Elasticcon: Elastic Controllers for Casual Interaction

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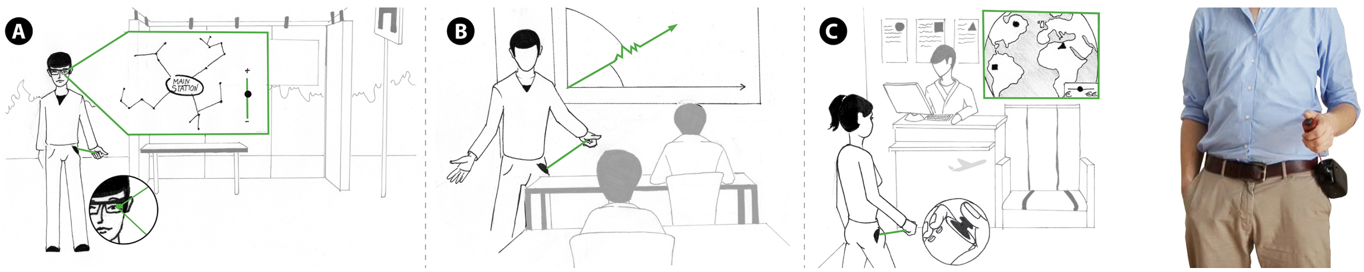

Figure 1. Elasticcon: Controlling a private head-worn display (A), use as generic controller in everyday life (B) and for distant display interaction (C).

ABSTRACT
We explore the high potential of elastic controllers for casual interaction in mobile and ubiquitous computing scenarios. While several remote interaction techniques with handheld or body-worn devices have been proposed, the usage of string-based, elastic interaction is still underexplored. Therefore, we first introduce a systematic design space along the axes reference system, interaction dimensions, sensing methods and haptic feedback. Our main contribution is *Elasticcon*, a versatile, wearable device with a retractable string and a set of exchangeable traction knobs. This elastic controller provides several degrees of freedom and allows rich interaction techniques. As a result of an iterative design process, we also contribute two working prototypes for belt-worn and handheld use. To demonstrate their versatility, we implemented several promising application scenarios. We tested Elasticcon in three smaller user studies investigating qualitative usability aspects and found initial evidence for elastic controllers as being comfortable, casual and yet accurate interaction devices.

General Terms
Design, Human Factors.

Author Keywords
mobile interaction; multi-modal; elastic input; mobile input device; wearable; string-based interaction; casual interaction

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation: User Interfaces: Input Devices and Strategies, Interaction Styles.

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INTRODUCTION
Current trends in mobile computing are characterized by a rapid development and increasing popularity of smart and body-worn devices, such as smartphones, smartwatches, intelligent gadgets and augmented reality glasses. This trend is accompanied by a wide range of emerging application scenarios which require flexible, casual and yet powerful eyes-free control techniques. One good example are head-worn displays, which have to be controlled in fast-paced environments where our gaze and attention are divided. Similarly, the increasing number of large wall-sized displays (including TV sets) demands unobtrusive and easy-to-use remote control techniques for various private and professional applications.

To meet these requirements, several remote control technologies and interaction techniques have been proposed. Morris et al. [14] provide a detailed overview of emerging technologies for always-available mobile interaction. A remaining problem of these approaches is that the resulting interaction styles often do not fit all needs of mobile, casual and distant interactions simultaneously. To improve on that and to enrich the options to choose from, we wanted to provide a means of haptic, eyes-free control, yet one that also remained as unobtrusive as possible. For that, we investigated the potential of string-based elastic interaction and handheld isotonic input.

Manufacturing and using ropes and strings have a long tradition in human history, e.g. to measure distances and refer to sub-ranges. Human-computer interaction researchers have discovered the potential of string-based interaction with direct haptic feedback [21, 4], using specific body-worn personal controllers [3, 12, 16] as well as means for tangible manipulation [23, 18]. However, this is still an underexplored paradigm, especially with regard to distant or mobile interaction. As we will demonstrate, body-attached elastic strings can provide a couple of degrees of freedom (DoF), have a self-referential orientation and are even space-saving. Early preliminary studies of body-worn retractable string devices from Koch and Witt [12] have addressed basic selection tasks based on a position-controlled transfer function that maps each traction position to a fixed virtual object position with a zero-order function. Their study showed that users are able to achieve higher interaction accuracy and a more intuitive interaction style than with standard game pads.

Based on these promising findings, we further explored the design of tiny and generic elastic devices that provide the possibility to work in various real-world mobile scenarios in a casual and yet efficient way. With this paper, we contribute:

- A systematic exploration of the promising *design space of string-based elastic interaction* that can provide a mobile, always-available, space-saving, casual, highly accurate (c.f. [12]) and intuitive interaction.
- Two fully-functional, retractable string-based prototypes, called *Elasticcons*, that combine the sensing of a three-dimensional cone-shaped interaction space with a comprehensive set of exchangeable input knobs.
- A structured *repertoire of essential interaction principles*, based on the rich DoF of the Elasticcons, which underlie various tasks of respective real-world *use cases* under mobile and eyes-free operation conditions.
- *Promising qualitative results* on the basis of three small-scale user studies, which examined the participants' casual interaction behavior, user experience and satisfaction for different interaction tasks.

DESIGN SPACE OF ELASTIC INTERACTION

Physical *elastic interaction* is based on materials or mechanisms that can be deformed reversibly with an applied force. Familiar elastic objects are for example stretchable composite fabrics that often consist of an elastane thread or mechanical springs that can be tensed or compressed as used for example in retractable measuring tapes. The use of elastic properties in the design of input devices can provide haptic feedback and self-centering capabilities that can improve performance. In the following we contribute a novel design space along the dimensions *reference system*, *interaction dimensions*, *sensing methods* and *haptic feedback* of elastic controllers.

Reference System

Due to the fact that interacting with elastic materials and mechanisms requires the application of force at least in one specific direction, the associated reference system plays an important role. We will distinguish between three types of reference systems, illustrated by the example of a retractable string (see Figure 2): *ground-based (A)*, *body-centric (B)* and *hand-based (C)* systems.

Ground-based approaches refer to fixed anchor points, which are mounted on the ground, a wall or other immobile/heavy objects. Based on this principle, all associated actions are related to an *absolute* spatial reference system. Sato et al. introduced for example several ground-based position-tracking scenarios in mixed-reality [21], virtual and CAVE-like environments [4]. Ground-based systems are inherently unsuitable for mobile and some remote application scenarios, because the setups are typically not portable.

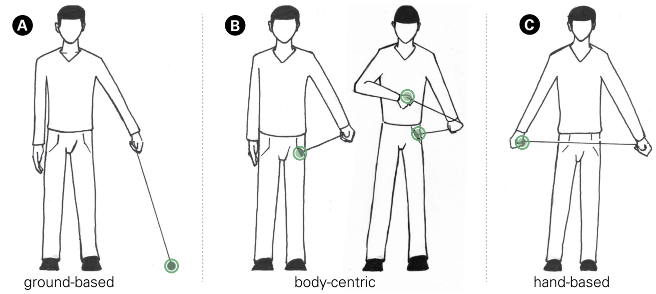

Figure 2. A string can be attached to the ground *(A)*, a person's body *(B)* or hand *(C)*. Respective anchor positions are marked in green.

In contrast, *body-centric* systems are body-based interaction approaches, in which the current position and orientation of a body-attached device acts as the origin of a *relative* reference system. Several mounting positions are possible such as chest, hand, wrist or waist. A number of body-centric retractable string techniques in the literature make use of the interaction space in front of the wearer and thus self-referential orientation [3, 12, 16].

The unanchored bimanual *hand-based* interaction provides elasticity in two directions and creates a *highly dynamic* reference system with a persistently *changing origin* and *orientation*. This special case appears when both parts are unanchored and taken in the hand. As described by Guiard [8], humans use their non-dominant hand to define the reference base, while the dominant hand determines the active position relative to it. Both parts are related to each other or even, as a whole, to the environment. For example, Baillot et al. [1] evaluated the bimanual use of a shape-measuring tape, called ShapeTape, for wearable and mobile interaction.

Furthermore, we assume that the given reference system plays an important role for the user's *mental model* of an interactive information space. Ground-based approaches, such as Rope Revolution [23], provide a more immersive experience and let users become a physical part of the virtual system, while body-centric interaction techniques are characterized by an independent personal interaction space, such as that of the interactive ID badge by Pohl et al. [16]. Hand-based systems have their own reference system which is dependent on the orientation of the user and the spatial environment.

Interaction Dimensions

As the work of Schwarz et al. demonstrates [19], cords can be sensed in many different dimensions. They can provide suitable continuous as well as discrete input capabilities for mobile applications. We consider that promising potential in our holistic design approach, take a closer look at the interaction dimensions and distinguish between *simple direct manipulations*, such as pulling, bending, sliding, pinching and twisting and *complex gestural interactions* (see Figure 3), such as knotting and winding the string.

In general, strings can be *manipulated directly* along their radial, tangential and longitudinal axis. The radial axis can be *pinched* (4) with at least two fingers. The tangential axis can

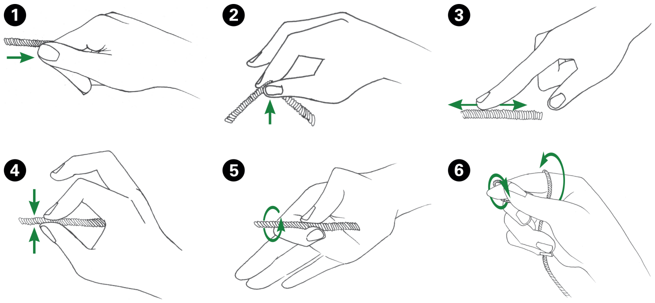

Figure 3. Manipulating Strings: *pulling (1)*, *bending (2)*, *sliding (3)*, *pinching (4)*, *twisting (5)* and *complex interactions (6)*.

be deformed by *twisting* (5) or *bending* (2) the string. The possible rotation angle depends on the material characteristics, especially the stiffness level, the mounting points and the anchor type (fixed, swivel joint). Following the mental model of traversing along a path, the longitudinal axis can be used as a *slider* (3). Furthermore, there is the possibility to *pull and release* (1) the string in a specific direction. The radial, tangential and longitudinal manipulations are single, separate interactions, while several *complex gestural interactions* (6) consist of sequences or parallel actions. Such gestures however need to be learned and might unnecessarily complicate the interaction. The given resistance of the string material has a strong impact on the haptic feedback, the direct manipulation techniques, and essentially influences the user experience [24].

Besides manipulating strings directly, the respective environment is also an integral part of string-based interaction. The position in space in conjunction with the associated *reference system* can provide further DoF. As an example, in the case of a retractable string anchored on one side, the position can be measured *linearly*, along a *circular* or *conical* area (see Figure 4). Rotations around the axis formed by the taut string allow for example *deflection-based* manipulation techniques with two additional dimensions *rX* and *rY* (see Figure 4, conical). All of the continuous actions can be discretized and applied to a virtual information space with a defined selection grid. Furthermore, it is also possible to track complex and symbolic mid-air gestures to trigger specific actions.

Sensing Methods

In order to capture and process the interaction dimensions described above, suitable sensing methods are required. Generally, we can make a rough distinction between *material-based* and *mechanical* measurement techniques to recognize quantifiable stretch and deformation states.

Material-based methods focus on composite and particularly treated materials that receive measurable attributes in a special weaving, coating or nanostructuring manufacturing process. A majority of these materials are based on resistance-measuring techniques. Perner-Wilson and Satomi provide a detailed survey of conductive materials [15]. Pressure-measuring approaches instead are based on composite materials that quantify the volumetric compression caused by the deformation. These materials have a natural feel, but the restricted elongation in extension remains a limiting factor.

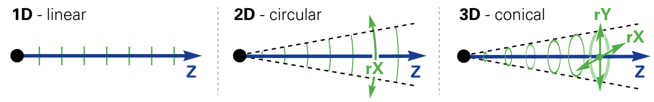

Figure 4. Dimensions of a one-sided anchored retractable & deflectable string, the possible degrees of freedom and discretization levels.

Mechanical tracking techniques are independent from measurable materials, but employ spring-guided mechanisms that allow elastic properties to be measured, for instance, with electrical components or attached sensors. As opposed to the first category, mechanical techniques can provide extremely long extensions by means of retractable winding mechanisms. Complex engineered constructions can enable shape-changing and extensive deformation behaviors. For example, Gupta et al. [9] use mechanical components to simulate different spring rates under computational control. The advantage of mechanical approaches is that they allow sensing of complex deformation properties and behaviors.

There are several additional approaches in-between the *material-based* and *mechanical* categories which combine special measurable materials with mechanical sensing components[1]. A related example is the work of Schwarz et al. [19] that combines conductive thread and a mechanical rotary encoder to locate the touch position and the twist of a cord.

Haptic Feedback

The provision of haptic feedback in elastic, mobile and in particular eyes-free systems can be used to assist, guide and lead users in their interactions and movements. Values, selections, and valid ranges can be made physically perceptible, communicate system states and actions, and improve overall accuracy and precision. We differentiate two types of haptic feedback: *passive* and *active*.

Passive feedback uses physical properties, such as plasticity, deformation resistance or surface structure, compound materials or purely mechanical constructions. Passive feedback cannot be controlled computationally and has to be considered from the beginning. The choice of an appropriate stiffness for all elastic parts is an important prerequisite for achieving a comfortable, low-fatigue elastic interaction. Casiez et al. [6] examined the correlation between stiffness level, elastic displacement and a suitable control gain parameter for elastic rate-controlled pointing devices.

Active feedback enables directed forces and tactile stimulation through electric/electronic actuators under computational control. We can subdivide the active feedback into *force-feedback*, *virtual force-feedback* and *tactile display* methods. *Force-feedback* exerts real physical forces and typically requires a fixed anchor point. In contrast, *virtual force-feedback* creates perception of force without using external mechanical hardware, as introduced, for example, by Rekimoto [17]. While force and virtual force-feedback define a force vector, *tactile display* methods focus on feedback in the form of vibration, whose intensity can be controlled.

[1]Further examples and technical details of the introduced sensing methods are available on our website: *http://www.imld.de/elasticcon*

RELATED WORK

In this paper, we focus on string-based elastic interaction techniques and therefore group previous work into *ground-based*, *surface-attached* and *body-centric* interactions as well as work on *directly manipulable cords and tapes*.

Ground-based Interaction. Several string-based elastic controllers that are fixed to a static construction have been proposed and consist of 2D or 3D operating spaces in which elastic manipulations are performed and tracked. Zhai built a suspended elastic resistance device called *Elastic General-purpose Grip* that captures the elastic deflection with a 6DoF tracker inside a rubber-band tensioned handle [24]. Sato et al. developed a series of tension-based force feedback devices named *Spidar*. Their first prototypes use gravity in combination with pulsing relays [11], while later versions integrate DC-motors which provide an active and non-uniform feedback under computational control [21].

GameTrak [22], a commercial position-tracking game controller introduced in 2000, captures the position of the hands with two retractable and angular deflection-measuring strings that are fixed to the hands and linked to a ground-based controller. Hand motions for gameplay are tracked in realtime.

Mockup Builder [7] uses two ceiling-mounted Gametrak controllers that are attached to the user's hand combining touch on the surface with hand tracking in the air. This technique enables spatial modeling of 3D models above a tabletop.

Instead of using retractable strings for an absolute position tracking, Yao et al. [23] use a retractable rope for collaborative and social interaction. They propose an interaction repertoire for kinesthetic and social rope actions like releasing, rotating, pulling, intertwining, skipping over, folding or translating.

Surface-attached Interaction. Another related field of research investigates the extension of existing isotonic pen- and finger-based applications with elastic mechanisms to enhance user performance. These approaches are either based on attached passive elements such as rubber-bands that support users' input with an increasing physical resistance [10] or on motorized strings attached to the pen or finger that provide active and directed haptic feedback [13, 20].

Body-centric Interaction. A special form of body-centric elastic interactions focuses on the usage of body-worn retractable strings, which is also the focus of our work. These approaches build on mechanical wind-up mechanisms that are able to change the line segment length through pulling. The traction provides continuous haptic feedback.

Blaskó et al. [3] presented a small wrist-worn dual-display that uses a retractable string control to provide access to a set of information sources. Angular cells can be reached by pulling and angular deflection, which is captured with optical 3D tracking technology display elements integrated in the retracting string are used as visual support.

Koch and Witt [12] proposed a chest-worn and more comprehensive retractable string prototype that tracks 3D positions with built-in potentiometers and features an extra trigger button at the end of the string. However, further DoF are not provided at this point. The authors presented a voxel-based approach in a cone-shaped interaction with a 3x3x3 selection grid comparing it to a regular gamepad in a study. Users could select items more accurately with the retractable string, although participants mentioned limitations of the hardware design (cumbersome trigger button). We follow the call of the authors for further usability improvements and application scenarios and discuss these aspects in detail in our work. We propose suitable real-world applications and novel interaction styles, explored a variety of smart traction buttons, and also conducted a comprehensive user study.

Pohl et al. [16] introduced a belt-worn retractable system with a display mounted at the end of the string. Instead of pulling a tractable knob away from the dual-display (as described by Blaskó et al.), they employ the traction of an interactive badge display itself. The authors propose layered interaction spaces in front of the user and present an interactive floor plan application as a use case, in which the user can switch between depth layers and pan by using the extension distance and orientation of the interactive display badge. A broader usage is however not discussed.

Directly Manipulable Cords and Tapes. A number of approaches focus on direct manipulation techniques for cords such as *sliding*, *pinching* and *twisting*. These techniques are suitable for a wide field of applications and have been proposed for virtual 3D modeling [2], as input methods for mobile devices [19] and to create flexible tangible controllers for common daily tasks (e.g. light control, music player, general computer control) [18]. Our design concept combines aspects of these direct manipulation techniques.

OUR ELASTICCON DESIGN

While several specialized and application-oriented prototypes that use retractable strings have been proposed, we see high potential in a more *generic* controller device with rich DoF and universal mappings, which could be used for *casual interaction* in a wide variety of mobile applications, for large or head-worn displays, or even as smart home controllers. Before presenting the details of our Elasticcon design, we briefly outline the design goals guiding our iterative development process.

Design Goals. To achieve maximum *comfort of use*, we target a natural and low-fatigue use with an appropriate stiffness level (*G1*). Moreover, our design should consider the *entire integration of our upper limbs* including the wide range of motor and perceptual skills to provide comprehensive and synergetic interaction (*G2*). One of our primary goals was *unobtrusiveness* to provide enjoyable, casual and peripheral interactions with minimal instrumentation (*G3*). We deem it necessary to design a *robust* device, that should be able to withstand the pulling force of a human and snap-backs caused by sudden releasing actions (*G4*). The *sensed properties* shall include the pulling length and direction as well as input from *customizable* traction knobs (*G5*). We aim at high-resolution, *precise* position tracking and traction control (*G6*). Our last important requirement is the *flexibility* of the design to sup-

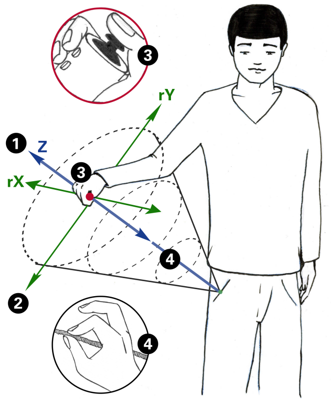

Figure 5. Interaction space in front of the user with our belt-worn Elasticcon. Further input capabilities are provided by the traction knobs.

port versatile fields of application including mobile and eyes-free scenarios (*G7*).

Design Concept. With Elasticcon we support coarse and fine motor skills as well as haptics in a tiny wearable and retractable mobile input device. To achieve this, we propose combining several of the interaction dimensions introduced earlier, i.e. *traction, deflection* and *string manipulations*, with additional exchangeable *knobs* and *haptic feedback*. The resulting interaction space is depicted in Figure 5.

1. Traction. First of all, a retractable knob can be pulled away from the body to control a one-dimensional space. The given DoF can be used continuously as well as discretely with a position- or rate-controlled transfer function. We assume that the knob, which is mounted on a small belt-worn case, does hardly disturb the wearer. The fairly unobtrusive controller can act as a personal companion.

2. Deflection. To handle more complex interaction tasks, which cannot be mapped to the 1D pulling depth, the string's deflection can be used. For these additional DoF, the angle of the string needs to be tracked with an operating angle of 25°in all directions. Similar to the work of Pohl et al. [16], our design uses a cone-shaped interaction space in front of the user.

3. Knobs. User interfaces often support primary and secondary tasks. Primary or foreground tasks refer to interactions that may require high precision control and fine motor skills, while secondary or background tasks are executable with a lower mental demand and coarser movements. The work of Zhai et al. [25] has shown that all parts of the human upper limbs can work together in synergy and can significantly improve performance, especially by considering the fingers. We envision a set of exchangeable knobs based on several physical components such as thumb joysticks, rocker switches, tactile buttons and pressure-sensitive sensors. Every knob has at least one button or other means to simply trigger an action. In addition, knobs allow for a wide range of position-, movement- and pressure-sensing interactions that particularly address primary tasks, while secondary tasks can be executed by pulling and deflecting the string (see Figure 10). Besides contributing additional DoF for rich interaction, knobs can also be simply used for clutching mechanisms. Thereby, the limitations of the interaction range, e.g., the string's pulling length, can be overcome by pressing a button at the maximum length and thereby temporarily decoupling the traction sensing. The user can then go back to a more convenient position at the origin, release the button and again pull out the knob for an extended range.

4. String Manipulation. A conceptual dimension of our design is the retractable string itself. Pulling the string away from the body establishes a physical connection between the wearer's hip and her extended arm. The primary hand defines the length and direction of the string, while the second hand can interact with the retractable line segment (see Figure 2). This enables a powerful bimanual interaction repertoire of quantifiable events. Touching the string at a specific location subdivides the segment. The touch location can either indicate a predefined discretized state, represent a specific or single value in an absolutely-mapped continuous range or change the value relatively to the current selection. Another promising technique that we introduce is bimanual triangulating deflection, that transforms the extracted and tense line segment with the second hand into a highly dynamic and changeable triangular shape. Additional string manipulations, as presented in the section Interaction Dimensions, provide further examples.

Haptic Feedback. Our Elasticcon design comprises both passive and active feedback without restricting the mobility of the user. We envision a retractable traction system driven by a spring-loaded mechanism, that provides tension-based feedback that also can be locked. Its traction resistance can be changed and is even able to exert pull-back forces with an integrated servo motor. This allows to define validity ranges by limiting the maximum traction length, creates the ability to guide the user to a predicted value range or even provides information about the represented data itself by changing the traction resistance dynamically. Furthermore, our design puts emphasis on vibro-tactile feedback. We integrate vibration motors in our traction knobs, that are able to exert different intensities and frequency patterns, thus enabling haptic confirmation feedback.

Synergistic Interaction. We put a particular emphasis on the synergy of the possible interaction dimensions. Our envisioned concept takes advantage of the *physical demands* (considering different muscle groups and joints), the *physical environment* (optimized for mobility and unobtrusive design), *cognitive demands* (does not overstress cognitive functions) and enables a *comprehensive interaction repertoire*, that provides several DoF with a set of input modalities. Since the dimensions are not mutually exclusive, they can be seamlessly combined and flexibly mapped to interaction tasks. The specific mapping and the logical transfer function depend on the application, the type of task that has to be accomplished and also the situational context. In the following two sections, we provide some exemplary mappings of these input channels to both application tasks in specific use cases as well as to well-known and frequent interaction tasks.

USE CASES

In the following, we will illustrate how the Elasticcon design can be used in daily-life activities. We describe three out of the many possible use cases (see Figure 1), which also cover currently emerging mobile technology trends. We exemplify the capabilities of Elasticcon for 1) an unobtrusive private interaction with *wearable displays and glasses*, 2) the effective use in personal and professional environments as a digital Swiss knife that can for example be used for *business presentations*, and 3) the remote interaction with large *public displays* in a casual way.

Private Use: Wearable Displays and Glasses

While technologies of wearable displays or glasses is continuously evolving, suitable precise control mechanisms are still underexplored. Current work focuses either on *hands-free approaches* including speech recognition, blink detection, brain computing or head tracking – obviously not supporting precise interaction – or on *manual approaches*, which use free-hand gestures, touch input on the glasses or separate smartphones. While the latter allow for precision, glass-mounted touchpads might be perceived as obtrusive or additional smartphones are required.

In order to compensate for the lack of haptic feedback and to provide a precise and space-saving manual input technique, we propose the use of our belt-worn Elasticcon for the control of content displayed on the head-worn displays. For example, instead of repeating swiping actions on a touchpad for adjusting parameters, Elasticcon enables a fast eyes-free browsing technique by pulling the string. Furthermore, deflection or additional knobs can be used as additional DoF for example for navigating multi-dimensional menus or interacting with other content overlays.

Personal and Professional Use: Business Presentations

For everyday tasks in ubiquitous and mobile application contexts, the Elasticcon controller could be used as a wearable, universal input device that enables more peripheral and haptic interactions and brings the primary content back to the center of attention. Elasticcon provides a comprehensive set of discrete and continuous DoF, which can be flexibly used for many tasks such as controlling a presentation (see Figure 1, B). For a slide deck presentation, the presenter can, for example, simply pull the controller forward to quickly browse through the deck and find a particular slide. She can also push a traction knob to select a slide and does no longer have to hold the controller permanently in the hand as required by traditional remote controllers. Furthermore, there is no need to look at the controller (as opposed to a smartphone remote-control App). Advanced features like deflection- and distance-based zooming of content or vibro-tactile feedback as a reminder to keep the presentation time are also conceivable. In other application contexts, radial menus could for example easily be operated by the Elasticcon controller.

Public Use: Remote Interaction with large-sized Displays

Large, partly interactive, displays in the public are increasingly widespread. Interactive information booths and transaction terminals can be found in airports, shopping malls, or train stations. By pairing the smartphone and the associated Elasticcon controller (which could also be integrated into the phone's body in the future) with a public display, content can be explored. For example, travel destinations can be found and visited by zooming and panning a digital map combining deflection- and traction-based movements of the belt-worn Elasticcon (see Figure 1, C). Even three-dimensional scenes can be explored with the additional help of the thumb-controlled joystick built in Elasticcon's traction knob while the deflection-based panning technique can effectively work in synergy.

Moreover, Elasticcon's capabilities of complementary isotonic and elastic DoFs can potentially be applied to many other application areas, such as puppeteering, animation control, industrial and machinery operation or drone control.

ESSENTIAL INTERACTION TASKS

Selection, manipulation and navigation are well-known and frequent interaction tasks for many user interfaces. Based on the analysis of our use cases, we can identify three more specific, yet essential and recurrent tasks: precise *single value and range-selections* for adjusting parameters, *hierarchical menus* for choosing options, functions or switching states and *navigation* in multi-dimensional *zoomable information spaces*. We implemented all of the identified essential interaction tasks with Elasticcon to facilitate a systematic and practical investigation.

Single Value and Range Selection

The affordance of a retractable string (and the one DoF associated with pulling it) nicely maps to controlling distance, position and to adjust sub-ranges.

Single value selection. The physically traveled distance can be mapped to a one-dimensional data structure, such as a list, stack or layer in order to browse virtual information spaces. Therefore, we propose a pulling-based selection technique that manipulates a single value in a given data set such as images, songs or documents. In addition, continuous control is supported, for instance, volume control based on the change of length of the pulled string.

Range selection. A number of applications require range selections, where multiple items are marked simultaneously or value ranges are selected. We use buttons mounted in the traction knobs as indicators defining the start and end positions of range selections. We hypothesize that this technique reduces unintended selections and is even suitable as a clutching mechanism supporting relative adjustments.

Hierarchical Semicircle Menu

Pie menus often provide faster and more reliable selections than traditional linear menus, because the selection of an item particularly depends on direction instead of movement distance [5]. We implemented a basic multi-level menu based on the deflection of our Elasticcon. By moving the arm in an outward direction, the item associated with the corresponding angle range is selected, while moving the arm on a circular path browses through the set of items (see Figure 6). As we

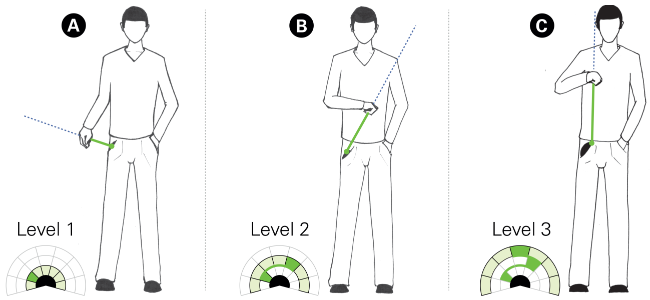

Figure 6. Selection in a half-pie menu with a hierarchical depth of three with five associated items each (mirrored for better illustration). The deflection angle and the pulling distance define the users current selection.

have found out in preliminary discussions and feedback interviews, people tend to have problems navigating within the area that is directly in front of them. To address this issue, we decided to use half-pie menus, thus restricting the interaction space to an interaction zone that is more comfortable for users.

Navigation in Zoomable Information Spaces

We also investigated how pan and zoom actions can be achieved with retractable string-based input in Geographic Information Systems (GIS) as a popular example of a zoomable information space.

Zooming. We use the traction of the string as a *position-controlled* and continuous zoom function. The wearer can pull the string away from her body to zoom out, and release it to zoom in. The pulled distance within the operating range of the user represents the altitude between ground-level and the view from the universe in the GIS (see Figure 7, A). We decided to use a *pull-out/zoom-out* mapping in order to achieve an implicit interaction that is suitable to common spatial mental models and their relation. The pulled knob can be interpreted as a virtual camera, which moves the user away and increases the altitude. A nonlinear transfer function maps the current pulling distance considering the user's maximum pulling distance to an appropriate zoom level. Therefore, we implemented the zoom level on a percentage basis, where the values between these reference points are interpolated according to a smoothed mapping function. Based on this mapping, zooming is finely graduated in lower altitude ranges, while higher ranges are mapped more coarsely.

Panning. In order to provide a fast and precise panning technique suitable for small as well as large distances, we decided to realize the panning actions based on a *rate-controlled* transfer function. We implemented two different settings. Our first setting focuses on *deflection-based panning* that maps the deflection of the pulled string to a specific direction. The wearer can explore the zoomable information space by pulling out the knob to define the altitude, while the deflected position indicates the panning motion vector and its velocity (see Figure 7, B). The knobs provide tactile feedback when the maximal deflection value is reached to help prevent motions in non-trackable regions. In our second setting, we introduce a *joystick-based panning* interaction that uses the thumb-joystick of our wireless-control to govern the panning motion vector and its velocity. This joystick configuration allows us to divide the 3D interaction space into clearly separate 1D and 2D spaces, where string length controls the 1D parameter and the bi-directional joystick the 2D parameter. This separation is presumably more suitable for independent zooming and panning than the previous technique, which uses the string to control all parameters.

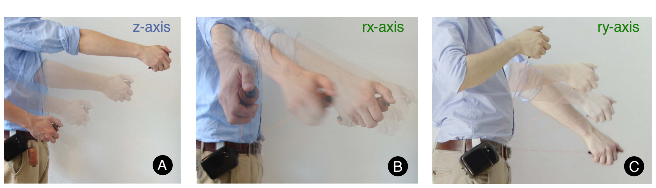

Figure 7. Pulling-based zooming (A) & deflection-based panning (B, C).

PROTOTYPES

During an extensive iterative development process, we built a number of functional low-fidelity prototypes with standard retractable ID card holders and measuring tape components to explore different spring rates and other parameters. Simultaneously, we experimented with a wide range of different electrical switches and sensors. As a result of our iterative design process, we built a working prototype that combines the functionality of retractable string-based input with a comprehensive exchangeable set of haptic input modalities (see Figure 8, 10).

In order to realize the traction (1), deflection (2) and additional knobs (3), i.e. the components of our design concept (cf. Figure 5), the prototype required the implementation of three main functional units: a retractable winding mechanism, related sensing, processing and transmission as well as suitable traction knobs. For that we used a dentless 24-step incremental rotary encoder (see Figure 8, A) to measure the pulling distance by referencing the rotation state (ap-

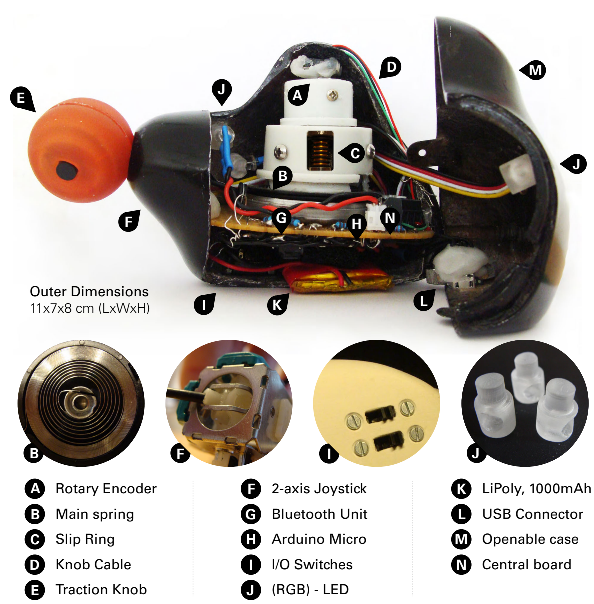

Figure 8. Component overview of our first Elasticcon prototype.

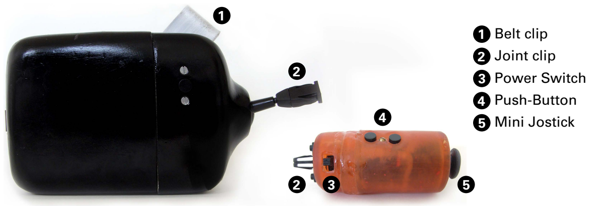

Figure 9. Our second belt-worn Elasticcon and the compoundable wireless control unit with two push-buttons and a thumb joystick.

prox. 1.1mm res., Ø45mm spool diameter) of a spring-loaded wind-up mechanism *(B)* that holds the retractable cable with an overall operating range of 40cm in place. The cable is a thin (Ø2.2mm), robust and flexible three-wire standard audio cable. A slip ring *(C)* with its center at the origin transmits 5V power and two analog or, as needed, pulse-width modulated control signals *(D)* from the casing through the rotating cable reel to the draggable traction knob *(E)*.

The directionality of the corresponding pulling direction is tracked by a two-axis cardan joint *(F)* from a regular thumb joystick. We integrated an HID & SPP compatible Bluetooth module *(G)* with a transmission rate of up to 2.1Mbps for a versatile wireless connectivity. Our main logic board consists primarily of an Arduino Micro *(H)*. Two miniature slide switches (power, HID mode mouse / joystick) *(I)* and three state LEDs (power, charging, connection state) *(J)* were integrated in the casing. The device is powered by a 3.7V lithium polymer battery *(K)* and can be charged and programmed via an external Micro-USB connector *(L)*. The casing *(M)* is made of polyester resin and fibre-reinforced polymer varnished in black (Design Goal, *G*4).

The set of traction knobs is made of custom Ø35mm polyester resin spheres and cylinders with two symmetrical depressions suitable for a safe and pleasant grip (*G*1). To realize the different combinations, we used standard components including a rotary encoder, a Force Sensitive Resistor (FSR), miniaturized tactile buttons, vibration motors and symmetrical rocker switches with a neutral position (see Figure 10).

In addition, we built a second retractable string-based Elasticcon (see Figure 9) that can be mounted with a belt clip and provides a wider operating range with a lighter pulling resistance. This was possible since we built the traction knob as an autonomous wireless controller and omitted the signal cable. In order to capture extremely fast pulling actions, we used a worm drive with an absolute measuring potentiometer instead of an incremental rotary encoder to avoid shifts of the sampling rate. A majority of the remaining components correspond to the first Elasticcon prototype as described above.

To reduce complexity and first focus on synergistic interactions of traction, deflection and input knobs, we did not integrate further advanced string manipulation techniques (as described under 4. in our design concept) yet.

EVALUATION & DISCUSSION

To evaluate our design concept and the Elasticcon prototype implementation, we conducted three small-scale studies to investigate: the selection of exact value ranges using *pulling-based interaction techniques* (S1), the selection of items in a pie menu using *deflection-based interaction techniques* (S2) and finally, suitable input mappings to freely navigate in Google Earth as an example of a zoomable information space using a *combination of both techniques* (S3) (see Figure 11).

For the study, we invited nine unpaid participants, seven males and two females, aged between 25 and 45 (avg. 29). Everybody participated in all parts of the study while standing in front of a screen and executing the tasks with our belt-worn Elasticcon (with joystick knob). The study took about an hour per participant. For this paper, we focus on the *qualitative evaluation* of the study. In-study observations and video recordings allowed us to analyze the users' behavior, and a post-survey questionnaire with nine items graded on a five-point Likert scale was used for satisfaction measurements.

Qualitative Results

First of all, we received positive feedback concerning the retractable mechanism and observed that people naturally adopted a casual posture (cf. Figure 1, right) and enjoyed the interaction while they used our Elasticcon. In the first study (S1) in which participants had to select numeric values, one person said *"I was really surprised and pleased how natural and accurate it felt to select data by pulling a string"*. The post-survey questionnaire backs these observations of a pleasant, easy and familiar interaction (see all questions and response values in Figure 12).

While all of the people that we observed and interviewed were able to quickly become familiar with the *pulling-based*

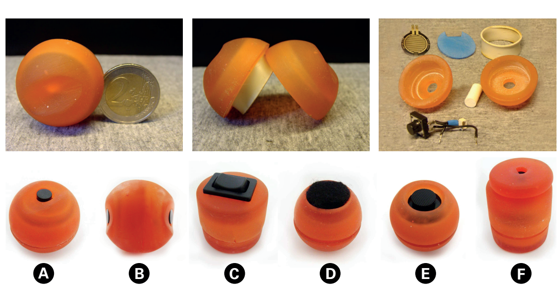

Figure 10. Proposed knob modalities: push-button with vibro-tactile feedback *(A)*, two push-buttons *(B)*, rocker switch *(C)*, pressure-sensitive pad and push-button *(D)*, thumb slide joystick *(E)* and rotary knob *(F)*.

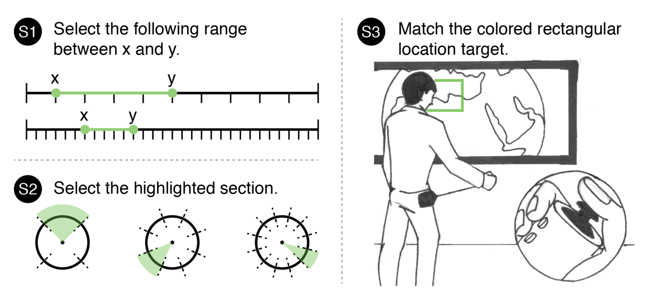

Figure 11. Study parts: Range Selection (S1), Directional Selection (S2) and Navigation in a Zoomable Information Space (S3).

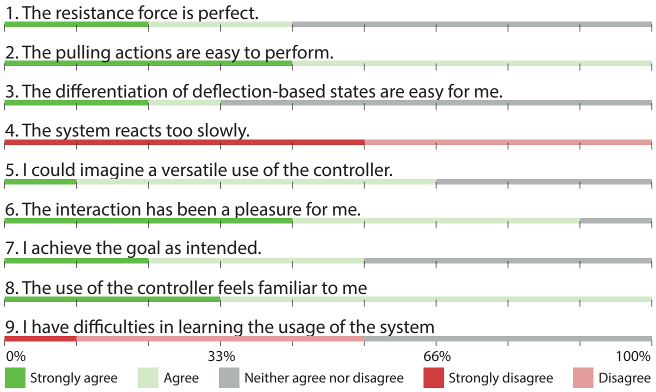

Figure 12. Survey results of questions scored on a five-point Likert scale.

interactions, some had issues using our *deflection-based* radial selection techniques in the second study (S2). A participant mentioned: *"I expected an inverted selection, as I was accustomed to control my game console"*. To address this issue, the transfer function of the controller has to be more adaptable to user preferences. Although we integrated an individual calibration routine to set the maximum pulling distance in relation to the arm extension, it seems very important to also take the *mapping of the y-axis* into consideration, because participants have different expectations of how it should behave. Some expected an inverted control scheme (move upwards: select below), others a non-inverted (move downwards: select above).

Furthermore, some participants mentioned that they sometimes slipped out of place while pushing the selection trigger of the knob. The reason for that is probably the resulting deflection while exerting force on the button. A simple solution to address these issues could be to use temporary buffered data values before the selection is confirmed. Beside these problems, all participants emphasized that they could imagine to use *deflection-based* interactions to quickly access functions due to the simple, spatial and memorable action. In addition, we observed that those participants who initially had problems with Elasticcon were able to rapidly learn how to use the system once the issue had been identified.

Finally, we asked our participants to compare the *deflection-based* and the *joystick-based* panning techniques (cf. essential interaction tasks) using GoogleEarth (S3). Users preferred our novel, simultaneous and synergetic combination of a body-relative, position-controlled depth-axis (z) for zooming and the rate-controlled thumb-joystick for panning in large zoomable information spaces. A likely reason for this result and a general advantage could be the neutral position of the thumb-joystick and the great dexterity of the fingers in finely adjusting it. This assumption is supported by a user comment *"The joystick control is more precise for me, since I can immediately stop by releasing my thumb."*. However, the performance of the setup could be further improved by using a high-quality thumb-joystick, as suggested by some participants with gaming experience. In addition, it would also be interesting to test *deflection-based* panning with an additional velocity trigger button.

CONCLUSION AND FUTURE WORK

In this paper, we investigated the potential of string-based elastic interaction by first outlining a comprehensive design space. We presented *Elasticcon* as a generic controller combining a retractable string mechanism and multiple, exchangeable interactive knobs. With this controller, we contributed a device with multiple DoF for coarse and fine elastic interaction and rich additional input channels. To investigate the feasibility for body-centric interaction, we built two fully-functional *Elasticcon* prototypes and demonstrated their potential for mobile and remote-controlled real-world interaction tasks. Our observations within three small-scale user studies let us suppose that the range of Elasticcon's performance with respect to traction and deflection motion has a sufficient potential for typical mobile interaction tasks. The cone-shaped interaction space is enhanced by finger-operated and continuous input knobs, thereby combining position- and rate-controlled mappings. While many improvements are still conceivable, we believe we were able to demonstrate the wide applicability of this interaction device for selection, manipulation and navigation tasks.

For future work, the device needs to be miniaturized and technically improved to enhance the user experience. Another interesting aspect is the functional integration and evaluation of the string manipulation techniques. In terms of usability, we would also like to run a study comparing the impact of the different knob modalities on task performance for various activities. While our qualitative observations show initial evidence of the suitability of our holistic interaction approach, further comprehensive investigations are required for mobile usage of the device in real-world contexts, actual workflows and its impact on social behavior and public acceptance.

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