STRAIDE: A Research Platform for Shape-Changing Spatial Displays based on Actuated Strings

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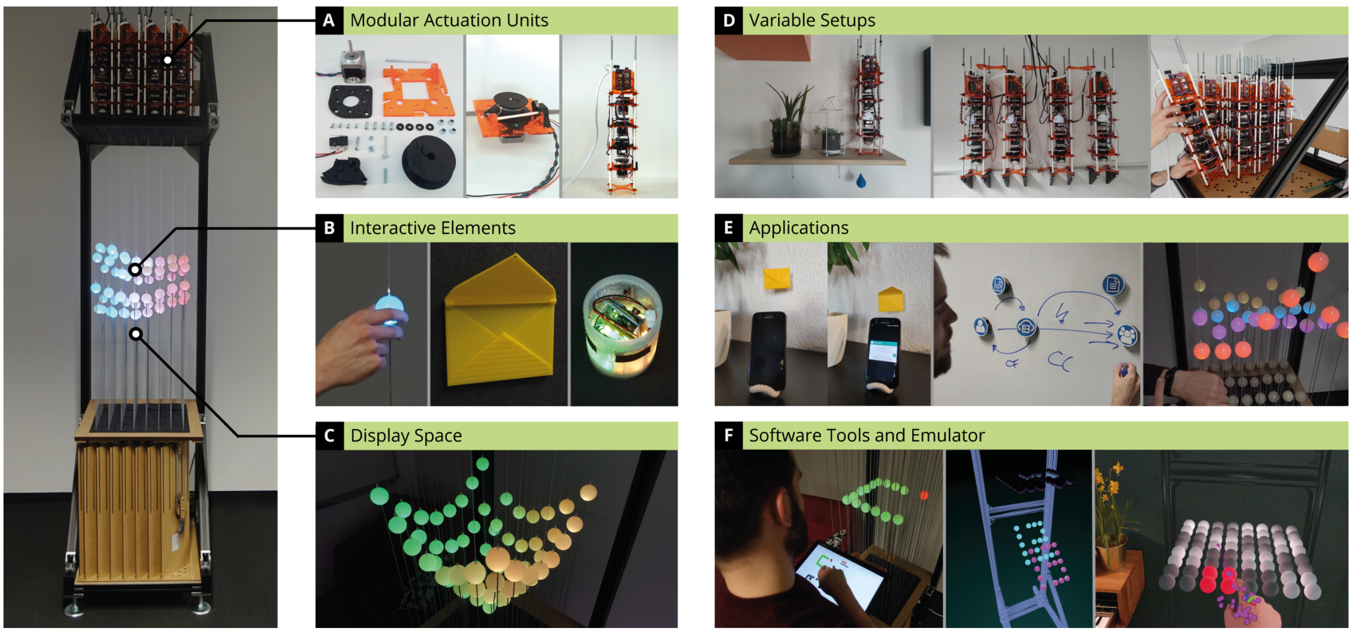

Figure 1: STRAIDE comprises modular actuation units (A) that actuate a variety of passive or (inter)active elements (B) to create casual visualizations in mid-air (C). The actuators are arranged in different setups (D) to enable situated applications with an increasing number of elements (E) ranging from ambient notifications to visual storytelling to casual information visualization. A set of supplementary software tools (F) reduces the effort of application development.

ABSTRACT

We present STRAIDE, a string-actuated interactive display environment that allows to explore the promising potential of shape-changing interfaces for casual visualizations. At the core, we envision a platform that spatially levitates elements to create dynamic visual shapes in space. We conceptualize this type of tangible mid-air display and discuss its multifaceted design dimensions. Through a design exploration, we realize a physical research platform with adjustable parameters and modular components. For conveniently designing and implementing novel applications, we provide developer tools ranging from graphical emulators to in-situ augmented reality representations. To demonstrate STRAIDE's reconfigurability, we further introduce three representative physical setups as a basis for situated applications including ambient notifications, personal smart home controls, and entertainment. They serve as a technical validation, lay the foundations for a discussion with developers that provided valuable insights, and encourage ideas for future usage of this type of appealing interactive installation.

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CCS CONCEPTS

• **Human-centered computing** → **User interface toolkits**; *Interaction devices*; *Visualization systems and tools*; • **Hardware** → *Emerging interfaces*.

KEYWORDS

Prototyping Platform, Spatial Display, Shape-Changing Interface, Tangible Interaction, Casual Visualization, Data Physicalization

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1 INTRODUCTION

Emerging smart technologies and ambient intelligence seamlessly *"weave themselves into the fabric of everyday life"* [86] as they provide situated, ubiquitous, and personalized digital services. This development is driven by research [72] investigating novel approaches that go beyond established graphical user interfaces by exploring qualities like aesthetic appearance, calmness, or tangibility. In this direction, a variety of shape-changing interfaces (SCI) has been developed in the past 20 years to embody digital information [75]. They suit research exploration of tangible and situated visualizations in everyday spaces. One particular class of SCIs are pin-arrays [20, 48] which extend familiar two-dimensional (2D) graphics and visualizations into the three-dimensional (3D) realm by computationally controlling the height of individual pins. This is used for functional or hedonic use cases [64], like 3D information visualization and education, or entertainment and interior design. Their inherently three-dimensional data representations are often directly manipulable resulting in a multi-sensory perception [32]. Therefore, such shape-changing displays (SCD) improve the mediation of data, and additional interactive capabilities (like mid-air gestures [48]) yield such systems to become fully functional user interfaces in the future. However, most SCD prototypes are heavy and complex systems [2] that are mostly presented in showrooms. Their fixed setup limits the rapid exploration of shape-changing visualizations in situated use cases. In contrast, we are inspired by the flexibility and appearance of string-based installations [5, 28, 80] and similar kinetic art works [74]. A system of individual winches [87] can be used to control the vertical position of elements with extensive strokes. Enhancing these fascinating mid-air visualizations by direct interaction with each element could make for promising user interfaces in personal and situated use cases [40].

With this work, we introduce STRAIDE, a **Str**ing-**A**ctuated **I**nteractive **D**isplay **E**nvironment (see Figure 1). Our main goal is to foster prototyping of interactive spatial displays for situated physical visualizations in everyday spaces. Therefore, we introduce a platform that incorporates modular hardware components and a set of software tools, which reduce the effort in implementing shape-changing applications on custom physical setups. Designers can freely pick a subset of interactive elements, mountings, and arrangements to realize their vision. STRAIDE utilizes string-based actuators (Figure 1A) to lift objects in mid-air, which enable significantly larger strokes and simplified construction compared to state-of-the-art pin-arrays. A variety of passive, e.g., everyday objects, or specifically crafted (inter)active elements with additional output and input modalities (Figure 1B) are used as primitives for visualizations. By individual actuation, the elements form illusions of collective shapes in mid-air which enable the creation of dynamically animated, simple, iconographic, or abstract visualizations (Figure 1C).

To empower the community in building shape-changing applications using such setups, we validate a set of design parameters by conducting technical experiments to achieve a cost-effective and modular hardware setup. For its construction, we rely on digital fabrication methods that can be easily manufactured in FabLabs. To ease programming, we developed software tools (Figure 1F) that enable simple control and emulation of this hardware and facilitate the exploration of applications that employ shape-change. These include easy-to-use libraries in different programming languages, a sketching application for creative content creation, emulators for remote development, and in-situ Augmented Reality (AR) representations. In line with Ledo et al. [43], we evaluated the hardware of our research platform by demonstration and its software by usage. Therefore, we explored several setups (Figure 1D) ranging from individual actuated elements to a linear arrangement to an 8×8 matrix with 64 illuminated elements. They facilitate casual applications for everyday use [42] (Figure 1E) like ambient notifications, personal smart home controls, and entertainment applications. Furthermore, a team of external developers evaluated our software tools in a semester-long project.

In summary, the main contributions of this paper are:

- **Design considerations:** Adapting the concept of string-actuated spatial displays for dynamic and situated physical visualizations in everyday spaces.
- The **physical realization** of an **open research platform**, called STRAIDE, that allows to built various instances of tangible mid-air displays with custom elements in variable arrangements.
- A suite of **developer tools** to ideate projects with an easy-to-use visual designer, implement applications with a powerful platform emulator, and experience in-situ AR representations.
- A set of **implemented real-world applications** using three representative physical setups with multifaceted design parameters in different contexts.
- **Insights and lessons learned** from our iterative development process and feedback from application developers confirming our hardware's feasibility and the usefulness of our software tools.

2 RELATED WORK

STRAIDE aims at modular spatial interfaces with elements that can be freely arranged within a versatile display space. To create visualizations, each element is individually actuated from above. Therefore, our work relates to *data visualization in the physical world* (2.1), *shape-changing & mid-air interfaces* (2.2) as well as contributes to current *research challenges* (2.3) in designing and building dynamic and situated shape-changing displays.

2.1 Data Visualization in the Physical World

The emerging research field of *data physicalization* explores how data can be *embedded* into objects or *situated* in a specific context using physical representations [14, 88]. Physical data visualizations have been classified along different characteristics, such as passive or active physical visualizations, and interactive installations [5–7] (see Dragicevic and Jansen's overview of examples [13]). Driven by the advances in digital fabrication methods, a series of research explored how 3D-printed and laser-cut models can be used to create passive visualization artifacts (e.g., physical bar charts [31] or sculptures of shape and time [89]). To support more collaborative interactions, building blocks have been used for calendars, polls [51], travel and activity logging [24] as well as storytelling [33]. In addition, dynamic physicalizations build on digitally actuated tangible mechanisms to support shape changes in real-time. Such approaches have been applied, for example, in slow exercising feedback [53], shared [68] or embodied [90] data sculptures, actuated physical charts [51] as well as in many forms of shape-changing interfaces [30, 32, 64]. Taking inspiration from this body of previous research on data physicalizations, STRAIDE is set between specific or small-sized applications and large-scale art installations to provide situated and dynamic visualizations in personal and everyday spaces.

2.2 Shape-Changing & Mid-Air Interfaces

STRAIDE follows the idea of a shape-changing interface in which digital data is linked to its physical properties [39] so that users can directly interact with tangible representations of information. Following the classification by Rasmussen et al. [64], shape-changing interfaces showcase a variety of properties that can be computationally controlled, e. g., the orientation [82], volume, texture [20], viscosity [19], or spatiality [5]. The category of texture-changing SCIs is the most popular [64], also called 2.5D displays. These devices alter the height of individual display elements using electromechanical, fluid-based, magnetic, or smart material actuators [79]. They can visualize rough approximations of three-dimensional shapes building on the concept of imagined physics [59]. Their primary 2.5D output in the form of the individual elements' height is extended by additional color information supplied by projectors (Relief [47], inFORM [20]), embedded LEDs (Emerge [78], ShapeClips [27]), or Augmented and Virtual Reality (Sublimate [46], SCI+AR [50]). Such secondary output will be considered and extended in STRAIDE's design rationale.

Another related research area investigates mid-air interfaces, which elevate particles or objects in mid-air by employing magnetic [44], acoustic [61, 70], or air flow [3, 22] levitation. Next to the position of the individual flying elements, size [21], rotation [67], color [83], or connected structures [55] are used as the prime visual output. We aim for a similar appearance without the complex actuation of levitation while still altering the individual positions of elements to form three-dimensional shapes in mid-air. Inspired by predominantly artistic installations, we instead utilize a string-based actuation from above for situated visualizations in everyday spaces. Previous work from companies like greyworld [26], ART+COM Studios [5–7], WHITEvoid [87], TAIT [80], Hypersonic [28], and sosolimited [74] showcased versatile and flexible actuation mechanisms with simple elegance.

Overall, STRAIDE takes advantage of convenient properties from all three previously mentioned categories of devices. We apply the simple and thus cost-effective (≈ 40€/element) actuation mechanism of string-based art installations. It differs from state-of-the-art SCDs [20, 47, 78] to drastically increase stroke lengths ($> 1m$) while maintaining similar vertical accuracy ($\approx 0.3mm$ step height). To create a comprehensive user interface with elevated elements in mid-air, we further extend this string-based approach with a variety of additional features like interactive or shape-changing elements. Similar to individual winches for string-based art installations [87], STRAIDE enables free arrangement of modular actuators which was rarely demonstrated in shape-changing interfaces [27] by now.

In previous work, functional and hedonic use cases [64] have been explored that inspire our application development. Shape-changing displays are predominantly used to showcase functional applications, e.g., for 3D information visualization (Relief [47], Emerge [78], ShapeClip [27]), productivity (inFORM [20], SensaBubble [71]), education (ZeroN [44], Sublimate [46]), or physical telepresence (inFORM [45]). Hedonic or similar artistic usage is present in art pieces (Aegis Hyposurface [23], ART+COM Studios [5]), interior objects (ActuEater [56], LiftTiles [76]), or stage lighting (Kinetic Lights [87]). As we aim to support the exploration of functional and hedonic use cases similar to the ones previously explored, both aspects will guide our design rationale and the subsequent application development. Our flexible and adaptable setup will further allow to explore an even broader range of applications in the future as the hardware itself can be matched to a specific context.

2.3 Challenges in 2.5D Display Development

Our work relates to four of the grand challenges in shape-changing interface research as stated by Alexander et al. [2]: As most shape-changing interfaces are unique and complex prototypes, one major technological challenge is the development of *modular toolkits*. Rapid prototyping could reduce the effort required to develop such novel devices. One solution could be the exploration of the smallest possible building blocks for the construction of dynamic physicalizations [8, 25, 27, 41, 63]. Alternatively, prototypes can be constructed as actuation platforms with the possibility to add custom elements specific for a certain use case [57].

Recent technological advances and miniaturization (e.g., in WiFi-capable microchips, battery technology, or soft mechanics) enable the integration of mechanical and electronic components for direct input and extended visual [1], tactile [58], or auditory [10] output. Respective embedded features would be in line with the challenge for incorporating *additional I/O modalities* directly into shape-changing interfaces [2].

Apart from modular hardware, easy-to-use *end-user programming* tools were demanded by Alexander et al. In contrast to predominant programming that is closely tied to the specifications of the underlying hardware, they should foster rapid prototyping and include non-domain experts into the process (cf. PolySurface [16]). Therefore, we will provide a set of novel tools that simplify the ideation, prototyping, and implementation of applications for STRAIDE-based instantiations.

Finally, carefully considering the *aesthetics* of the physical instance itself and respective applications is important throughout the development. An appealing look, such as shown by TRANSFORM [29] or BreakingWave [28], engages the viewer and improves the overall user experience.

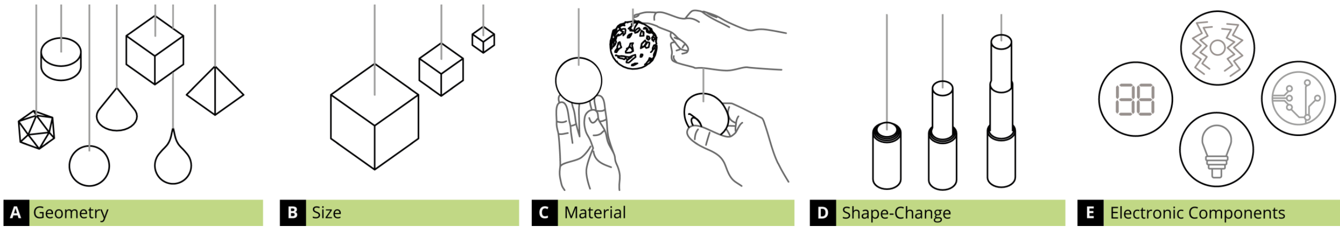

Figure 2: Display elements can differ in their geometry (A), size (B) as well as material, texture, and other haptic properties (C). In addition, shape-changing capabilities (D) as well as further electronic components (E) (e.g., touch input, vibrotactile feedback, displays, and illumination) can be integrated.

3 STRAIDE DESIGN RATIONALE

While proprietary solutions for string-based actuation exist [5, 7, 26, 28, 87], such systems are rarely used in the field of human-computer interaction [65, 69] and never as an interface with direct input capabilities. Therefore, STRAIDE facilitates research of situated shape-changing applications. It employs the *spatiality* type of shape-change [64] by having visual primitives that form 3D shapes, iconographic symbols, and dynamic animations in mid-air. These interchangeable objects can be both passive and (inter)active to enrich visualizations with additional output and input. We further envision custom arrangements of the visual primitives and their actuators to adapt each instance to a specific use case. To guide our technical design exploration, we will first break down the design parameters of such spatial interfaces by considering *interactive display elements* (3.1) and discussing their potential *assemblies* (3.2). Furthermore, we elaborate on promising *visualizations* (3.3) and possible *types of interactions* (3.4).

3.1 Interactive Display Elements

STRAIDE creates visualizations by arranging individual elements in mid-air. These primitives may vary along multiple dimensions to facilitate different use cases and their requirements (see Figure 2). Passive properties define the appearance of each element, while active features embrace additional output and input capabilities.

The *geometry* of the individual elements can be designed according to functional requirements (e.g., spherical elements for visualizing scatterplots) or aesthetic aspects (e.g., geometries that match the furniture), as shown in Figure 2A. While a sphere is a generic shape, non-axisymmetric geometries enable viewpoint-dependent visualizations (cf. [6]), and flat geometries (e.g., tessellated disks) can be combined to form a continuous 3D surface (as exemplified by [23], see Figure 4E). The *size* of the elements influences their overall visibility and potential interaction (see Figure 2B). Bigger geometries facilitate input with individual elements while smaller ones seem to be part of a collective interactive structure. The overall visual and haptic appearance of STRAIDE is also driven by the *material* of the elements (Figure 2C). Considerations regarding physical properties like hardness, stiffness, elasticity, or roughness are as important as the psychophysical character or personality we assign to certain substances.

Apart from such static geometries, elements can incorporate a variety of active properties. For instance, each object itself can include *shape-changing* capabilities as we imagine elements that can rotate, twist, or stretch (see Figure 2D and [12]). Additional *visual output* can be provided by internal illumination or displays (Figure 2E). Actuators such as vibration motors can be directly embedded to extend the output capabilities to different sensory channels. Furthermore, *electronic components* which are dedicated to sensing, computation, wireless communication, and power supply can be incorporated.

3.2 Physical Assemblies of Elements

In most cases, not a single element, but the combination of multiple elements will constitute STRAIDE's visualizations. They can be assembled in various ways and thus respective parameters need to be addressed (see Figure 3).

Advances in pin-array research lead to an increasing *number of actuated elements* which improves the information density and the approximation of geometric shapes. However, previous work

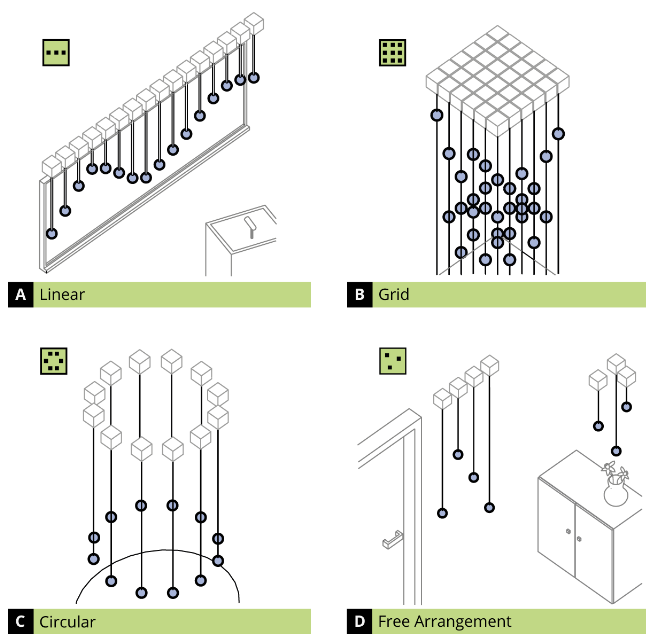

Figure 3: Physical assemblies of actuated elements come in different arrangements and layouts. For instance, elements can be placed in a linear order (A), arranged along a regular grid (B) or a circular path (C), or positioned where they are needed (D).

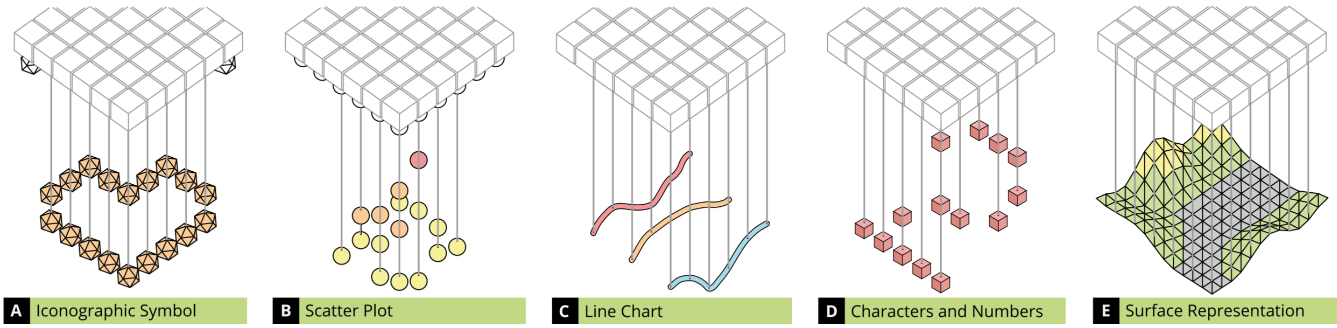

Figure 4: Visualizations in space range from figurative symbols like a heart icon (A), to data visualizations like scatter plots (B) and line charts (C), to 2D characters like a "2" (D), and surface representations (E). The figure illustrates the visualizations along an exemplary matrix setup.

showcased how a few elements can be sufficient for various applications [17], by using abstract encoding. The *arrangement* of individual elements is commonly based on a regular grid (Figure 3B). It resembles the arrangement of square pixels on a screen, thus simplifying construction and control. Depending on the application, different setups might be favored, like a circular path (Figure 3C) with visually pleasing symmetry [52], or an irregular positioning in proximity to real-world objects (Figure 3D). For each regular arrangement, different *layouts* are feasible. While a grid layout (see Figure 3B) is convenient for 2D continuous data, a linear layout (see Figure 3A) facilitates rendering one-dimensional data, e. g., a line chart. Regarding the *spacing* between elements (e.g., on a grid or arc), dense arrangements utilize the display space most effectively. In contrast, larger inter-element gaps will allow the user to reach and interact with inner elements. Inspired by previous SCIs [47] and artistic installations [9, 34, 77], we consider the *interconnectedness* of the individual elements. Using flexible materials or loosely coupled structures, multiple elements can have a physical and therefore visual connection to form rows, areas, or other arbitrary collectives. For instance, elements can be individual nodes of a tessellated surface or a puppet can be controlled using multiple actuators.

In terms of the elements' suspension, there are different feasible *mounting* options using flexible strings. If an element is suspended on a single string, it is free to rotate and swing which is required for some interaction techniques (see section 3.4). If not, this can be prevented by additional bracing strings connected to the base, as shown in Figure 3B. Finally, the strings themselves can visually represent data using, for example, functional materials such as embedded fiber optics [60] or augmented reality overlays [36].

3.3 Visualizations in Space

As STRAIDE enables diverse visualizations in physical space, we will discuss feasible visual output in the following (see Figure 4). Overall, they heavily depend on the chosen physical assembly and the number of actuated elements. Instead of high-resolution data visualizations, STRAIDE rather facilitates iconographic (Figure 4A), metaphoric, or abstract visualizations. As stated by Pousman et al. [62], users might gain awareness insight (e.g., shifting patterns, trend detection), social insight (e.g., communication, evaluation), or reflective insight (e.g., self-reflection, motivation) from such casual visualizations. Furthermore, these are comprehensible to a broad range of users with different age, abilities, or education. Additional output capabilities of the individual elements, such as individual colored illumination, encode data and help to differentiate and identify parts of a visualization.

By controlling the visual properties position and color for each element, visual primitives can be formed. A single element encodes a *point* in the three-dimensional visualization space. It may be part of a scatter plot (Figure 4B) or a handle for interaction (see section 3.4). Neighboring elements can be physically (Figure 4C) or semantically (e.g., by color, cf. Figure 1E, right) combined into *lines* to highlight their connectivity. Elements from multiple columns and rows can yield numbers (Figure 4D), text, glyphs, or similar 2D shapes that depict data similar to conventional GUI applications. Alternatively, they can form a *surface* representation with continuous 2D data (Figure 4E). Finally, elements can be arranged to form a compound 3D *shape* in mid-air. These, most often pictorial or abstract, shapes suit casual visualizations or entertainment as morphing shapes in mid-air appear fascinating [37]. However, the creation of convex shapes with STRAIDE is limited as elements cannot be arranged directly above each other.

As STRAIDE offers extensive strokes, the vertical offset of shapes and other collective structures can be adjusted for ergonomics or to encode data (e.g., the lower a shape is hanging, the less time remains). Due to the suspension from above, STRAIDE's visualizations can further be located close to real-world objects resulting in situated physicalizations [88] (cf. Figure 11A). This proximity creates a context that fosters comprehension, for instance, a drop-shaped element above a plant can be easily interpreted as the plant's specific water needs.

Just as important as those static properties are the dynamic features of an SCI to create animated visualizations or react to data changes in real-time. The application of movement and color animations needs to be carefully considered as they can encode data and mediate emotions [84]. To convey these sometimes subtle impressions, we will require suitable tools for experimenting, developing, and testing future visualizations, animations, and interactions (see section 4.4). Additionally, custom development tools will help to rethink familiar 2D visualizations into 3D concepts with a limited resolution so that developers can use the full potential of our system in the future.

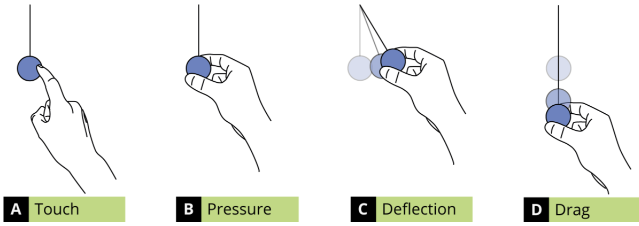

Figure 5: The hanging elements facilitate a rich space of different types of interaction, such as single-touch (A), pressure detection (B), deflection (C) and drag (D).

3.4 Types of Interaction

Following the classification by Rasmussen et al. [64], shape-changing interfaces can feature *no*, *implicit*, *direct*, or *indirect interaction*. Most string-based installations feature *no interaction* modalities. Such kinetic sculptures autonomously change shape or alter their appearance based on digital information. The inclusion of input capabilities will distinguish STRAIDE from these systems as it becomes a functional interface.

Following an *implicit interaction* approach, the users may not recognize that their behavior influences the shape-changing output. A feasible example is presence detection: If a user enters the room or steps close to the device, personally relevant data can be shown or views can be adapted to the user's preferences.

Direct interaction is the most promising approach that most tangible user interfaces including STRAIDE aim for (see Figure 5). It features important haptic feedback when the user intentionally interacts with the system's elements. Versatile direct input may include detection of *single-touch* (Figure 5A), multi-touch *grabs*, manual *deformation*, or applied *pressure* (Figure 5B). Additionally, the flexible string-based mounting allows to *deflect* elements in horizontal direction (Figure 5C) and *drag* them along the vertical axis (Figure 5D) [35].

Finally, *indirect interaction* is a viable extension for STRAIDE as today's smart devices can provide sophisticated remote input for the system. The other way around, interconnected systems, IoT sensors, and web-based services can provide data for STRAIDE to visualize so it can be explored by the user. In this way, the system enables the representation of and interaction with data from the real world to be experienced within the physical space.

This concludes our design considerations regarding a spatial user interface that combines string-based actuation with additional interaction capabilities. We considered different static and dynamic properties for individual elements as well as their assembly to create visualizations in mid-air. In the following, we will introduce our physical research platform guided by technical experiments and design explorations which is the foundation for developing different STRAIDE instances and applications.

4 STRAIDE RESEARCH PLATFORM

Propelled by the necessity for shape-changing interface toolkits [2], we envision STRAIDE as an open research platform. As previously described in section 3, STRAIDE aims to support different setups and applications in a modular design. Through *technical design* (4.1), we identify suitable mechanisms and components. The results are applied in different *physical instances* (4.2) which showcase the versatility of our approach. Self-contained modules and elements are used to rapidly prototype interfaces for different use cases. We discuss their technical limitations and related challenges in section 4.3. Finally, we introduce *software tools* (4.4) to explore the capabilities of this platform and its application for different use cases.

4.1 Technical Design

To simplify and accelerate building future instances of STRAIDE, we set up objectives for its hardware implementation. First of all, it should only be built from readily available components and materials. Subsequent processing should mostly rely on 3D-printing and laser cutting which is feasible in most FabLabs. The overall design needs to be modular to facilitate rearrangement and adaptability if requirements change. Reducing the number of varying components will further simplify maintenance. With these guidelines in mind, we began an iterative design approach starting with an extensive exploration of *interactive elements*. We then conducted a series of tests to find an effective method of *actuation* for these objects. Finally, we integrated both electronics and the *actuation mechanism* into a self-contained unit.

Interactive Elements

As the individual elements make up the final visualizations, we explored their diverse properties first (see Figure 6). Different *geometries* and *sizes* are easily conceived, since scaled and 3D-printed shapes can be used as passive elements (Figure 6A). We found that one can attach nearly any object from the everyday environment (e.g., small toys, Lego bricks, tiny plants) as long as they can be lifted by the actuators. We examined different *materials* like injection molded plastics, translucent filaments, and epoxy casts regarding their processability, appearance, and light dispersion for embedded illuminants. To showcase elements with *shape-changing properties*, we designed assemblies of actuated parts that elongate in one direction (Figure 6B), or can be fold (Figure 1E, left) or bent (Figure 11C). Finally, we enhanced passive elements with directly *embedded electronic components*. As illumination is the most prominent secondary *output* for shape-changing displays, we built prototypes with a single or multiple colored LEDs (WS2812 RGB and SK6812 RGBW

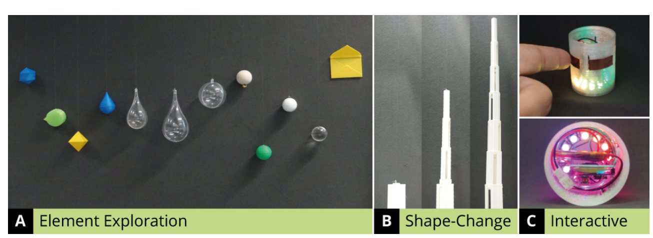

Figure 6: In our technical exploration we evaluated a variety of elements (A, left to right) with different shapes, sizes, materials, shape-changing capabilities (B) as well as interactive elements (C). The latter example uses a WiFi-capable micro-controller powered by a battery to control LEDs and detect touch.

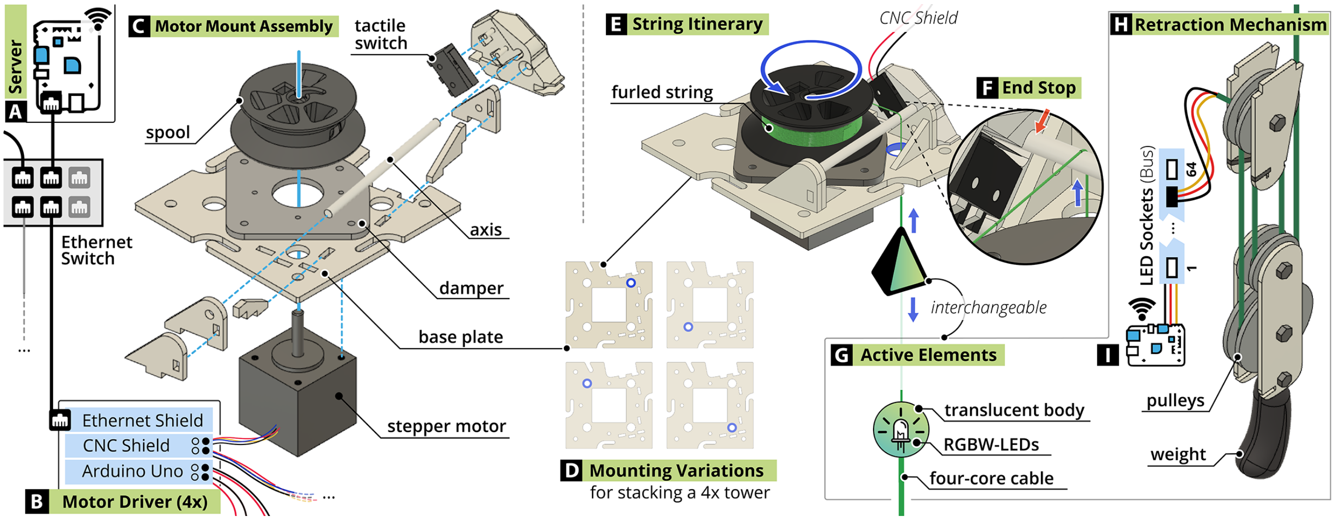

Figure 7: The schematic illustration shows the interplay of the most important components of STRAIDE: A central server (A) controls the system and sends all required commands over Ethernet to the respective motor driver (B) of an actuation tower. Each actuation tower integrates up to four motor mounts (C) which are axially symmetric providing different mounting variations (D). To actuate an element, the string is horizontally wound onto the spool and vertically redirected around an axis (see string itinerary, E). When the string is tensioned, an endstop switch (F) is triggered by this axis. Finally, active elements (G), such as RGBW-LED spheres, can be attached to the strings. They are stabilized by a retraction mechanism (H) from underneath and controlled by a WiFi-enabled LED control unit (I).

LEDs) in a flat, ring-shaped, or cubical arrangement. Furthermore, we embedded small microcontroller boards (Wemos D1 mini) with additional LiPo batteries directly in hollow elements (Figure 6C) that control the LEDs or similar components like dot matrices or vibration disks. They also enable *input* capabilities like capacitive sensing for touch detection.

Actuation

As stated by Taher et al. [79], feasible components for actuating SCIs range from electromechanical motors and magnets to fluid-based actuators to smart materials. Thereof, we picked stepper motors as they best suit our requirements regarding torque, granularity, speed, and position feedback.

For most motors, the *torque* is directly proportional to their size. An appropriate stepper motor needed to be as small as possible to enable dense arrangements while having enough torque to lift elements (weighing less than $250g$) and withstand mechanical and user-induced resistance (e.g., while dragging). After thoroughly testing different actuators (NEMA11-17), we settled on NEMA14 steppers with a size of $34 \times 34 \times 35mm$ and a torque of $18Ncm$. A key advantage of stepper motors is their high rotational accuracy which yields a fine *granularity* (vertical resolution). By employing the motors' micro-stepping capabilities, precise control of the elements' vertical positions is possible (step height: $\approx 0.3mm$). The maximum *speed* of actuation amounts to 1256 $^{mm}/_{s}$. As the speed and *acceleration* can be computationally controlled, we can achieve rapid artificial movements, required for quick responses to changing data. But we can also simulate calm and slow motion which appears peaceful and organic [11, 64]. Finally, all stepper motors feature open-loop *position feedback*. This eliminates the need for bulky gearboxes or additional position sensing hardware which reduces the number of required components and associated sources of error.

To match the selected actuators, we chose the remaining electronic components like motor drivers (*Pololu A4988*, TI DRV8825, Trinamic TMC2100), microcontroller boards (*Arduino Uno*, Espduino), and shields (*Arduino CNC Shield V3*) from readily available parts originally intended for four-axis CNC machines (see Figure 7B and Figure 8B, top). For communication in between modules, we tested I²C and Ethernet of which the latter was favored due to its versatility and reliability. On average, the associated costs equal ≈ 40€ to actuate an element, including the actuators, mounts, control system, and power supply.

Actuation Mechanism

Components used in previous shape-changing displays [20, 47, 78] featured only limited stroke lengths ($\approx 10cm$) which minimizes their visualization space. As the actuation unit of STRAIDE is positioned above the display space, gravity allows us to apply a roller mechanism (see Figure 7). This approach achieves extensive strokes while sustaining the motors' fine granularity. Additionally, the mechanism's simplicity and the small number of required components simplify the overall construction. Nonetheless, the string-based actuation limits the direct interaction potential due to a loose coupling and obstructive strings.

In a subsequent iterative process we designed, tested, and improved motor mounts that combine the actuators, vibration dampers, limit switches, and set screws in one compound module (Figure 7C). After several completely 3D-printed prototypes, we opted for a laser-cut base made from $3mm$ acrylic, laser-cut dampers from

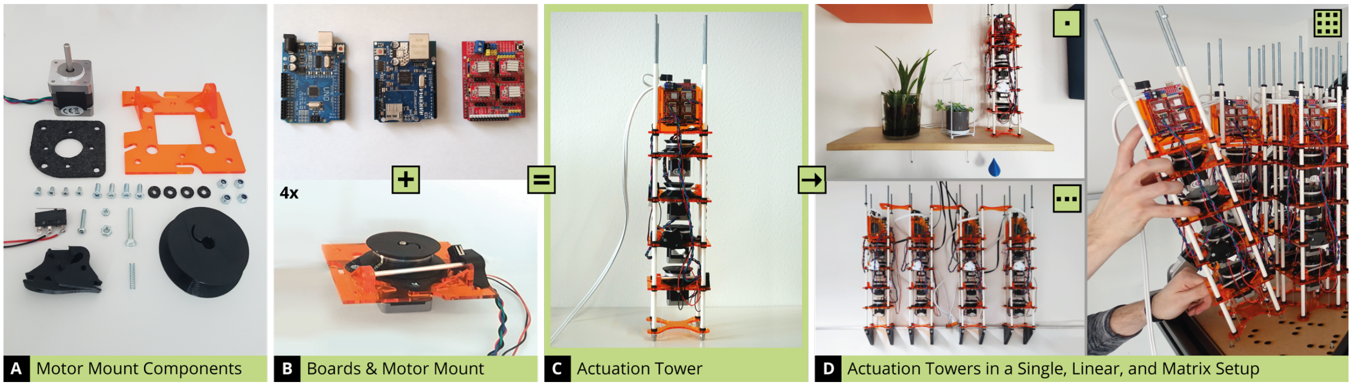

Figure 8: STRAIDE's actuation is based on stepper motors in custom laser-cut mounts (A) that are assembled and combined with a stack of microcontroller boards (B) to form self-contained actuation towers (C). These are employed in different setups (D), for instance in a Single, Linear, or Matrix Setup.

synthetic felt, and a few 3D-printed components with complex geometry. This yields fast fabrication as a plug-in system. In a few manual assembly steps, a braided translucent string is wound on a spool attached to the stepper motor's axis (Figure 7E). Previous tests with monofil fishing lines or nylon sewing threads yielded bouncy actuation due to their flexibility. The string is running from the spool over an additional axis which is pivoted on a tactile switch (Figure 7F). When the resistance on the string increases, the switch is triggered. This is used both for calibration of the element's upper position and to detect drag input from the user. To be able to attach any kind of element to the actuators, a tiny general-purpose jewelry hook is mounted to the end of the string.

As STRAIDE's development benefited greatly from open-source hardware [38] and software [4] projects, we published all required details for reproduction under CERN-OHL-S and GNU General Public License respectively. Comprehensive building instructions, as well as all files of 3D-printed and laser-cut parts, firmware, and developer tools, are available on our project website[1]. We hope to see novel adaptations of STRAIDE within the HCI and maker community.

4.2 Physical Instances

The aforementioned motor mounts and electronic components are combined into self-contained assemblies, which enable the exploration of applications in different scenarios. As a dense arrangement was preferred in subsequent tests, we combined four identical motor mounts (cf. Figure 7D) in an actuation tower with all the required electronic components stacked above (see Figure 8C). This tower (dimensions: $10 \times 10 \times 40cm$, weight: $1500g$) requires two connections (power, Ethernet) and is capable of lifting four elements of up to $250g$ weight with a $5 \times 5cm$ spacing. Multiple of these self-contained assemblies can be combined in different setups as long as sufficient power and network resources are available. To demonstrate the viability of our toolkit, we arranged 1, 4, and 16 towers as described in the following:

[1]Project website: https://imld.de/straide

Single Setup: A single tower can be used in a private setting adjacent to a real-world object as shown in Figure 8D. It provides up to four proxy elements to visualize ambient information (cf. blue drop for water level), and the built-in drag input enables simple interaction.

Linear Setup: Four actuation towers are mounted in a linear arrangement to a passive whiteboard (Figure 8D) using simple 3D-printed brackets. Through the use of an intermediate deflection mechanism, 16 elements are ordered along a single row.

Matrix Setup: Finally, we combine 16 actuation towers in a more complex matrix prototype (Figure 8D). It actuates 8×8 elements at once with stroke lengths up to $120cm$. The upper actuation unit is supported by a sturdy frame made from aluminum extrusions which facilitates simple adaptation and reconfiguration. Its dimensions are $50 \times 70 \times 250cm$ and it is open and accessible from three sides (cf. Figure 1, left). Alternatively, a truss system could suspend the actuation unit from the ceiling (load $\approx n \times [1.5kg$ actuation tower $+ 4 \times 0.25kg$ max. element weight]), allowing interaction from all sides of the display space. The elements in this setup are 64 spheres made from translucent white epoxy resin with directly embedded RGBW LEDs that are powered via thin cables from below (see Figure 7G). To store these $200m$ of supply cables, they are retracted in a box below using a luff tackle mechanism (Figure 7H).

4.3 Technical Limitations & Challenges

As anticipated, we faced common technical challenges with our actuation system, in particular regarding oscillations, noise, heat, and communication. The string-based mounting introduces unwanted oscillations of elements due to abrupt movements and resonances. We found that maximal speed and acceleration of the movements need to be adjusted according to the elements' weight and shape. While these parameters are controllable via our software interface, automated adaption with element recognition could be included in the actuation control firmware. In its current state, the matrix setup of STRAIDE is too noisy to be used as a calm and ambient interface, but we will improve the inter-mount damping and utilize more advanced stepper motor drivers like the TMC2100 with *stealthChop*

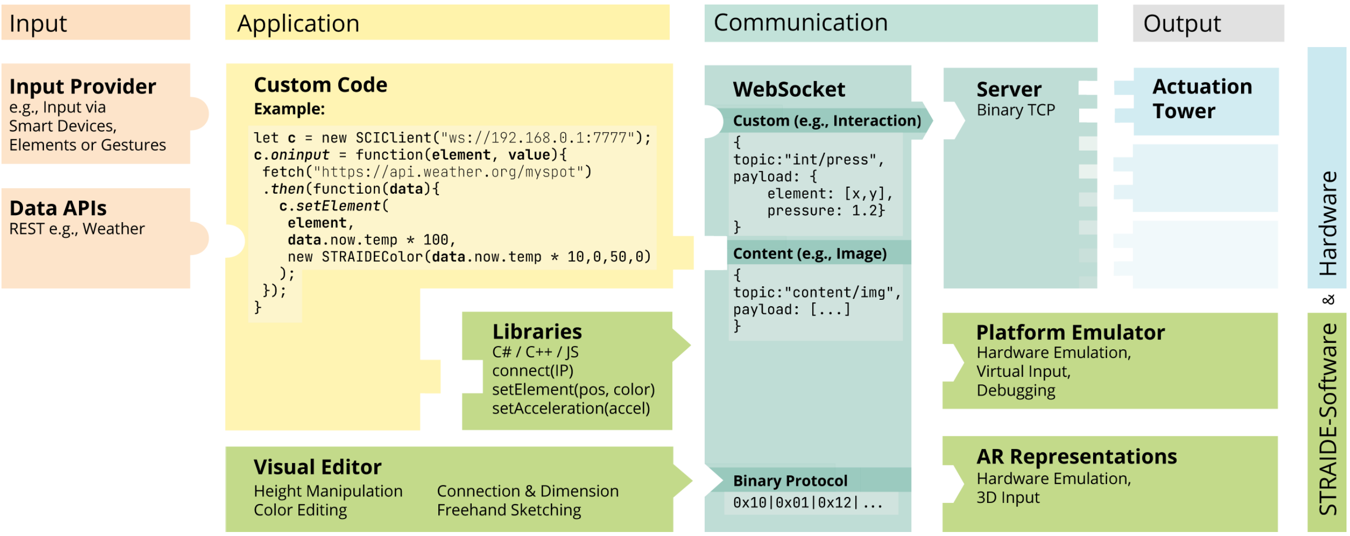

Figure 9: The simplified schema illustrates the components of a custom application as well as the STRAIDE software which supports the development. External data (red) is transformed into a visualization using application-specific code (yellow). Our software libraries (green) can be used to simplify the connection establishment and control over the hardware. They employ an efficient binary protocol, but other human-readable formats of messages are supported as well. The application can communicate via WebSockets (teal) to either the real device (blue) or our software tools (green), namely the Platform Emulator and the AR Representations, as they provide the same interface.

functionalities. The heat produced in the stepper motor coils becomes a problem in dense arrangements of the actuation towers and needs to be counteracted by adding continuous air circulation using fans. Especially 3D-printed components close to the motors (e.g., rolls) need to be made out of heat-resistant filament like ABS so they do not reach their Vicat softening temperature. While our first iterations of the actuation tower used I²C to communicate to a central microcontroller, we later switched to Ethernet-based TCP communication to ensure reliable data exchange for an increasing number of clients.

During the exploration of different element properties (especially self-actuated shape-change and embedded electronics) miniaturization was a major challenge. For example, it was more practical to use cable connections in our 8×8 prototype outsourcing the control system instead of integrating custom circuitry (comprising sensing, computation, communication, and power supply) directly in each sphere. However, these lower cables not only affect the visual appearance and stability of our matrix setup but also limit the accessibility of elements for interaction.

Additionally, rude direct input will occasionally cause stepper motors to stall. Although a precise positioning is achieved during normal operation, such deviations can not be detected with our current hardware. Therefore we regularly recalibrate the motors in their topmost position. Motor drivers with stall detection features might further ensure precise position control over long periods of time.

Finally, we expect future technological advances to enable more sophisticated adaptations of our system. For instance, incorporating novel actuation mechanisms such as in Bezalel [66] could help to reduce the number of required actuators.

4.4 Software & Tools

As our hardware controllers feature Ethernet connectivity, each individual actuation tower can be operated using TCP messages. To simplify the control of multiple modules at once, we added an intermediate server (NodeJS on Raspberry Pi 4B, see Figure 9). It provides an external WebSocket interface that allows developer teams to use a wide range of different programming languages, frameworks, and hardware platforms since various WebSocket implementations are available. Feasible clients range from desktop software platforms, over web technologies, to Mixed Reality frameworks, or even embedded physical computing clients such as IoT sensors. The server follows the publish/subscribe communication paradigm [15] which loosely couples software modules and promotes flexible extension (e.g., input elements). It can currently process and visualize incoming content of different types: *image-based content* encodes position and color in two separate image files (cf. Figure 10A), *geometry-based content* can be provided as a rudimentary .obj geometry definition file, and *low-level messages* can control the position and color of one or multiple elements at once. While the first two support creative workflows for non-domain experts, the latter provides the most accurate control. Therefore, we implemented custom libraries in different programming languages (JavaScript, C#, C++) simplifying the software development. They provide functions for establishing connections and setting the properties of elements, as well as events for system state changes and user input. Custom applications may gather and evaluate data from an external REST-API using custom logic and display a corresponding visualization by setting the position and color of the elements (see Figure 9).

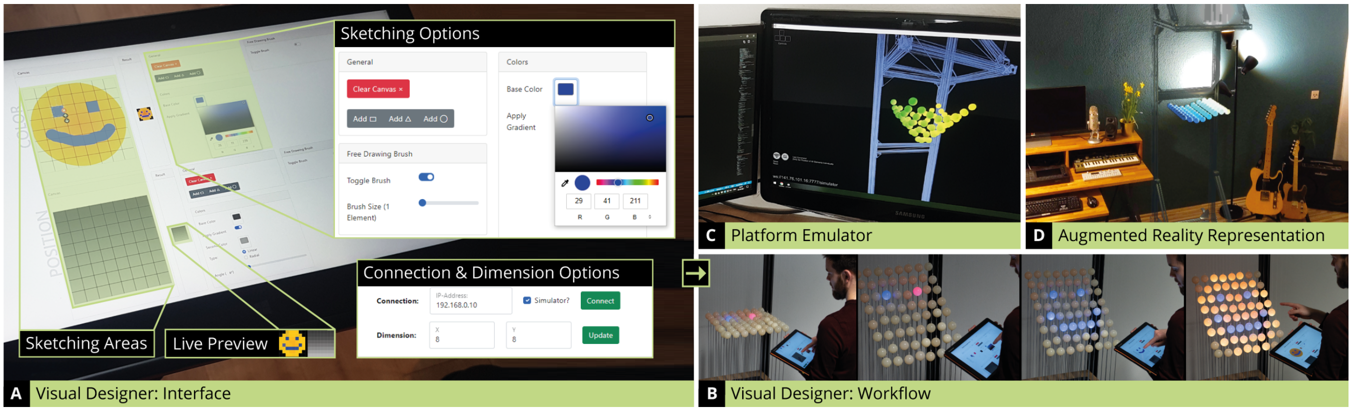

Figure 10: We present a set of tools to support the ideation and implementation of applications for STRAIDE. The web-based Visual Designer (A) facilitates early ideation of mid-air shapes for different STRAIDE configurations, in this example an 8×8 matrix. Users can add and manipulate geometric objects and adapt their solid color or gradient (B). The standalone Platform Emulator (C) supports remote development in desktop environments. In-situ Augmented Reality representations (D) help to experience not yet built hardware setups in their intended environment.

Nonetheless, the ideation, design, and development of novel applications for 2.5D shape-changing interfaces remain challenging. Therefore, we argue for the importance of easy-to-use ideation and development tools that support experts and laymen by reducing the required effort of this process (see Figure 10).

To support ideation and brainstorming sessions in an early concept phase, we provide a **Visual Designer** (see Figure 10A). We implemented a mobile web application that allows sketching, iterating, and discussing ideas in real-time, e.g., on a handheld device like a tablet with touch or pen interaction. The physical actuators are configured with a 2D position along a customizable grid. The Visual Designer represents them as two large canvases, one for selecting the elements' colors and the other for defining their vertical position. The designer can create, compose, or modify 2.5D geometries by using predefined shapes or a free-form brush (see Figure 10B). All designs and configurations created in the Visual Designer can be both exported and imported to persistently save and reload any intermediate or final states. Furthermore, results can be the foundation for later application development as they can be fed to the server using the aforementioned image-based approach.

We provide a **Platform Emulator** to reduce the burden of dealing with an additional physical device during application development in a desktop environment (see Figure 10C). It allows developers to virtually set up an existing or even envisioned version of STRAIDE with customized parameters. The standalone emulator closely mimics the behavior of the actuation system by considering physical parameters and technical limitations of selected hardware components (e.g., maximal actuation velocity, handling of commands). However, element-dependent behaviors like deformations or oscillations are not yet implemented. From a developer's perspective, it provides an identical software interface. Developers can seamlessly switch between using the virtual emulator or a real device by changing the WebSocket server address. This emulation tool supports the interactive exploration and evaluation of application prototypes based on a 3D visualization in real-time. As it is written using the Unity [81] game engine, it can be deployed for different operating systems. Furthermore, we added native support for autostereoscopic displays like the Looking Glass 15.6" Pro [18] to enable three-dimensional exploration in desktop environments.

We contribute the idea and implementation of providing true-to-scale **Augmented Reality representations** of STRAIDE implementations at various real-world places (see Figure 10D). As the intended context of an application is decisive for its appearance, intermediate and final results need to be evaluated accordingly. We envision how interactive virtual representations of customized hardware platforms can be freely positioned in a room using AR glasses (HoloLens 2 [54]). In detail, the designer can freely place the virtual shape-changing display in space and deploy an application. This can be used to experience and iterate not yet built hardware setups and respective novel applications as it can be operated in unison with the Visual Designer or custom content using the universal WebSocket interface.

5 EXAMPLE APPLICATIONS

Next, we will introduce a series of applications employing the STRAIDE research platform to demonstrate its capabilities and versatility. In addition, they allow us to validate the technical feasibility and thus provide a first evaluation by demonstration [43]. The exemplary use cases show the utilization of different physical instances (see section 4.2), ways to adapt established visualizations to the 3D realm, and novel scenarios for the usage of SCIs. We see great potential for applications in the private domain including ambient visualizations, entertainment, and smart home integration, and also showcase applications for a professional or educational context.

The most minimal *Single Setup* consists of a single meaning-bearing element that is vertically actuated. Even without active properties, its shape enables sense-making as in the case of an element formed

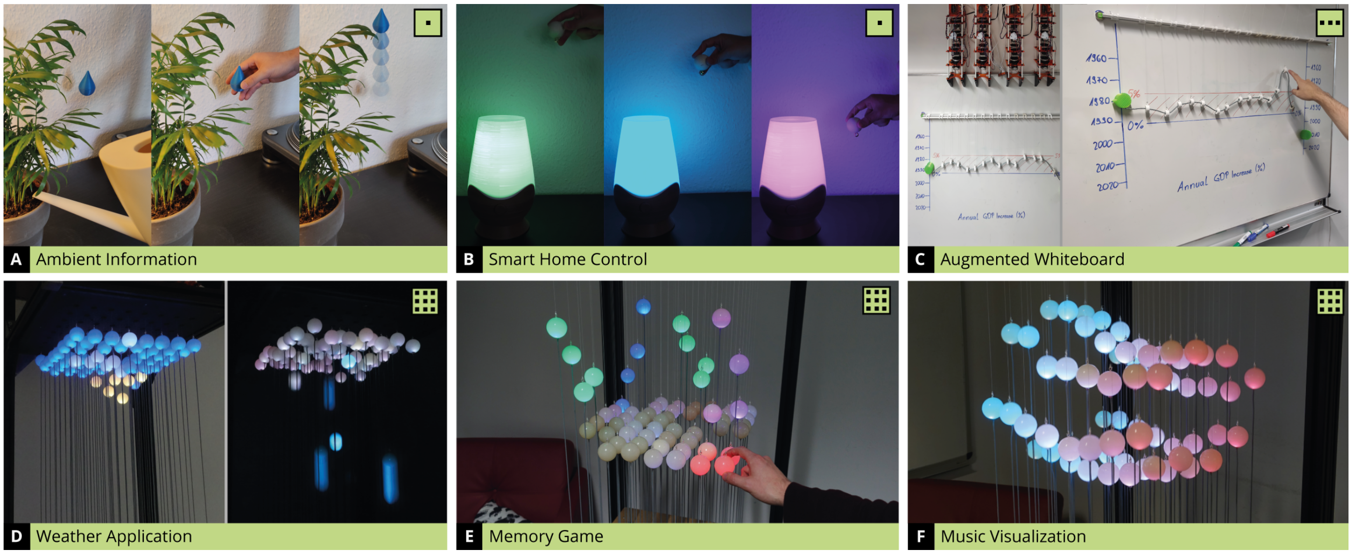

Figure 11: We implemented several applications using our different setups. In a private context, individual elements are used as ambient visualizations (A) and smart home controls (B). The linear arrangement augments a hand-drawn diagram with a dynamic graph (C). The matrix setup facilitates a weather application (D) with different conditions (e.g., sunny, rainy), a 3D memory game (E), and a morphing music visualization (F).

like an envelope icon. Its vertical position is a calm **ambient representation** (see Figure 1E, left) of a vertical gauge that conveys the approximate number of unanswered messages of the day. In another approach, we make use of spatial relations of the actuated element to nearby objects like a plant (see Figure 11A). In such a situated data physicalization [88], the proximity to everyday objects allows to reduce the number of elements to a minimum while remaining comprehensible. The closer the blue raindrop is to the plant, the less water remains. After watering the plant, the user can simply pull the element to reset the timer. In a similar manner, we employed interactive elements in a **smart home** as physical controls (see Figure 11B). Our application works similar to conventional smart home control centers with output for distributed sensors, sliders to toggle and dim lights, and buttons to activate absence mode. But we rather employ aesthetically pleasing elements that fit the private environment and offer non-disturbing ambient information about the system's current state.

In our *Linear Setup* we employed 16 elements in a linear arrangement to use it for 2D visualizations like physical line charts or interactive storytelling on a whiteboard. In the **line chart** (see Figure 11C) all elements control the course of the graph within a diagram area defined by sketched axes on the whiteboard. In a future combination with a digitizing whiteboard, such as Kapp [73] or Kaptivo [49], STRAIDE's dynamic properties can enhance traditional hand-drawn information visualization (e.g., in an educational context) in an appealing and engaging way. The same principle is used in the **interactive storytelling** application (see Figure 1E, center). Physical props assist the presenter in creating interactive diagrams or charts. Users create predefined animations that physically animate items in unison with hand-drawn scenes.

Three exemplary applications were implemented using our *Matrix Setup* ranging from casual information visualization to entertainment to ambient art. The first one is a self-sufficient **Weather Application** (see Figure 11D). It displays the weather conditions using figurative depictions for the sun, different clouds, rain, snow, or fog. For instance, clouds are illustrated as gray accumulations at the top and individual elements fall like rain. Live data is gathered from an online weather API (Open Weather [85]). To demonstrate STRAIDE's viability for entertainment, a **Memory Game** (see Figure 11E) was developed which is a 3D variation of the well-known board game. It uses spatial arrangements of groups of 2×2 elements to form distinct three-dimensional patterns. Eight pairs of these patterns are randomly distributed but hidden in the initial state. The user reveals shapes by selecting a row and a column using direct input on the outer elements. The game's difficulty depends on the utilization of color and the similarity of shapes. Finally, a **Music Visualization** (see Figure 11F) was implemented that creates a three-dimensional shape in mid-air. It is rhythmically morphed based on the music's BPM and frequency distribution. Color animations follow the color scheme of the song's album cover. The application highlights STRAIDE's appealing qualities as its visual output is well suited for pleasing or ambient visualizations in private spaces. It showcases that STRAIDE can act as an extravagant interior object with additional interactive capabilities on top.

These examples demonstrate the universal applicability and flexibility of STRAIDE in a broad range of scenarios. In the next section, we go into more detail about our experiences and discuss the advantages and limitations of the STRAIDE research platform.

6 EVALUATION

As outlined by Ledo et al. [43], evaluating HCI research toolkits is challenging. Therefore, they discuss appropriate strategies which range from the execution of technical experiments, to the demonstration of realized examples, the discussion of its usage with practitioners, and the application of heuristics.

Inspired by the idea of a multifaceted methodology for validation, we also aim to discuss STRAIDE in a differentiated manner from multiple perspectives. While we started to ground the overall mechanical design of the research platform by a series of technical experiments, we further realized multiple applications to demonstrate the functionality, versatility, and potential of the toolkit approach. Although these strategies validate the technical feasibility to a large extent, we see it as particularly important to additionally evaluate our software contributions and gain insights, how future developers are able to use the repertoire of STRAIDE tools.

6.1 Procedure: Investigating the applicability of the software development tools

We recruited three computer science students (P1-P3) aged 21-24 years to work with the STRAIDE developer tools in a semester-long project (6 months). The students had no previous knowledge about SCIs or 3D visualizations but had advanced programming expertise. Due to the pandemic, the team had to use our software tools for remote development. They had to implement applications for the matrix setup in a private context. They were tasked to design and develop use cases that take advantage of the convenient properties of this novel tangible display. In the end, we were able to transfer their applications to the real hardware and approve their operational reliability. Afterward, we prepared a quantitative questionnaire with 28 open-ended and rating questions regarding the value of utilized software tools and the tradeoffs of remote application development. Additionally, we conducted a 45-minute-long semi-structured interview with each participant to get more in-depth statements about the application development and the workflow within the team.

6.2 Developer Feedback: Insights & Lessons Learned

The most important feedback from the developers is grouped into three overarching themes. We elaborate on the participant's statements and draw lessons from their findings below:

Low-resolution spatial displays spark creative application concepts. In their early ideation phase, all developers (P1-P3) followed a data-driven approach with the goal of visualizing personal data in a tangible way. However, we found that different design strategies emerged during the application development using the STRAIDE software tools.

Since we did not provide any instructions for conceiving new applications, we were surprised by the variety of applied design strategies. P1 and P2 analyzed relevant data for private users (e.g., weather forecast, activity data, or calendar organization) by identifying typical visualizations (e.g., pictograms, bars, or charts). They adapted these visuals to 3D and low-resolution spatial displays by first using static snapshots and later adding animations. P1 used mixed tools to capture initial concepts, namely hand-drawn sketches for quick ideas, 3D models to communicate visualizations, and the Visual Designer to test them on the system. In contrast, P3 was tempted to directly start with iterative programming as the provided libraries yielded quick results. P3 thereby skipped a comprehensive visual ideation phase and focused on a music equalizer visualization in a more practical hands-on programming approach.

Overall, all participants were able to transfer some visualizations from conventional 2D GUI applications (e.g., weather icons), revise others (e.g., clock, see Figure 1F, center), or conceived new ones from scratch. In particular, the limited number of elements was widely debated. But the developers also highlighted that this constraint fostered creative ideation. P3 concluded "I think that the resolution is insufficient for visualizing scientific data, but for my [music] application, creative aspects were important", while P1 said "Typically, you have many [available pixels] and do nothing with it. We had little and achieved plenty".

Accurate and customizable simulation tools ease application development for modular SCIs. We provided the team with a suite of developer tools to support their collaborative remote development. Of these, they most appreciated the Platform Emulator and the low-level library in JavaScript. The emulator was a "viable alternative to the real sculpture" (P3) and "the best way to get a feel for [STRAIDE] without having direct access" (P2). It allowed "to work from everywhere" and "in parallel" (P1) and therefore "development was significantly faster" (P2). Based on the participant's ratings in the questionnaire, the emulator was most helpful to test API functions, develop software, test the behavior of STRAIDE, and present results. However, it was less advantageous to develop and evaluate concepts as "lighting conditions and performance of STRAIDE were difficult to estimate by the emulator" (P2). It was highlighted that the emulator tries to replicate an idealized version of STRAIDE which leaves aside the dangling strings (P1), lighting (P1, P2), noise (P3), or the environment (P2). The provided alternative, the AR previews, were seen as superior regarding appearance (P1) and ambiance (P1, P3), but the missing haptic input (P2) and the required additional hardware were criticized. Our low-level libraries were valued as "very intuitive" (P2), but higher-level functionalities were requested, e.g., for gradients, transitions, or feedback (P2, P3). A more sophisticated version in the form of a drag-and-drop software system with predefined modules for basic visualizations might even suit end-user programming, but only to a limited extent (P2, P3). Overall, we derive that our software tools enable and accelerate remote and collaborative application development. However, their limited features need to be extended in the future to better match the real-world conditions and to enable application development for end-users without programming skills or knowledge about the hardware. Overall, conceptualizing and developing new visuals and applications remains challenging due to the combined complexity of hardware and software.

Tradeoffs associated with string-based user interfaces. While we already highlighted the advantages of STRAIDE, e.g., regarding stroke, simplicity, and flexibility, its string-based actuation also entails disadvantages. Therefore, we asked the developer team about tradeoffs, aside from the low resolution, that need to be considered when developing applications with STRAIDE. A major point is the "impossibility to move elements along the horizontal plane" (P1) which would have been required for an envisioned racing game. Another is the time it takes to transition views and the introduced asynchronism while "elements move to a new position" (P2). Furthermore, the strings limit interaction with inner elements (P3), are visually distracting (P1), and the "lack of horizontal stability might make it look messy" (P3). This is particularly obvious in the matrix setup, as elements are densely packed and the internal LEDs illuminate the strings. For the future, the developers suggested further interactions to complement the direct input, namely "context-sensitive switching" (P1), "speech recognition" (P2), or "gesture recognition" (P1, P3). Future adaptions of STRAIDE with more detailed 3D output and sophisticated input capabilities could become promising complements to conventional user interfaces.

7 CONCLUSION & FUTURE WORK

In this paper, we presented STRAIDE, an open research platform for shape-changing spatial displays using string-based actuation to explore dynamic and situated physical visualizations in everyday spaces. Therefore, we introduced a modular hardware and software system that can be customized along manifold design parameters regarding (inter)active elements, physical assemblies, as well as output and input capabilities. To technically validate the STRAIDE approach and demonstrate its versatile potential for physical visualizations, we implemented a variety of real-world applications. These include ambient notifications, personal smart home controls, and entertainment using variable physical setups with increasing complexity. In addition, we have shown how accompanying software tools can support the application development process. Finally, we discussed insights from our iterative design process, technical experiments, and elaborated on findings from interviews with external developers. Overall, we hope that our work inspires future research towards rapid prototyping of physical visualizations and shape-changing spatial displays, and the deployment of situated SCIs in everyday spaces.

For future work, we plan to further explore new promising applications, investigate novel elements that use, for example, more complex embedded electronics or novel materials, and research how additional interaction techniques can be integrated into STRAIDE. Due to the positive feedback on our in-situ AR representations, we plan to study additional Mixed Reality enhancements for STRAIDE. While the platform already implements several essential components, STRAIDE can and will be extended as a toolkit. We aim to gain more insights from the community over the next years to further validate it. Therefore, it is particularly important for us to discuss our open research platform by sharing our knowledge, documentation, and developer resources online as well as in hands-on workshops with practitioners, researchers, and end-users. We specifically want to encourage further research in using and developing the presented STRAIDE platform and hope to contribute with this work to the research agenda of shape-changing displays.

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