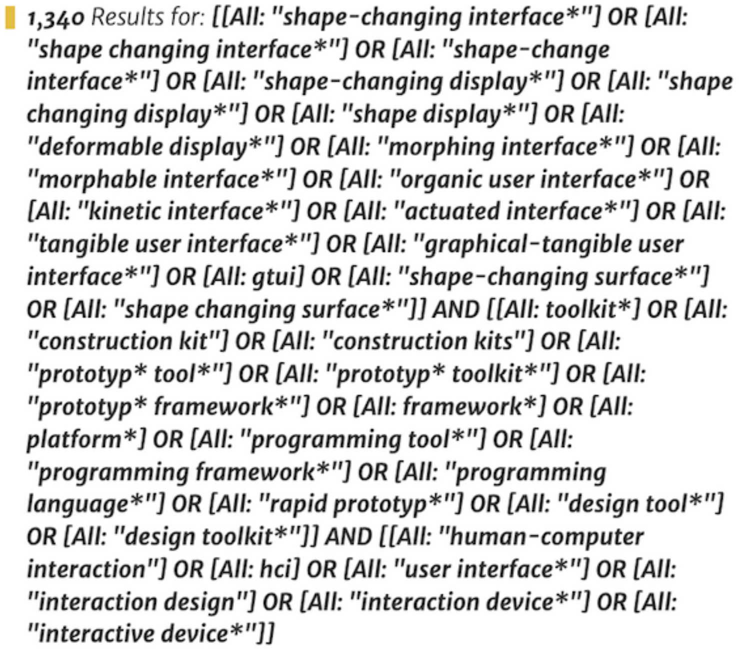
[1] https://www.researchrabbit.ai/, *last accessed 03.2026*



1,340 Results for: [[All: "shape-changing interface*"] OR [All: "shape changing interface*"] OR [All: "shape-change interface*"] OR [All: "shape-changing display*"] OR [All: "shape changing display*"] OR [All: "shape display*"] OR [All: "deformable display*"] OR [All: "morphing interface*"] OR [All: "morphable interface*"] OR [All: "organic user interface*"] OR [All: "kinetic interface*"] OR [All: "actuated interface*"] OR [All: "tangible user interface*"] OR [All: "graphical-tangible user interface*"] OR [All: gtui] OR [All: "shape-changing surface*"] OR [All: "shape changing surface*"]] AND [[All: toolkit*] OR [All: "construction kit"] OR [All: "construction kits"] OR [All: "prototyp* tool*"] OR [All: "prototyp* toolkit*"] OR [All: "prototyp* framework*"] OR [All: framework*] OR [All: platform*] OR [All: "programming tool*"] OR [All: "programming framework*"] OR [All: "programming language*"] OR [All: "rapid prototyp*"] OR [All: "design tool*"] OR [All: "design toolkit*"]] AND [[All: "human-computer interaction"] OR [All: hci] OR [All: "user interface*"] OR [All: "interaction design"] OR [All: "interaction device*"] OR [All: "interactive device*"]]

Figure 3.2: The search string used to identify new literature. Although this screenshot was captured in March 2026, the actual literature search was conducted in January 2026. During the search, 1 341 results were returned for our query, of which 803 were research articles.

3.2.2 Database Search

Expanding the dataset with the database search

To complement the seed paper identification strategy and reduce potential bias, a structured database search was conducted. The purpose of this second step was to broaden the coverage of the literature review and to identify additional works that may not have been captured through the backward/forward snowballing.

The search was performed in the *Association for Computing Machinery* (ACM) Digital Library [2] which is widely recognized as the primary source for peer-reviewed HCI research.

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[2] https://dl.acm.org/, *last accessed 03.2026*

The search string was selected based on the literature and divided into three blocks.

The search string was structured into 3 conceptual blocks, briefly **SCI**, **TOOL**, and **HCI**. It was developed iteratively based on terminology identified during the seed paper analysis in the Subsection 3.2.1 “Initial Step”.

The first block **"SCI"** captured specific terms and synonyms related to SCIs that were found in the literature.

SCI :
("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 second block, **"TOOL"**, targeted terms describing prototyping support, tools, and frameworks.

TOOL :
(toolkit* **OR** "construction kit" **OR** "construction kits" **OR** "prototyp* tool*" **OR** "prototyp* toolkit*" **OR** "prototyp* framework*" **OR** framework* **OR** platform* **OR** "programming tool*" **OR** "programming framework*" **OR** "programming language*" **OR** "rapid prototyp*" **OR** "design tool*" **OR** "design toolkit*")

Lastly, the third block, **"HCI"**, was used to position the search more clearly within the broader HCI context.

HCI :
("human-computer interaction" **OR** HCI **OR** "user interface*" **OR** "interaction design" **OR** "interaction device*" **OR** "interactive device*" **OR** soft robotics)

Searching ACM Digital Library

The search was conducted within the publications by combining the defined blocks without restricting the publication date. We applied a filter to the content type by selecting the "Research article" option. This decision was made to capture early work as well as more recent contributions in this field, while excluding content types such as tutorials, keynotes, demos, or abstracts [Mahmud et al., 2025].

Figure 3.2 shows the search query used to retrieve additional literature during the database search.

Building the search string's logic

The keywords were enclosed in *quotation marks* to ensure they exactly matched the search terms. While the words within the blocks were separated by the Boolean operator *OR*, the 3 blocks were combined using the Boolean operator *AND*. Wildcards like *asterisk* were included where appropriate to capture variations of relevant terms.

Merging the two steps into a dataset and screening it

The initial database search was performed in January 2026 and updated in March 2026. The records retrieved from this search were merged with the candidate publications identified in the seed paper step and then screened according to the eligibility criteria described in the following section.

3.3 Eligibility Criteria

Inclusion and exclusion criteria

To ensure relevance to the research questions, a set of inclusion and exclusion criteria was defined.

Publications were included if they:

- describe a toolkit, framework, or prototyping system related to SCIs,
- present a system intended to support the design or prototyping of shape-changing artifacts,
- describe a fabrication pipeline or modular system that enables SCI development
- were published in peer-reviewed venues such as conferences or journals
- written in English.

Publications were excluded if they:

- were duplicates during the search,

- focus exclusively on shape-changing applications without discussing prototyping support,
- focus on shape-changing materials without an interface or prototyping context,
- describe purely theoretical concepts without implementation,
- describe perception studies or user studies unrelated to prototyping systems
- are short abstracts or non-peer-reviewed publications.

These criteria were applied consistently across all stages of the screening process. Because terminology in this field varies widely, related concepts such as *tangible interfaces, morphing interfaces, soft robotics, jamming interfaces, deformable interfaces* and *programmable materials* were considered.

The eligibility criteria were defined according to the complexity of the field.

3.4 Screening Process

The identification step, in which we combined the candidate publications with the database search, yielded n = 2212 records. After removing (n = 621) duplicates, we started screening our dataset (n = 1491).

First step - title and abstract

The screening process followed a multi-stage approach. First, all publications identified through seed paper snowballing and database search were screened based on titles and abstracts. At this stage, clearly irrelevant records were removed, including publications in artificial intelligence, cognitive engineering, and virtual reality.

Second step - introduction and conclusion

In the second step, the remaining papers were reviewed based on their introduction and conclusion sections to assess whether they addressed prototyping support for SCIs. In this way, we could distinguish between papers that only

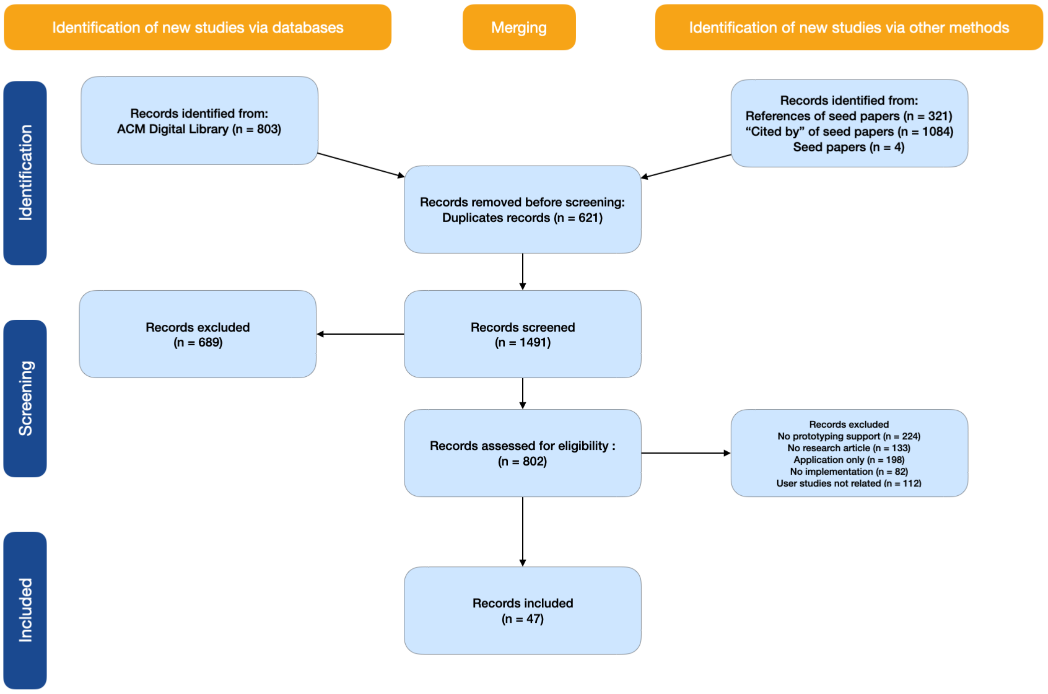

Figure 3.3: The PRISMA flow diagram offers an overview of our corpus collection process. We have adapted this flow chart to reflect the specific methodology we employed. The screening and identification of literature were conducted concurrently.

presented SCI prototypes, applications, and those that contributed reusable tools, systems, frameworks, or fabrication approaches.

Third step - inclusion or exclusion criteria

Finally, the full texts of the remaining publications were examined to determine whether they met the inclusion criteria outlined in Section 3.3 "Eligibility Criteria". During this stage, we could still identify additional relevant publications through backward and forward snowballing if they were strongly connected to the selected papers and aligned with the scope of this thesis. For this task we used *Connected Papers* [3]. This process ensured that the final corpus contained publications that directly address prototyping toolkits, frameworks, or related systems for SCIs. The review process and filtering stages are presented in the PRISMA flow diagram in Figure 3.3.

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[3] https://www.connectedpapers.com/, *last accessed 03.2026*

3.5 Data Extraction and Coding

This section outlines the approach used to examine the included papers in this thesis. Initially, it discusses the process of the literature analysis and the creation of the coding. Subsequently, it elaborates on the various sections of the coding.

Organizing the literature review with a spreadsheet

After the final corpus of 47 publications was selected, each publication was entered into a spreadsheet in *Apple's Numbers* [4] for data extraction and coding. For each publication, we recorded bibliographic data, including authors, year, and venue. We documented details about the toolkit in the next columns, including supported technologies, workflow stages, and the evaluation approach. This approach allowed us to systematically organize and analyze the diverse range of prototyping toolkit papers identified through the review process.

We developed a codebook.

The codebook was developed in an iterative process. At first, we conducted open coding on a subset of the corpus and noted recurring themes related to toolkit characteristics, design-to-fabrication workflow support, and evaluation. These labels were then compared, merged, and refined into code groups that reflect our 3 research questions and the dimensions highlighted in prior work on SCIs and toolkit evaluation in HCI [Alexander et al., 2018; Charmaz, 2006; Ledo et al., 2018; Rasmussen et al., 2012].

We extended the spreadsheet to include the coding groups.

To analyze the final dataset, we extended our spreadsheet with the codes, where each row represents one of the 47 papers in our final corpus and each column represents a specific part of the analysis aligned with our research questions [Garrard, 2020; Lambrichts et al., 2021]. This coding-matrix-based approach enabled us to compare toolkits and identify patterns, trends, and gaps in the literature. The complete coding matrix is provided in Appendix C "Coding Matrix".

For classification and organization, we follow an open-coding process to structure and compare the literature

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[4] https://www.apple.com/de/numbers/, *last accessed 20.01.2026*

[Charmaz, 2006; Lambrichts et al., 2021]. The coding was used to identify recurring themes and characteristics across the selected toolkit papers and to establish connections between the literature and the research questions.

To identify the data necessary to address our research questions, we inspected our collection of literature, bearing in mind the following inquiries:

RQ1: **Actuation Type**, **Scale** and **Target User Group**

Code groups for RQ1

For RQ1, we used coding dimensions derived from recurring distinctions in SCI research, particularly regarding actuation type, system scale, and target users [Rasmussen et al., 2012; Sturdee and Alexander, 2018]. We chose these categories because they capture core characteristics of SCI prototyping systems and could be used to classify the final corpus.

RQ2: **S**upport for the **design-to-fabrication workflow**

Code groups for RQ2

For RQ2, the stages of the design-to-fabrication workflow supported by the toolkits were inspected. We aimed to identify which parts of the prototyping process were addressed and which stages remained less supported. We defined the coding on how each paper described its contribution, with attention to whether the proposed system supported only one particular stage or multiple stages of prototyping. Therefore, the following codes were chosen: Design, Fabrication, and Workflow.

RQ3: **Evaluation Strategies**

Code groups for RQ3

For RQ3, we adopted the evaluation framework proposed by Ledo et al. [2018], who analyzed 68 toolkit papers and identified four primary evaluation strategies. We coded each paper according to the evaluation approaches used in their work: Demonstration, Usage, Technical, and Heuristics.

The codes were refined through repeated comparison across papers, merging similar labels and splitting overly broad ones where necessary. The final codes were then used to aggregate results and structure the analysis in Chapter 4 “Results”. Allowing multiple labels helped us to preserve the complexity of the contributions rather than forcing them into overly narrow categories.

The extracted and coded data form the basis for the descriptive overview presented in Chapter 4 “Results” and the analytical discussion in Chapter 5 “Discussion”. All codes are provided in the codebook attached in Appendix A “Codebook”.

Chapter 4

Results

In this chapter, we present the results of qualitative content analysis by describing the final corpus of publications. In the following sections, we report the outcome of the identification and screening process and then give a brief overview of the dataset. These publications form our coding matrix, which is the basis for the analysis presented in Chapter 5 “Discussion”.

4.1 Review Outcome

47 publications were included for analysis.

After all screening stages were completed, we had a final dataset consisting of 47 publications. They were published between 2008 and 2026 in venues such as the *Conference on Human Factors in Computer Systems* (CHI), the *Conference on Tangible, Embedded, and Embodied Interaction* (TEI), the *ACM Symposium on User Interface Software and Technology* (UIST), the *ACM Conference on Designing Interactive Systems* (DIS), as well as related journals and conferences. This distribution reflects both the strong grounding of SCI prototyping research in HCI venues and the field’s broader multidisciplinary character.

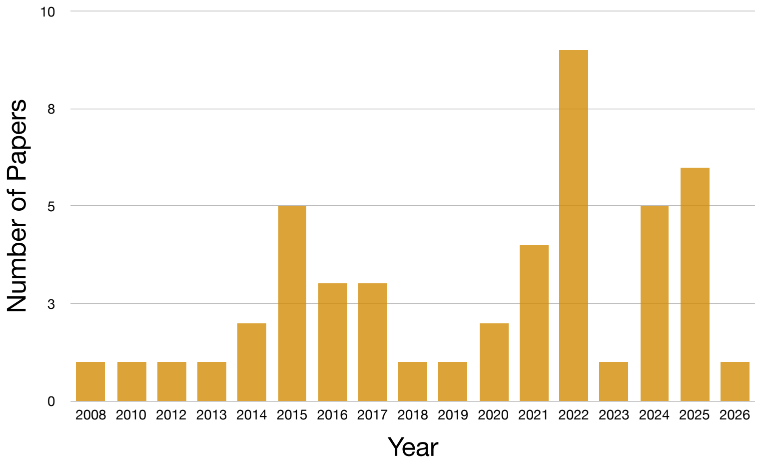

Figure 4.1: The histogram displays the number of prototyping toolkits research papers identified in the literature search over the years. The chart was created with *Apple's Numbers*.

4.2 Publication Over Time

Most papers were published after the year 2014.

Figure 4.1 shows the distribution of papers over time. In the early years of the corpus, there are few papers, while the number of publications increases more clearly from 2014 onward. The strongest concentration appears in recent years, especially between 2021 and 2025. This pattern indicates that prototyping toolkits for SCIs have become a more visible topic over time, although the final corpus represents some part of the whole field.

4.3 Coding Overview

Coding matrix was developed and we allow multi-labeling.

The following coding matrix summarizes the distributions of the codes for the 3 research questions. All codes can be found in Appendix C "Coding Matrix". Because we allowed multi-label coding, we could assign some papers to more than one code within a group. An overview of the code assignments across the final corpus is shown in Table 4.2.

RQ	Groups	Codes and frequency
RQ1	Actuation Type	Smart materials (17), Electromechanical (18), Pneumatic (14), Magnetic (2)
	Scale	Desktop (43), Body (5), Spatial (3)
	Target user group	Designers (30), Non-experts (13), Researchers (26)
RQ2	Design	CAD (17), GUI (13), Simulation (11), Framework (1), Physical (9)
	Fabrication	Manual (18), 3D Printing (10), Modular (14), Laser cutting (9)
	Workflow	Low automation (10), Medium Automation (24), High Automation (12)
RQ3	Evaluation strategies	Demonstrations (17), Technical Performance (23), Usage (22), Heuristics (3)

Table 4.2: Summary of the coded distributions across the final corpus. Because multi-label coding was used, the reported frequencies indicate code assignments rather than mutually exclusive paper counts.

Chapter 5

Discussion

This chapter interprets the results of the literature review in relation to the 3 research questions outlined in Chapter 1 “Introduction”. While Chapter 4 “Results” provided a descriptive overview of our final corpus, we focus here on what the identified patterns mean for the current state of the toolkits for prototyping of SCIs. We discuss how the reviewed toolkits can be classified, which stages of the design-to-fabrication workflow they support, and how they are evaluated. At the end, we address the limitations.

5.1 Classification of Toolkits

SCI field evolves over time and is more researched.

RQ1: What toolkits and frameworks have been proposed for prototyping shape-changing interfaces, and how can they be systematically categorized? The reviewed literature in the coding matrix suggests that SCI prototyping has evolved from rather specific, technically focused systems to more modular, reusable platforms. In the earlier years of our corpus, many contributions were still closely tied to one particular interaction technique. Over time, however, we can see a stronger interest in systems that support variation, reuse, and experimentation across different use cases.

Actuation type is a characteristic used for the classification.

The first important finding concerns actuation. Table 4.2 shows that electromechanical, pneumatic, and smart-material-based actuations dominate the corpus, while magnetic systems appear only rarely. This is not surprising, since these 3 types are already well established in the prior SCI literature. Electromechanical systems such as *ShapeClip* [Hardy et al., 2015], *MorphMatrix* [Dai et al., 2024], or *ThreadTessel* [Zhang et al., 2025] offer a relatively high level of control and precision, but they often come with greater mechanical complexity and a higher implementation effort.

In contrast, smart-material and pneumatic approaches, for example *ANISMA* [Messerschmidt et al., 2022], *MorpheesPlug* [Kim et al., 2021], or *SoftBioMorph* [Nicolae et al., 2024], often support softer, lighter, and sometimes more body-near forms of interaction. This suggests that the material and actuation choices of toolkits are not only technical decisions, but also shape which kinds of interaction become easier to prototype.

Scale is the next coding group which we will use.

The second finding concerns scale. Most systems in the corpus are situated at the desktop level, while body-scale systems appear less often, and spatial systems remain the least common category. We can interpret this as a practical consequence of toolkit development. Desktop systems are easier to fabricate, test, and evaluate within a research setting. On the other side, spatial systems usually require more resources, more space, and more complex infrastructure.

We observe the target user groups.

The third pattern is regarding the target user group. In Table 4.2, we examine a strong orientation towards designers and researchers. This shows that SCI prototyping remains, to a large degree, an expert-oriented activity. Upon reviewing the coding, we noted that more recent papers indicate a shift towards broader accessibility. Toolkits such as *MiuraKit* [Cui et al., 2023], *ThreadTessel* [Zhang et al., 2025], and *Mimosa* [Liu et al., 2024] suggest that educational contexts and less expert-driven forms are becoming available.

In summary, we can categorize prototyping toolkits for SCIs by actuation type, scale, and target user group. It brings more clarity and makes choosing the right toolkit easier. Furthermore, we can examine a limitation. The literature uses many terms for shape-changing interfaces, which makes the search difficult. Therefore, we see our search string as a good start point for further research.

5.2 Support for the Design-to-Fabrication Workflow

RQ2: How do prototyping toolkits for shape-changing interfaces support the design-to-fabrication workflow, and what aspects of this workflow are emphasized or constrained by existing tools?

Toolkits support the early-stage design.

The findings for RQ2 show that current SCI toolkits for prototyping support some parts of the design-to-fabrication workflow quite well, while other parts remain much less developed. Our corpus suggests that many toolkits are strong at supporting early-stage design exploration but weaker at providing fully integrated workflows from concept to final artifact.

A smaller but conceptually important subset of toolkits adopts physical design approaches (coded as Physical/Framework in Appendix C), which prioritize “thinking-through-making” and material-led exploration over digital constraints. These papers emphasize tactile engagement as essential for developing design intuition, particularly through craft practices that reveal material behaviors unavailable in CAD. For example, Parkes and Ishii [2010] describe designers moving from observing modules to directly manipulating raw actuators during a “constructive phase,” while Liu et al. [2024] champion “middle tech” handicraft with SMAs to enable creative personalization. Similarly, Mohindra et al. [2025] encourages “ludic engagement” where designers puppeteer magnets to discover emergent behaviors rather than pursuing high-precision digital control.

This material-driven approach extends to laboratory synthesis as the primary design activity. *SoftBioMorph* [Nicolae et al., 2024] and *Aqua-Morph* [Huang et al., 2025] treat material formulation itself as computation, where shape-changing behavior emerges from bio-polymer or hydro-gel composition rather than geometric modeling. Frameworks such as *Morphees* [Roudaut et al., 2013] provide a theoretical structure through ten “shape resolution” features, while *DisplayFab* [Hanton et al., 2024] identifies fabrication breakpoints to guide sustainable system design.

GUI and CAD have a strong presence.

The first clear result from the coding matrix in Appendix C is the strong presence of design support through graphical user interfaces (GUIs), computer-aided design (CAD)-related tools, and in some cases, simulation. This indicates that toolkit research has increasingly sought to reduce the technical difficulty of prototyping by offsetting some of the complexity with software support [Brocker et al., 2022; Dai et al., 2024; Kim et al., 2021; Yu et al., 2024].

In several papers (*MorpheesPlug* [Kim et al., 2021], *MilliWare* [Yu et al., 2024], *SoRoCAD* [Brocker et al., 2022], *MorphMatrix* Dai et al. [2024]), this takes the form of graphical interfaces, modular design tools, or parametric environments that help users configure motion, structure, or behavior. We can therefore say that one of the strengths of current research on SCI toolkits is that it makes early design decisions more manageable.

We observe different fabrication methods.

From the coding matrix in Appendix C “Coding Matrix”, we could see that the fabrication support is diverse. The corpus includes not only approaches based on molding [Kolvenbag et al., 2022], 3D printing [Everitt and Alexander, 2019], laser cutting [Everitt and Sturdee, 2022], and modular assembly [Otaran et al., 2025], but also new approaches. We reviewed toolkits such as *Electriflow* [Purnendu et al., 2021], which introduces soft electro-hydraulic building blocks for prototyping shape change, *FabricatINK* [Hanton et al., 2022], which works with electronic ink, or *Aqua-Morph* [Huang et al., 2025], which proposes a design method for fabricating hydrogel-based structures. But there is still no clearly dominant fabrication pathway. This suggests that the field still lacks a common workflow structure. This should not necessarily be understood as a weakness. It implies that different materials and fabrication methods are used in the field of SCIs.

We observe the level of workflow automation.

In the review, we examined the workflow automation. Most papers fall into the categories of low or medium automation, while only a smaller number provide highly integrated workflows. This means that users often need to bridge important steps manually, for example, from material preparation to assembly, or from physical construction to interaction programming.

Therefore, we can conclude that prototyping toolkits help with modeling, fabrication, or configuration, but less often with connecting all these stages into a single workflow. SCI toolkit research has made progress in supporting design and fabrication, but it still experiences difficulties with workflow integration.

5.3 Evaluating Strategies

RQ3: How are shape-changing interface prototyping toolkits evaluated in the literature, and what methodological gaps and remaining challenges can be identified for their future development?

We adapt the evaluation strategies of Ledo et al. [2018].

To answer the third research question, this thesis draws on the evaluation framework proposed by Ledo et al. [2018], which presents 4 evaluation strategies. We incorporated them into our coding approach to examine the corpus. The review shows that evaluation of prototyping toolkits in the SCI field remains dominated by demonstrations. Many papers establish the value of a toolkit by showing a range of example artifacts, scenarios, or application fields. This can be seen in early and later work alike, for example, in *Morphees* [Roudaut et al., 2013], *ShapeClip* [Hardy et al., 2015], *ChainFORM* [Nakagaki et al., 2016], *Electriflow* [Purnendu et al., 2021], *MiuraKit* [Cui et al., 2023], and *Robotecture* [Wang et al., 2025], where the toolkit is presented through prototypes that illustrate what kinds of SCIs can be built with it.

Evaluation through different user groups and not only in the research lab.

Usage is another important part of the findings. In several papers, for example *PolySurface* [Everitt and Alexander, 2017], *ShapeKit* [Zhou et al., 2025], *TEX(alive)* [Martinez Castro et al., 2022], toolkits are not only shown in research, but also used by designers, researchers, and DIY makers in workshops or comparative studies. In this way, the evaluation moves beyond technical feasibility, and a discussion could begin on whether the toolkit supports exploration, creativity, or usability in practice.

Trend of combining Usage and Technical performance

Technical performance is the third suggested evaluation strategy that we examined in our review. This is especially apparent in works where the contribution depends heavily on performance, responsiveness, or precision. From our coding matrix, we observe a trend toward combining evaluation strategies, Usage and Technical performance. Early papers like *Morphees* [Roudaut et al., 2013] and *Changibles* [Roudaut et al., 2014] focused on technical feasibility, while recent papers like *ANISMA* [Messerschmidt et al., 2022] and *XRtic* [Muthukumarana et al., 2022] emphasize human-centric metrics using standardized tools like the *Creativity Support Index* (CSI) and the *System Usability Scale* (SUS).

A small number of papers have evaluated heuristics.

Compared with these three evaluation strategies, the fourth type, Heuristics, is only a small subset of the corpus, indicating that a more comprehensive evaluation is possible but not yet standard. We could observe a heuristic as a design rationale in *MorpheesPlug* [Kim et al., 2021]. There, they conducted a user study as an evaluation. From a methodological perspective, this suggests that SCI toolkit evaluations still focus primarily on demonstrating feasibility rather than on building cumulative, comparable evidence across toolkits. While combining usage-based and technical performance measures is becoming more common, there is little work on shared benchmarks, standardized task sets, or heuristics tailored specifically to SCI toolkits. As a result, it remains difficult to systematically compare how different toolkits support creativity, learning, or long-term use.

In summary, the review finds that research on prototyping toolkits places greater emphasis on evaluation. Demonstration remains the dominant strategy, usage-based studies are becoming more common, and technical performance evaluation continues to play a strong role. However, end-user experience remains underexplored.

5.4 Limitations

In this section, we will summarize the limitations.

Modify the search string for IEEE Xplore

The sample size of 47 papers is a relatively small corpus, which may diminish the significance of the statistical results, but it is the basis for further, deeper research. Due to constraints in time and resources typical of a bachelor's thesis, we conducted the database search only in the ACM Digital Library. There, we could find more publications related to our research field than in *IEEE Xplore* [1]. IEEE Xplore is a library with a broader mechanical scope, which could be helpful if the research questions were more focused on material science. We suggest that future researchers modify the given search string when using it there.

There might be errors in the data

Since the analysis was carried out by a single individual, there is a possibility of inaccuracies in the coding of the literature. Despite conducting an organized analysis and coding of the dataset in Section 3.5 "Data Extraction and Coding", there may still be some qualitative imperfections.

We encourage future research to examine evaluation.

In our coding scheme for RQ3, we adopted all four evaluation strategies proposed by Ledo et al. [2018], including heuristics. However, heuristic-based evaluation appears in only a small subset of our corpus (9 papers), mirroring Ledo et al. [2018]'s finding that heuristics are relatively rare in toolkit research. The lack of heuristics tailored to SCI toolkits may represent a methodological gap for future work.

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[1] https://ieeexplore.ieee.org/Xplore/home.jsp, *last accessed 20.03.2026*

Chapter 6

Summary and Future Work

The following chapter presents an overview of this thesis's contributions. Based on our findings, we conclude the thesis by suggesting future research directions.

6.1 Summary and Contributions

Overall summary

The objective of this thesis was to provide an overview of the literature on prototyping toolkits and to inform future research and development. To achieve this, a systematic review of the existing literature was conducted to answer the research questions, outlined in Chapter 1 "Introduction". As methodology, we combined backward and forward snowballing from four key papers with a structured search in the ACM Digital Library. After screening and eligibility assessment, a final corpus of 47 publications was established and analyzed using a coding matrix aligned with the three research questions.

Summary of our findings

We showed in the first part of our research that existing toolkits can be meaningfully positioned along actuation type, scale, and target user group, and that underexplored areas, such as magnetic or large-scale toolkits, exist. Then, we observed that many toolkits strongly support early-stage design, but fully integrated pipelines from design to fabrication and implementation remain rare, leaving some of the prototyping burden on users. Lastly, we found that evaluation practices concentrate on demonstrations and technical performance, with only a minority of studies systematically examining usage over time or with non-expert audiences.

Overall, this thesis contributes a consolidated overview of SCI prototyping toolkits that can serve as a starting point for future work. Researchers, designers, and non-experts can use the classification and coding matrix to locate existing toolkits, identify gaps in actuation or workflow support, and design new toolkits and evaluations that build more directly on prior work.

6.2 Future Work

In this section, we introduce possible future work that may be conducted after this thesis.

Modifying the search string and expanding the corpus

As discussed in Section 5.4 "Limitations", future work could broaden the scope of the review by refining the search string and extending the corpus of relevant publications. In the present review, only one paper was retrieved from IEEE Xplore, which suggests that additional relevant work may exist there. Future reviews should therefore consider including additional databases, particularly IEEE Xplore and other engineering-oriented sources, to capture more research at the intersection of HCI, fabrication, robotics, and materials science. Since SCI research is described using a wide range of terms and concepts, it would also be valuable to continue refining search strings and retrieval strategies for this interdisciplinary field.

Building a web platform for toolkits

Additionally, researchers could build a web platform to collect all prototyping toolkits. In this way, it would be beneficial for all user groups to access it, find the toolkit they need, and see its characteristics [Lambrichts et al., 2021].

Appendix A

Codebook

This appendix provides the full codebook used in our analysis, including all code groups and codes. Tables A.1, A.2, A.3 outline the codes in the identified dataset and their definitions.

RQ1		
Codes	**Frequency**	**Definition**
Actuation Type		
Electromechanical (ELECTR)	18	Toolkits using motors, linear actuators, or pin-based displays
Pneumatic (PNEU)	14	Toolkits based on air pressure, including inflatable structures, soft pneumatic actuators, and vacuum-based jamming interfaces
Smart-materials-based (MATER)	17	Toolkits leveraging smart materials that respond to environmental stimuli
Magnetic (MAGNET)	2	Toolkits using magnetic fields to actuate materials or control magnetic particles for shape change
Scale		
Desktop (DESK)	43	Toolkits for creating small-scale prototypes used on a desk or tabletop, ranging from handheld devices to objects up to approx. 30 cm
On-Body (BODY)	5	Toolkits specifically designed for on-body or wearable SCIs, including haptic devices, smart textiles, and shape-changing accessories
Spatial (SPACE)	3	Toolkits for larger installations or room-scale interfaces that users can walk around or through, exceeding approx. 50 cm
Target User Group		
Designers (DESIG)	30	Interaction designers, industrial designers, or design students with limited technical expertise in electronics or programming
Researchers (RESEA)	26	HCI researchers or academic users exploring interaction paradigms and conducting studies
Non-experts (NONEX)	13	Maker community, DIY-enthusiasts with fabrication skills, or educators

Table A.1: Codes for RQ1

RQ2		
Codes	**Frequency**	**Definition**
Design		
GUI	13	Toolkits offering visual programming environments, block-based interfaces, or graphical design tools
CAD	17	Toolkits integrated with or providing CAD software modeling tools
Simulation (SIMUL)	11	Toolkits that include simulation possibilities for previewing shape-changing behaviors before fabrication
Framework (FRAME)	1	Refers to a theoretical or systematic structure used to guide the design and comparison of interfaces
Physical (PHYS)	9	Indicates that the design process is driven by hands-on experimentation, physical crafting, or laboratory synthesis rather than digital software
Fabrication		
3D Printing (3DPR)	10	Toolkits that rely on additive manufacturing, including 3D printing
Laser cutting (LASER)	9	Toolkits using laser cutters for fabrication of components
Modular (MOD)	14	Toolkits providing modular components that users assemble without custom fabrication
Manual (MAN)	18	Toolkits requiring manual fabrication techniques like sewing, molding
Workflow Gap		
Low Automation (AULOW)	10	Toolkits requiring significant manual intervention, custom fabrication, or expert knowledge
Medium Automation (AUMED)	24	Toolkits providing partial automation, but requiring user decisions and manual fabrication steps
High Automation (AUHIG)	12	Toolkits offering end-to-end automation from design specification to fabrication output

Table A.2: Codes for RQ2

RQ3		
Codes	Quantity	Definition
Evaluation Strategies		
Demonstrations (DEMO)	17	Demonstrations of the toolkit's capabilities by creating an example application or prototype
Usage (USAGE)	22	Evaluated through usage studies where external users create their own prototypes, proving insights into usability
Technical Performance (TECH)	23	Evaluation through technical benchmarks, performance measurements such as actuation speed, force output, or fabrication accuracy
Heuristics (HEURI)	3	Evaluation through expert-driven inspection of the toolkit by using heuristics, checklists, or walkthroughs

Table A.3: Codes for RQ3

Appendix B

Classification of Toolkit Papers

This appendix provides the review matrix created during the review and coding process. Tables B.1, B.2 represent the classification of the SCI prototyping toolkits. The "Toolkit Name" column contains short names for the papers. To make it easier to find the paper, we added a reference to the author. The tables are parts of one table.

ID	Toolkit Name	Year	Authors	Venue	Actuation Type				Scale		
					Smart/Active	Electromech.	Pneumatic	Magnetic	Desktop	Body	Spatial
1	Surflex	2008	Coelho et al. [2008]	CHI	MAT				DESK		
2	Bosu	2010	Parkes and Ishii [2010]	DIS	MAT	ELECTR			DESK		
3	JammingUI	2012	Follmer et al. [2012]	UIST			PNEU		DESK		
4	Morphees	2013	Roudaut et al. [2013]	CHI	MAT				DESK		
5	Changibles	2014	Roudaut et al. [2014]	CHI		ELECTR			DESK		
6	jamSheets	2014	Ou et al. [2014]	TEI			PNEU		DESK		
7	ShapeClip	2015	Hardy et al. [2015]	CHI		ELECTR			DESK		
8	uniMorph	2015	Heibeck et al. [2015]	UIST	MAT				DESK		
9	LineFORM	2015	Nakagaki et al. [2015]	UIST		ELECTR			DESK		
10	Foldio	2015	Olberding et al. [2015]	UIST	MAT				DESK		
11	ChainFORM	2016	Nakagaki et al. [2016]	UIST		ELECTR			DESK		
12	aeroMorph	2016	Ou et al. [2016]	UIST			PNEU		DESK	BODY	
13	xPrint	2016	Wang et al. [2016]	CHI	MAT		ELECTR		DESK		
14	Living Hinges	2017	Jensen et al. [2017]	ICED	MAT				DESK		
15	PolySurface	2017	Everitt and Alexander [2017]	DIS		ELECTR	PNEU		DESK		
16	f3.js	2017	Kato and Goto [2017]	DIS		ELECTR			DESK		
17	ShapeMe	2018	Wessely et al. [2018]	UIST	MAT				DESK		
18	MorphIO	2019	Nakayama et al. [2019]	DIS			PNEU		DESK		
19	LiftTiles	2020	Suzuki et al. [2020]	TEI			PNEU				SPACE
20	NURBSforms	2020	Tahouni et al. [2020]	TEI	MAT				DESK		
21	MorpheesPlug	2021	Kim et al. [2021]	CHI			PNEU		DESK		
22	Magnetform	2021	Yehoshua Wald and Zuckerman [2021]	TEI		ELECTR		MAGNE	DESK		
23	Electriflow	2021	Purnendu et al. [2021]	DIS	MAT		PNEU		DESK		
24	PneuSeries	2021	Chen et al. [2021]	UIST			PNEU		DESK		
25	ANISMA	2022	Messerschmidt et al. [2022]	CHI	MAT					BODY	
26	ElectriPop	2022	Fang et al. [2022]	CHI	MAT				DESK		
27	FabricatINK	2022	Hanton et al. [2022]	CHI	MAT				DESK		
28	SupportingProto	2022	Everitt and Sturdee [2022]	TEI		ELECTR			DESK	BODY	
29	TEX(alive)	2022	Martinez Castro et al. [2022]	DIS			PNEU		DESK		
30	Rapid Proto Dynamic Fiber	2022	Kolvenbag et al. [2022]	UIST	MAT				DESK		
31	ReFlex	2022	Müller et al. [2022]	AVI		ELECTR			DESK		
32	STRAIDE	2022	Engert et al. [2022]	CHI		ELECTR					SPACE
33	SoRoCAD	2022	Brocker et al. [2022]	CHI			PNEU		DESK		
34	XRtic	2022	Muthukumarana et al. [2022]	IEEE	MAT					BODY	
35	MiuraKit	2023	Cui et al. [2023]	DIS			PNEU		DESK		
36	MorphMatrix	2024	Dai et al. [2024]	TEI		ELECTR			DESK		
37	DisplayFab	2024	Hanton et al. [2024]	CHI							
38	MilliWare	2024	Yu et al. [2024]	CHCHI			PNEU		DESK		
39	Mimosa	2024	Liu et al. [2024]	TEI	MAT				DESK		
40	SoftBioMorph	2024	Nicolae et al. [2024]	DIS			PNEU		DESK		
41	Aqua-Morph	2025	Huang et al. [2025]	TEI	MAT				DESK		
42	Magnetic Primitive	2025	Mohindra et al. [2025]	DIS				MAGNE	DESK		
43	Robotecture	2025	Wang et al. [2025]	TEI		ELECTR			DESK		SPACE
44	Shape-Kit	2025	Zhou et al. [2025]	CHI		ELECTR			DESK	BODY	
45	SparselyAct	2025	Otaran et al. [2025]	TEI		ELECTR			DESK		
46	ThreadTessel	2025	Zhang et al. [2025]	TEI		ELECTR			DESK		
47	Rapid Prototyping Studio	2026	Youn et al. [2026]	TEI	MAT	ELECTR			DESK		

Table B.1: Coding matrix for RQ1 showing actuation type and scale across the final corpus. Continue on the next page.

ID	Toolkit Name	Year	Authors	Venue	Target User Group		
					Designers	Researchers	Non-experts
1	Surflex	2008	Coelho et al. [2008]	CHI	DESIG		
2	Bosu	2010	Parkes and Ishii [2010]	DIS	DESIG		
3	JammingUI	2012	Follmer et al. [2012]	UIST		RESEA	
4	Morphees	2013	Roudaut et al. [2013]	CHI	DESIG	RESEA	
5	Changibles	2014	Roudaut et al. [2014]	CHI		RESEA	
6	jamSheets	2014	Ou et al. [2014]	TEI		RESEA	
7	ShapeClip	2015	Hardy et al. [2015]	CHI	DESIG	RESEA	
8	uniMorph	2015	Heibeck et al. [2015]	UIST		RESEA	
9	LineFORM	2015	Nakagaki et al. [2015]	UIST		RESEA	
10	Foldio	2015	Olberding et al. [2015]	UIST	DESIG	RESEA	
11	ChainFORM	2016	Nakagaki et al. [2016]	UIST	DESIG		NONEX
12	aeroMorph	2016	Ou et al. [2016]	UIST	DESIG	RESEA	
13	xPrint	2016	Wang et al. [2016]	CHI	DESIG	RESEA	NONEX
14	Living Hinges	2017	Jensen et al. [2017]	ICED	DESIG		
15	PolySurface	2017	Everitt and Alexander [2017]	DIS	DESIG		
16	f3.js	2017	Kato and Goto [2017]	DIS	DESIG		
17	ShapeMe	2018	Wessely et al. [2018]	UIST	DESIG		NONEX
18	MorphIO	2019	Nakayama et al. [2019]	DIS	DESIG	RESEA	
19	LiftTiles	2020	Suzuki et al. [2020]	TEI	DESIG	RESEA	
20	NURBSforms	2020	Tahouni et al. [2020]	TEI	DESIG	RESEA	
21	MorpheesPlug	2021	Kim et al. [2021]	CHI	DESIG		NONEX
22	Magnetform	2021	Yehoshua Wald and Zuckerman [2021]	TEI	DESIG		
23	Electriflow	2021	Purnendu et al. [2021]	DIS	DESIG	RESEA	
24	PneuSeries	2021	Chen et al. [2021]	UIST		RESEA	
25	ANISMA	2022	Messerschmidt et al. [2022]	CHI		RESEA	
26	ElectriPop	2022	Fang et al. [2022]	CHI	DESIG		
27	FabricatINK	2022	Hanton et al. [2022]	CHI			NONEX
28	SupportingProto	2022	Everitt and Sturdee [2022]	TEI	DESIG	RESEA	NONEX
29	TEX(alive)	2022	Martinez Castro et al. [2022]	DIS	DESIG		
30	Rapid Proto Dynamic Fiber	2022	Kolvenbag et al. [2022]	UIST		RESEA	
31	ReFlex	2022	Müller et al. [2022]	AVI		RESEA	
32	STRAIDE	2022	Engert et al. [2022]	CHI		RESEA	
33	SoRoCAD	2022	Brocker et al. [2022]	CHI		RESEA	NONEX
34	XRtic	2022	Muthukumarana et al. [2022]	IEEE		RESEA	
35	MiuraKit	2023	Cui et al. [2023]	DIS	DESIG		NONEX
36	MorphMatrix	2024	Dai et al. [2024]	TEI	DESIG		
37	DisplayFab	2024	Hanton et al. [2024]	CHI			NONEX
38	MilliWare	2024	Yu et al. [2024]	CHCHI	DESIG	RESEA	
39	Mimosa	2024	Liu et al. [2024]	TEI	DESIG		NONEX
40	SoftBioMorph	2024	Nicolae et al. [2024]	DIS	DESIG		NONEX
41	AquaMorph	2025	Huang et al. [2025]	TEI	DESIG	RESEA	
42	Magnetic Primitive	2025	Mohindra et al. [2025]	DIS	DESIG		
43	Robotecture	2025	Wang et al. [2025]	TEI	DESIG	RESEA	
44	Shape-Kit	2025	Zhou et al. [2025]	CHI	DESIG		
45	SparselyAct	2025	Otaran et al. [2025]	TEI	DESIG		
46	ThreadTessel	2025	Zhang et al. [2025]	TEI	DESIG		NONEX
47	Rapid Prototyping Studio	2026	Youn et al. [2026]	TEI	DESIG		NONEX

Table B.2: Coding matrix for RQ1 showing target user groups across the final corpus.

Appendix C

Coding Matrix

This appendix presents the full code matrix, which includes all 47 papers and the 3 research questions.

ID	Paper	Year	Venue	Actuation Type	Scale	Target User Group
1	Surflex	2008	CHI	MAT	DESK	DESIG
2	Bosu	2010	DIS	MAT/ELECTR	DESK	DESIG
3	Jamming UI	2012	UIST	PNEU	DESK	RESEA
4	Morphees	2013	CHI	MAT	DESK	RESEA/DESIG
5	Changibles	2014	CHI	ELECTR	DESK	RESEA
6	jamSheets	2014	TEI	PNEU	DESK	RESEA
7	ShapeClip	2015	CHI	ELECTR	DESK	DESIG/RESEA
8	uniMorph	2015	UIST	MAT	DESK	RESEA
9	LineFORM	2015	UIST	ELECTR	DESK	RESEA
10	Foldio	2015	UIST	MAT	DESK	RESEA/DESIG
11	ChainFORM	2016	UIST	ELECTR	DESK	NONEX/DESIG
12	aeroMorph	2016	UIST	PNEU	DESK/BODY	DESIG/RESEA
13	xPrint	2016	CHI	ELECTR/PNEU	DESK	NONEX/RESEA/DESIG
14	Living Hinges	2017	ICED	MAT	DESK	DESIG
15	PolySurface	2017	DIS	ELECTR	DESK	DESIG
16	f3.js	2017	DIS	ELECTR	DESK	DESIG
17	ShapeMe	2018	UIST	MAT	DESK	NONEX/RESEA
18	MorphIO	2019	DIS	PNEU	DESK	DESIG/RESEA
19	LiftTiles	2020	TEI	PNEU	SPACE	DESIG/RESEA
20	NURBSforms	2020	TEI	MAT	DESK	DESIG/RESEA
21	MorpheesPlug	2021	CHI	PNEU	DESK	DESIG/NONEX
22	Magnetform	2021	TEI	MAGNET/ELECTR	DESK	DESIG
23	Electriflow	2021	DIS	MAT/PNEU	DESK	RESEA/DESIG
24	PneuSeries	2021	UIST	PNEU	DESK	RESEA
25	ANISMA	2022	CHI	MAT	BODY	RESEA
26	ElectriPop	2022	CHI	MAT	DESK	DESIG
27	FabricatINK	2022	CHI	MAT	DESK	NONEX
28	Supporting Prototyping	2022	TEI	ELECTR	DESK/BODY	DESIG/RESEA/NONEX
29	TEX(alive)	2022	DIS	PNEU	DESK	DESIG
30	Rapid Fibers	2022	UIST	MAT	DESK	RESEA
31	ReFlex	2022	AVI	ELECTR	DESK	RESEA
32	STRAIDE	2022	CHI	ELECTR	SPACE	RESEA
33	SoRoCAD (2022)	2022	CHI	PNEU	DESK	RESEA/NONEX
34	XRtic	2022	IEEE	MAT	BODY	RESEA
35	MiuraKit	2023	DIS	PNEU	DESK	NONEX/DESIG
36	MorphMatrix	2024	TEI	ELECTR	DESK	DESIG
37	DisplayFab	2024	CHI			NONEX
38	milliWare	2024	CHCHI	PNEU	DESK	DESIG/RESEA
39	Mimosa	2024	TEI	MAT	DESK	DESIG/NONEX
40	SoftBioMorph	2024	DIS	PNEU	DESK	DESIG/NONEX
41	Aqua-Morph	2025	TEI	MAT	DESK	DESIG/RESEA
42	Mag. Primitive	2025	DIS	MAGNET	DESK	DESIG
43	Robotecture	2025	TEI	ELECTR	SPACE/DESK	RESEA/DESIG
44	Shape-Kit	2025	CHI	ELECTR	BODY/DESK	DESIG
45	Sparsely Actuated	2025	TEI	ELECTR	DESK	DESIG
46	ThreadTessel	2025	TEI	ELECTR	DESK	DESIG/NONEX
47	MeshModule	2026	TEI	MAT/ELECTR	DESK	DESIG/NONEX

Table C.1: RQ1 coding matrix for the final corpus, including actuation type, scale, and target user group.

ID	Paper	Year	Venue	Design	Fabrication	Workflow
1	Surflex	2008	CHI	CAD	MAN	AULOW
2	Bosu	2010	DIS	PHYS	MOD / MAN	AULOW
3	Jamming UI	2012	UIST	GUI	MAN	AUMED
4	Morphees	2013	CHI	FRAME	MAN	AULOW
5	Changibles	2014	CHI	SIMUL	MOD	AUMED
6	jamSheets	2014	TEI	PHYS	MAN	AULOW
7	ShapeClip	2015	CHI	GUI	MOD	AUHIG
8	uniMorph	2015	UIST	CAD	MAN	AUMED
9	LineFORM	2015	UIST	SIMUL	MOD	AUMED
10	Foldio	2015	UIST	CAD	3DPR / LASER	AUHIG
11	ChainFORM	2016	UIST	GUI	MOD	AUHIG
12	aeroMorph	2016	UIST	SIMUL	MAN	AUMED
13	xPrint	2016	CHI	CAD	3DPR	AUHIG
14	Living Hinges	2017	ICED	SIMUL	LASER	AUMED
15	PolySurface	2017	DIS	CAD	LASER	AUMED
16	f3.js	2017	DIS	GUI / CAD	LASER	AUHIG
17	ShapeMe	2018	UIST	CAD	MAN	AUHIG
18	MorphIO	2019	DIS	GUI	MAN	AUMED
19	LiftTiles	2020	TEI	GUI	MOD	AUMED
20	NURBSforms	2020	TEI	PHYS	MOD	AUMED
21	MorpheesPlug	2021	CHI	CAD	3DPR	AUHIG
22	Magnetform	2021	TEI	GUI	MOD	AUMED
23	Electriflow	2021	DIS	CAD / SIMUL	MAN	AUMED
24	PneuSeries	2021	UIST	PHYS	MOD	AUMED
25	ANISMA	2022	CHI	SIMUL	3DPR / MAN	AUHIG
26	ElectriPop	2022	CHI	SIMUL	LASER	AUHIG
27	FabricatINK	2022	CHI	CAD	LASER	AUMED
28	Supporting Prototyping	2022	TEI	CAD	LASER	AULOW
29	TEX(alive)	2022	DIS	GUI / CAD	3DPR	AUMED
30	Rapid Fibers	2022	UIST	PHYS	MAN	AULOW
31	ReFlex	2022	AVI	GUI	MAN	AUMED
32	STRAIDE	2022	CHI	GUI	LASER	AUMED
33	SoRoCAD	2022	CHI	CAD	MAN	AUHIG
34	XRtic	2022	IEEE	PHYS	MOD	AUMED
35	MiuraKit	2023	DIS	SIMUL	MOD	AUMED
36	MorphMatrix	2024	TEI	GUI / SIMUL	3DPR / LASER	AUHIG
37	DisplayFab	2024	CHI			
38	milliWare	2024	CHCHI	CAD / SIMUL	3DPR	AUHIG
39	Mimosa	2024	TEI	GUI	MOD / MAN	AULOW
40	SoftBioMorph	2024	DIS	PHYS	MAN	AULOW
41	Aqua-Morph	2025	TEI	CAD	3DPR	AUMED
42	Mag. Primitive	2025	DIS	PHYS	MAN	AULOW
43	Robotecture	2025	TEI	CAD	MOD	AUMED
44	Shape-Kit	2025	CHI	GUI	MOD	AUMED
45	Sparsely Actuated	2025	TEI	SIMUL	3DPR	AUMED
46	ThreadTessel	2025	TEI	PHYS	MAN	AULOW
47	MeshModule	2026	TEI	CAD	3DPR	AUMED

Table C.2: RQ2 coding matrix for the final corpus, including design support, fabrication, and workflow integration.

ID	Paper	Year	Venue	Evaluation Strategy
1	Surflex	2008	CHI	DEMO
2	Bosu	2010	DIS	USAGE
3	Jamming UI	2012	UIST	TECH / DEMO
4	Morphees	2013	CHI	TECH / HEURI
5	Changibles	2014	CHI	DEMO
6	jamSheets	2014	TEI	TECH
7	ShapeClip	2015	CHI	USAGE
8	uniMorph	2015	UIST	TECH / DEMO
9	LineFORM	2015	UIST	DEMO
10	Foldio	2015	UIST	DEMO / TECH
11	ChainFORM	2016	UIST	DEMO
12	aeroMorph	2016	UIST	TECH / DEMO
13	xPrint	2016	CHI	USAGE
14	Living Hinges	2017	ICED	TECH / USAGE
15	PolySurface	2017	DIS	USAGE
16	f3.js	2017	DIS	USAGE
17	ShapeMe	2018	UIST	USAGE / TECH
18	MorphIO	2019	DIS	DEMO / USAGE / TECH
19	LiftTiles	2020	TEI	DEMO
20	NURBSforms	2020	TEI	DEMO
21	MorpheesPlug	2021	CHI	USAGE / HEURI
22	Magnetform	2021	TEI	USAGE
23	Electriflow	2021	DIS	TECH / DEMO
24	PneuSeries	2021	UIST	TECH / DEMO
25	ANISMA	2022	CHI	USAGE / TECH
26	ElectriPop	2022	CHI	USAGE
27	FabricatINK	2022	CHI	TECH
28	Supporting Prototyping	2022	TEI	DEMO / TECH
29	TEX(alive)	2022	DIS	USAGE
30	Rapid Fibers	2022	UIST	TECH
31	ReFlex	2022	AVI	TECH
32	STRAIDE	2022	CHI	USAGE / TECH
33	SoRoCAD	2022	CHI	TECH
34	XRtic	2022	IEEE	USAGE / TECH
35	MiuraKit	2023	DIS	USAGE
36	MorphMatrix	2024	TEI	USAGE
37	DisplayFab	2024	CHI	
38	milliWare	2024	CHCHI	TECH
39	Mimosa	2024	TEI	USAGE / HEURI
40	SoftBioMorph	2024	DIS	DEMO
41	Aqua-Morph	2025	TEI	USAGE / TECH
42	Mag. Primitive	2025	DIS	DEMO
43	Robotecture	2025	TEI	DEMO
44	Shape-Kit	2025	CHI	USAGE
45	Sparsely Actuated	2025	TEI	TECH
46	ThreadTessel	2025	TEI	USAGE / TECH
47	MeshModule	2026	TEI	USAGE

Table C.3: RQ3 coding matrix for the final corpus, including evaluation strategies.

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