LivingDesktop: Augmenting Desktop Workstation with Actuated Devices

Gilles Bailly[1]   **Sidharth Sahdev**[1]   **Sylvain Malacria**[2]   **Thomas Pietrzak**[3]

[1]LTCI, CNRS, Telecom ParisTech, University Paris-Saclay, France
[2]Inria, France   [3]Univ. Lille, France
{firstname.lastname}   [1]@telecom-paristech.fr   [2]@inria.fr   [3]@univ-lille1.fr

ABSTRACT

We investigate the potential benefits of actuated devices for the desktop workstation which remains the most used environment for daily office works. A formative study reveals that the desktop workstation is not a fixed environment because users *manually* change the position and the orientation of their devices. Based on these findings, we present the *LivingDesktop*, an augmented desktop workstation with devices (mouse, keyboard, monitor) capable of moving autonomously. We describe interaction techniques and applications illustrating how actuated desktop workstations can improve ergonomics, foster collaboration, leverage context and reinforce physicality. Finally, the findings of a scenario evaluation are (1) the perceived usefulness of ergonomics and collaboration applications; (2) how the LivingDesktop inspired our participants to elaborate novel accessibility and social applications; (3) the location and user practices should be considered when designed actuated desktop devices.

Author Keywords

Augmented Desktop; Destkop Workstation; Actuated Devices; Mouse; Keyboard; Monitor

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

Desktop workstation remains the most used interface for office work tasks such as text editing, CAD, data analysis or programming. Indeed, pointing with a *mouse*, typing text on a *physical keyboard* and visualizing digital content on relatively *large monitors* are well suited for single users performing office tasks requiring a high level of productivity for extended periods. While several studies investigated how users interact with their devices (e.g. pressing keyboard keys, moving the cursor, etc.), it is not clear how they arrange their devices on the desk and whether we can leverage existing users' behaviors.
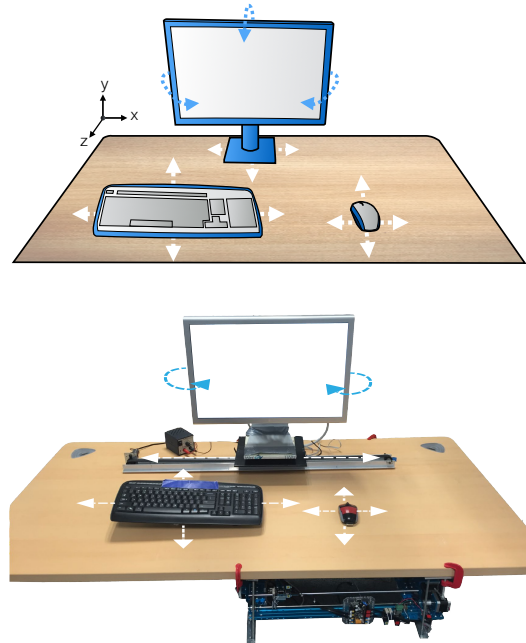
Figure 1. The LivingDesktop concept and proof-of-concept. The LivingDesktop is an augmented desktop with the mouse, keyboard and monitor capable of moving to improve ergonomics, foster collaboration, leverage context and reinforce physicality in the desktop workstation.

In this paper, we conduct a formative study investigating how users arrange and manipulate their desktop workstation devices (mouse, keyboard and monitor). While the desktop workstation is often considered as a *fixed* environment, our observations and interviews reveal that it is actually *semi-fixed* since users often change the position and the orientation of their devices. For instance, they can rotate the monitor to share contents, move the keyboard to adopt an ergonomic posture or move the keyboard and the mouse to make room for physical objects (e.g. food box, tablet).

Based on these findings, we investigate the potential benefits of actuated devices to create richer and more effective interaction on desktop workstations. Actuated interfaces are interfaces in which physical components move in a way that can be detected by the user [34]. They have shown promise in different applications such as tangible interaction [28], public displays [16] or virtual reality (VR) [41] but they have not been investigated in the traditional desktop workstation which has remained essentially the same for over thirty years.

We present the LivingDesktop (Figure 1), an augmented desktop with devices capable of moving autonomously. The LivingDesktop can control the position and orientation of the mouse, keyboard and monitors. It offers different degrees of control for both the system (autonomous, semi-autonomous) and the user (manual, semi-manual) as well as different perceptive qualities (visual, haptic) thanks to a large range of device motions.

The LivingDesktop has several advantages: (1) it improves *ergonomics* by continuously adjusting the position of its devices to help users adopting ergonomic postures and avoiding static postures for extended periods; (2) It facilitates *collaborative* works between local (e.g. located in the office) and remote co-workers. For instance, the teacher can control the mouse of a student during distant teaching; (3) it leverages context by reacting to the position of the user in the office, the presence of physical objects (e.g. tablets, food) or users' current activity to maintain a high level of comfort and (4) it reinforces physicality within the desktop workstation to increase immersion. For instance the monitor and the input devices shake when an explosion occurs in video games, providing both visual and haptic feedback.

We present a proof-of-concept of the LivingDesktop combining rail, robotic base and magnetism to control the position and orientation of the devices. We then conduct a scenario evaluation. Results show (1) the perceived usefulness of collaborative and ergonomics applications (2) how the LivingDesktop inspired our participants to elaborate novel applications including social communication or accessibility.

Our main contributions are 1) a proof-of-concept augmented desktop with devices capable of moving; 2) A set of interaction techniques and applications relying on the findings of a formative study; 3) Findings of a scenario evaluation.

RELATED WORK
The sustainability of the desktop workstation has encouraged researchers to explore ways to augment it. The most common approach is to augment the *software* aspect of the workstation such as new window managers (e.g. [7]). In comparison, little *physical* approaches have been investigated. When creating the LivingDesktop, we sought to build upon the related work in the area of augmented desktop and traditional devices (mouse, keyboard, monitor). We also discuss studies that have inspired the implementation of the LivingDesktop.

Augmented desktop workstation
The primary rationale of augmenting the desktop workstation is to better blend it in office activities. Several works aimed at enabling simultaneous work with *physical information* such as paper documents and digital information [1, 49]. The idea is to enhance paper documents that are cheap, familiar, easy to read, etc. with computation rather than replacing them with computers. For instance, the DigitalDesk [49] and InteractiveDesk [1] recognize and scan paper documents with a camera and augment them with videoprojection.

Other approaches make good use of *everyday human skills* to augment desktop workstation, typically designers who use Wacom tablets for drawing-like activities. In that respect, Hinckley *et al.* considers the ability of humans to use both hands in the real world and present a set of two-handed interaction techniques for desktop [14].

A final approach considers the *furnitures* surrounding the desktop workstation to extent peripheric interaction. For instance, office workers can use the desk as an input (touch or pen input for shortcuts) or output surface to extend the monitor display area with video-projection [3, 17, 45]. The chair can also be used as an input device to capture emotional data, gesture input and support office activities (e.g. [35, 36]).

Our approach also considers the desktop workstation as a whole that should be integrated in its environment, but our primary focus is on augmenting devices and their interaction.

Augmented devices
In parallel, several works augment independently input devices in order to provide novel input or output capabilities.

Some mouse prototypes introduce novel input modalities, for instance, to capture rotations [21, 24, 33] or multitouch input[1]. Others provide visual [50] or haptic [21, 22, 29] feedback. In particular, the Immersion FEELit mouse [37] is mounted on a pantograph to provide efficient haptic sensations but its displacements are limited to a few centimeters without the possibility to lift it. Park *et al.* embedded an electromagnet in a mouse operated over a metal plate to control the difficulty to move the mouse [29], but the mouse is not capable of moving.

Augmented keyboards have been proposed to sense gestures inputs [46, 52] or pressure inputs [9]. Other keyboards provide visual [4] or additional haptic feedback [2, 40].

Finally, actuated displays [6, 8, 20, 42, 44, 51] have been proposed in different contexts. For instance, TouchMover [44] is a touchscreen mounted onto a rail that exerts forces when users are pushing it in a VR context. In video-conferencing, tablet displays mounted on pan-tilt robotic platform have been proposed to increase immersion and telepresence [8, 20, 51]. RoCo [6] is a robotic display with 5 degrees of freedom to improve ergonomics.

Proxemic interaction and micro-mobility
The LivingDesktop is also related to Proxemic interaction and micro-mobility because it considers the distance between the desktop devices and: the user, the other devices, and possible objects on the desk. Proxemic interaction [11] describes the interaction between users and computing devices based on Hall's theory about people use of distance to mediate their interactions with other person [12]. Among others, Greenberg *et al.* describe the orientation and distance between persons or between a user and computing devices, as key measures mediating the interaction in the context of ubiquitous computing. Micro-mobility [23] is at a different scale and considers "*the way in which an artifact can be mobilized and manipulated for various purposes around a relatively circumscribed, or at hand, domain*".

---

[1]https://www.apple.com/magicmouse/

Objects capable of moving
In the literature on actuated devices [34, 38], the LivingDesktop is especially related to actuated tangibles on tabletops [5, 26, 28, 31, 32, 43, 48]. For instance, PsyBench [5] synchronizes the position of tangibles on a local and distant tabletop to enhance real time collaboration in distributed environment. Pico [31] moves tangibles and apply magnetic attraction and repulsion forces to users' movements to satisfy constraints between tangibles (e.g. relative distance) defined in software. TangibleBots [32] ensures physical/digital consistency when manipulating the digital model or allows efficient interaction with multiple tangibles. These works inspired some of the applications of the LivingDesktop (the category called Physicality) as well as the technologies to move objects: motorizing objects [32, 47] or augmenting the surface and using passive objects [28, 31, 48].

In summary, few physical interaction techniques have been proposed to augment the desktop workstation that has remained essentially the same for over thirty years. Some works enrich traditional devices with novel input or output modalities, but we still lack (1) insights on the potential of actuated mouse, keyboard and monitors and (2) how they can interact together in an unified desktop environment.

FORMATIVE STUDY: ARRANGING DESKTOP DEVICES
We conducted a formative study to understand how users currently arrange and manipulate their desktop devices.

Procedure
We collected data from two-month informal observations of desktop users in two laboratory institutions. We also conducted semi-structured interviews with 13 desktop users. The interview was divided into three parts. The first part included questions about personal information (age, profession, frequency of device use, etc.). The second part included questions related to their last working sessions and when, why and how did they arrange and manipulate their desktop devices. Finally, the interviewer presented the collected observations and discuss them with the interviewee.

The 13 participants (3 female), aged 19 to 43 ($\bar{x}$ = 30) including knowledge workers, designers, researchers and students reported occasionally or frequently doing web surfing (100% of them), using office applications (100%), programming (75%), gaming (45%). 93% of the participants (respectively 86%) use the keyboard (respectively the mouse) more than 6 hours per day. Finally, 93% of the participants occasionally or frequently use a second monitor.

Findings
77% of respondents reported having moved either the mouse, keyboard or monitor during their last use of their desktop workstation, beyond the simple fact of controlling the cursor on the screen with the mouse, suggesting desktop devices are generally not adequately located on the desk. We collected respondents' different motivations and organized them into three categories:

1. Ergonomics. Half of respondents reported to frequently rotate their monitor when the luminosity conditions are changing. We observed that users frequently adjust the home position of the keyboard (and some extent the mouse) when correcting or changing their body postures (e.g. moving the chair). Three interviewees tend to rotate their display in order to plug devices. One participant said "*My monitor is quite heavy and far from me. So, I sometimes get up from my chair to access the back of it*".

2. Collaboration. Half of the interviewees often rotate their monitor in order to show its content to somebody else. For instance, one participant reported "*I can rotate my monitor several times per hour when discussing a project with my colleague*". This can also happen with remote users. "*I sometime rotate my monitor [with a embedded webcam] while skyping to show something to the people I chat with*". In the opposite, we observed one user systematically rotating the monitor to prevent other users from seeing it. Finally, we observed several participants passing on mouse and keyboard to grant input control to somebody else.

3. Situation. One respondent rotates his monitor when moving in his office from his desk to a companion table. One respondent also reported rotating the monitor at home when switching activities: "I *work on my desk, but when I watch a movie, I rotate the monitor so this is visible while leaning on my bed*". "*Sometimes, I rotate the monitor in portrait mode when active reading or editing a document. Otherwise I use the landscape mode*". Three users occasionally or frequently use a laptop with their desktop monitor and reported "*moving [their] desktop monitor to fit the virtual desktops configuration to the location of the physical screens*". Observations and interviews revealed that users move their keyboard and mouse back to a specific location every evening when leaving work. Rationale was either because (1) they are office workers working in an open-space environment, (2) their employer requested them to do so, (3) their devices were wireless and required to be charged on their stations. Finally, we observed some participants moving their mouse and keyboard to temporally make some room on the desk for other objects such as food, paper documents or tablets.

In conclusion, while the desktop workstation is often considered as a *fixed* environment, it is actually a semi-fixed one where users are arranging and manipulating the mouse, the keyboard and the monitor to accommodate an ongoing task or a specific activity. In this paper, we investigate whether actuated devices may be a promising approach to support users' behaviors and enrich the desktop interaction experience.

THE LIVINGDESKTOP
The LivingDesktop (Figure 1), is an augmented desktop with actuated devices having similar form factors (size, weight) than current devices (Figure 2). The LivingDesktop can control the position and orientation of the mouse, keyboard and monitors, offering different degrees of control for both the system and the user (from autonomous to manual control). It also offers different perceptive qualities (visual, haptic) thanks to a large range of device motions. Actuating a desktop workstation with the LivingDesktop implies the following design considerations.

Devices. A desktop workstation is composed of a combination of input (mouse, keyboard, tablet, etc.) and output devices (monitor, speakers) that could be actuated. Other devices, typically a phone, are also often on a desk, even though it is not entirely a device of the desktop workstation itself.

Degrees of freedom. This dimension expresses the type of motions users can expect from an actuated device. Ideally, each device should provide 6 *degrees of freedom* (DOFs) with 3 translations (T) and 3 rotations (R) to allow a wide class of applications. However, we will see in the next sections that simple actuations on the horizontal plan (T_x, T_z, R_y) already support a wide range of applications (see table 1).

Levels of perception. The design space of actuated device motions is huge and includes speed, directions and range of motion [30]. Here, we focus on how these motions can be perceived by people in the office. In particular, we distinguish four levels of perception: (1) motions that can be visually perceived by both the user and people around (e.g., rotating the monitor can draw co-workers attention to initiate a collaboration); (2) motions that can only be seen by the user (e.g., moving the keyboard on the desk); (3) motions that can be haptically perceived by the user (e.g., the mouse can provide haptic feedback by shaking or opposing resistance to users' motions); (4) motions that are not consciously perceived by the user (e.g., one application in ergonomics slowly shift devices over time to avoid static postures).

Degrees of control. This dimension is a continuum inspired by HoverPad [43] expressing the degree of control of the user (respectively the system) on the devices. On one end of the continuum, the devices can be *autonomous*. The monitor or a mouse can for instance shake when an explosion occurs in a video-game regardless of the actions of the user. On the other end of the continuum, the user has the full control of the devices actuation (*manual*). In between, we emphasize two degrees of control: semi-manual control occurs for instance when the user is manipulating the mouse and the resistance is partially defined by the system; semi-autonomous control occurs when the system moves the mouse to guide the user's hand. Note that supporting different degrees of control might require powerful actuators (e.g. motors).

Interaction. Users can *explicitly* request devices to move/rotate with different interaction techniques. They can directly manipulate the device itself. They can also perform indirect interaction. To rotate the screen, users can for instance move the mouse, perform a mid-air pointing gesture or simply press a dedicated key on the keyboard. Indirect interaction is especially useful in configurations where the devices is out of hand reach. The interaction can also be *implicit*. It occurs in situations where the user interacts without being aware of interacting. For instance, the monitor can automatically rotate when the user is moving to her companion table.

Sensing context. The LivingDesktop senses the desktop workstation and its surroundings to adapt to user activity. In particular, it is aware of the position and orientation of the devices and objects (e.g. books) on the desk, of user's position and of the applications running on the computer.

Figure 2. Living Desktop setup consisting of a mouse, keyboard and monitor as well as a depth camera to track their position on the desk.

Figure 3. Left. The monitor relies on a servo motor for rotation and a rail for translation. Right. The keyboard is augmented with a robotic base allowing translation (Txz) an rotation (Ry) of the device

PROOF-OF-CONCEPT

Our proof-of-concept comes out of several compromises. Despite the advances in robotics, we are not aware of technologies allowing rapid prototyping of such environments. Introducing actuated devices within the desktop workstation raises several long-term challenges such as (1) the miniaturization of the actuators to keep devices with the same form factor and weight; (2) the quality of the actuation (for instance, the device should quickly react to system instructions to maintain a high level of interactivity and provide enough strength to guide/resists to the users' motions); (3) It should also allow a large variety of motions, ideally 3 degrees of freedom (DoF) in translation and 3 DoF in rotation with a large range of motion; Finally, (4) for deployment, the autonomy and cost should accommodate widespread adoption.

The LivingDesktop setup (Figure 2) comprises three actuated devices (monitor, mouse and keyboard) and a depth sensor to track the locations of the devices and the user.

Monitor. A 65cm × 49cm monitor (2560×1440) rests on a horizontal base capable of rotating at 180 degrees per second speed using a servo motor (TowerPro digital servo Mg995). We brought its rotation speed down to 60 degrees per second to reduce centrifugal forces and prevent the screen from toggling when rotating. A robotic rail (100cm× 9cm) on the table allows the monitor to translate sideways along the desk
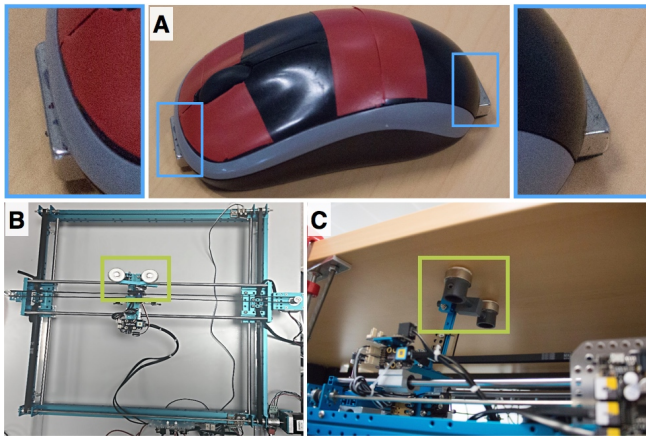
Figure 4. (A) Mouse augmented with two magnets. (B) A plotter under the desk control the position of the mouse. (C) A arm with two magnets to couple (or not) the mouse to the plotter

(Figure 3). The rail uses pulley and timing belt attached to a 12V dc motor with enough torque to translate the monitor screen sideways.

Keyboard. We augmented a wireless keyboard (Logitech MK320) with a robotic base that can translate and rotate (Figure 3). The base consists of a 12V DC motor driven differential drive system for locomotion and a 6V stepper motor for orientation control. The keyboard (6.8cm high) is slightly higher than traditional keyboard. The height may be reduced further depending on the choice of wheels and dc motors.

Mouse. A plotter (Makelblock XY-Plotter Robot Kit V2.0) is positioned under the desk to control the mouse position. Two strong magnets (2×1×0.5cm) are attached on the plotter arm and on the mouse (front and back) to magnetically couple these two elements on demand and maintain the orientation of the mouse. The strength of the magnetic field was chosen after several iterations to offer adequate resistance to the users movements without completely blocking their movements. Moreover, the actuator power should be stronger than the magnetic field to ensure that disengagement of the mouse is still possible. The working area is 310mm×390mm which is larger than common mouse pads.

Tracking devices, objects and hand gestures. We used a RGBD camera (Microsoft Kinect) fixed over the desk (Figure 2) and OpenCV to track the position and orientation of the devices. We consider all objects located less than 8cm over the desk on the depth image (Figure 5) as *objects* and then user colors tags to recognize the mouse and keyboard of other objects. Indeed, recognizing a device from its shape with the depth image may not be sufficient, especially because the hand can mask much of the device. We also ignore objects that are too small to be devices (typically, a pen). Feedback from the kinect sensor keeps track of the physical mouse and other devices on the table. From the depth image, the system can also recognize rectangular objects approaching the desk. Finally, it can recognize a pointing gesture performed by the user between 8 and 20 cm over the desk (see Figure 5).
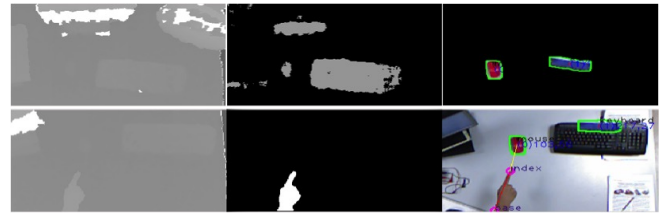

Figure 5. Top: The image is segmented by depth and color to track objects. Bottom: "pointing" gesture before and after depth segmentation.

Controller & Software. Devices communicate with our system using a Arduino micro-controller through an USB Serial port. Applications communicate with these devices thanks to a dedicated protocol. The system is then responsible for sending instructions to devices, analyzing the data from the depth camera, and relating that information with user activity. The prototype is based on Qt/C++/OpenCV and run under Linux. We developed a library that encapsulates the communication protocol, and provides a discovery protocol over serial ports to ease the detection and connection of devices.

APPLICATIONS

We foresee four main classes of applications that would benefit from the LivingDesktop. The first three directly result from the formative study. They describe *existing* users' behaviours and aim at improving ergonomics, fostering collaboration and leveraging context. The last class of applications is called "Physicality" and consists of bridging the gap between digital and physical desktop. The list of applications we are now presenting is not meant to be exhaustive but illustrates potential benefits of the LivingDesktop for each category. We will see in the section "Scenario Evaluation" that our participants also built on the LivingDesktop to elaborate novel usages. The applications are summarized in the table 1.

Ergonomics

Office work often requires people to remain in static positions for extended periods [13]. However, the restriction of movement leads to pain, fatigue and potential long-term injury such as the carpal tunnel syndrome[2], especially when people do not adopt the appropriate postures. The two following applications focus on these two problems: inappropriate postures (*Configuring*) and static postures (*Shifting*).

Configuring. When the user is sitting down in her working chair, the system detects her current posture either with sensors in the chair [35, 36] or computer vision system located above the desk (see implementation section). The system then moves the mouse, keyboard and monitors to ensure a safe working environment compatible with ergonomic postures: the monitor moves in front of the user, rises to have the top of the screen with the users' eyes and slightly tilt upward in order to avoid possible neck and shoulder pain [13]. The keyboard moves in front of the user just above the level of her lap. The mouse stays close to the keyboard to not have to reach far to grasp it. The keyboard can also slightly tilt away depending on the angle of the user's arm.

---

[2]

Application	Devices	DOFs	Perception	Control	Interaction	Sensing
ERGONOMICS						
Configuring *						
- **Initial configuration**	(mouse, keyboard, monitor)	T_{xyz}, R_{xyz}	Visual	Autonomous	Implicit	User posture
- Adjust posture [6]	(mouse, keyboard, monitor)	T_{xyz}, R_{xyz}	Visual	Autonomous	Implicit	User posture
- **Adjust brightness**	(monitor)	R_y	Visual	Autonomous	Implicit	Ambient light
Shifting	(mouse, keyboard, monitor)	T_{xyz}, R_{xyz}	$\emptyset$	Autonomous	Implict	User posture
Pluging *	(monitor)	R_y	Visual	Manual	Explicit - Indirect	
COLLABORATION						
Co-Working *	(monitor)	R_y	Visual	Manual	Explicit-Indirect	
Video-conference [8, 20, 51]	(monitor)	R_y, R_z	Visual	Manual	Explicit-Indirect	Mid-air gesture
Distant control						
- Touchy Talkie [39]	(mouse)	T_{xz}	Haptic	Semi-autonomous	Explicit-direct	
- **Distant teaching**	(mouse)	T_{xz}	Haptic	Semi-autonomous	Explicit-direct	
SITUATION AND CONTEXT AWARNESS						
Following *	(monitor)	R_y	Visual	Autonomous	Implicit	User location
Tidying *						
- **Recharging devices**	(mouse, keyboard)	T_{xz}	Visual	Autonomous	Implicit	Objects
- **Moving devices away**	(mouse, keyboard)	T_{xz}	Visual	Autonomous	Implicit	Objects
Devices on demand						
- **Bringing devices**	(mouse, keyboard, monitor)	T_{xz}, R_z	Visual	Autonomous	Implicit	Activity
- **Portrait/landscape mode**	(monitor)	T_{xz}, R_x	Visual	Autonomous	Implicit	Activity
PHYSICALITY						
Relief [27][44]	(mouse, monitor)	T_{xz}	Haptic	Semi-Manual	Explicit-Direct	
Shaking	(mouse, keyboard, monitor)	T_{xz}, R_{yz}	Visual/haptic	Autonomous		
Virtual Space *						
- **Peephole display**	(monitor)	T_{xy}	Visual	Manual	Explicit-Indirect	
- **Displays arrangement**	(monitor)	T_{xy}	Visual	Manual	Explicit-Indirect	

Table 1. The seven features of the LivingDesktop for the proposed applications. (1) Applications inspired from the formative study are marked with *; Novel applications are in bold; (2) Device; (3) Degrees of freedom (DOFs); (4) modality related to levels of perception; (5) Degree of control; (6) Interaction; (7) Sensing context.

Inspired by Roco [6], the LivingDesktop can also dynamically adjust the user's posture. The devices can either move away until the user adopts an appropriate posture, or subtly move to a position so that the user has a tendency to mirror the movements of the devices and adopt a better posture.

Some systems adjust the monitor brightness according to ambient light. A LivingDesktop with luminosity sensors extends this feature by slightly changing the orientation of the monitor according to the direction of light to avoid uncomfortable light reflection.

Shifting. The devices *slightly* shift over time to force users to regularly adjust their positions and avoid static postures for extended periods and prevent repetitive stress injury.

Pluging. Tapping on a dedicated keyboard key makes the monitor rotate and come closer to ease plugging/unplugging a device. A second tap moves it back to its default configuration. This can be used with most of the monitors on the market which have various plugs (usb, firewire, ethernet, dvi, etc.) located at their back.

Collaboration

Co-working. The LivingDesktop allows users to easily rotate the monitor, either to share screen contents with co-workers located in the office (Figure 6-left) or to prevent shoulder surfing. Users press a dedicated key on the keyboard (e.g. Function key) to enter in the pseudo mode "Monitor control". They can then control the orientation of the screen by dragging the mouse. Users can also double tap on the key to rotate the monitor to a bookmarked angle such as both the user and the visitor (sitting on the visitor chair) can see the screen. Double tapping a second time, rotates the monitor back to its default orientation. Instead of using the keyboard, a button can be located on the monitor itself. While this functionality can be more easily discovered than a dedicated key, it is slower because it requires larger arm movements. Moreover, it does not work when the monitor is out of arm reach.

Video-conferencing. The LivingDesktop can enrich video-conferencing experience. When a local user wants to show an element in the office (e.g. an object on the desk, an equation on the whiteboard, etc.) during a video-conferencing, she presses the dedicated key and points towards this object
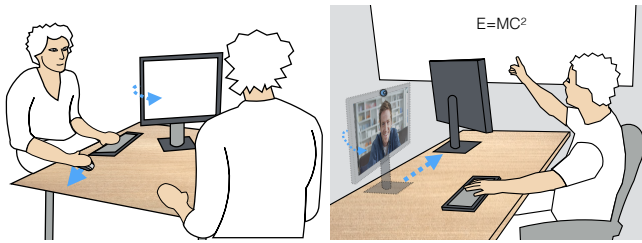
Figure 6. left. The user rotates the monitor to share screen content with his co-worker by using a dedicated key on the keyboard and moving the mouse. **Right.** The user presses a dedicated key and points towards an object to make sure that this object is inside the field of view of the webcam and visible from the remote user.

Figure 7. The monitor follows the user to be readable when working on her companion standing table.

Figure 8. The LivingDesktop anticipates when the user wants to put an object on the desk and make room for it.

as shown on Figure 6-right. The livingDesktop then rotates the local monitor (equipped with a built-in camera) and makes sure that this object is inside the field of view of the embedded webcam. The user can also use the mouse instead her hand to rotate the monitor. In this scenario, the local monitor reacts *explicitly* to the actions of the *local* user. The local monitor could also *implicitly* react to the actions of the *distant* user. For instance, the motions of the monitor are coupled to the head movements of the distant user. This application, inspired by [8, 20] makes the telepresence more engaging because it gives natural feeling of head movement as in a face-to-face conversation. While this application relies on an actuated monitor, the next one uses an actuated mouse.

Distant Control. The idea of this application is to control the mouse of a distant user. The actuated mouse can be used as a "touchy Talkie" [39] to communicate a message through the haptic modality: the user moves her mouse to shape a "heart". When the distant user touches his mouse, the mouse reproduces the same path to communicate the "heart" [39].

The actuated mouse can also be used for remote teaching. When the remote teacher wants to attract the attention of a student on a specific element on the screen, he can take the control of her cursor but also the mouse to physically guide the hand of the user through haptic feedback. While traditional systems allow distributed users to share *digital* contents, the Living Desktop also allows them to share *physical* devices [5] and to assist them with haptic feedback.

Situation and Context awareness

Following. The monitor "follows" the user in her office (e.g. standing on his companion table) by changing its orientation. It displays notifications (e.g new emails, agenda alerts, missed calls, etc.) and adapts the size of what is displayed so it can be read regardless of the distance (Figure 7).

Tidying. To keep the desk tidy, the devices move away when the user shuts down the computer, when he leaves his office or after a period of inactivity (e.g. 10mn). Moreover, the devices can move to their charging stations. This is especially useful with state of the art wireless devices (e.g. keyboard with embedded screens [4] or actuators [2], shape-changing mouses [21]) using more energy than conventional devices.

The LivingDesktop can also make room for other objects (Figure 8). It detects (with computer vision) when the user
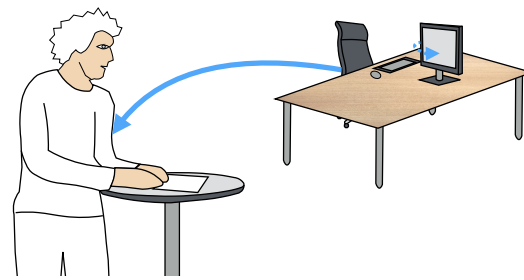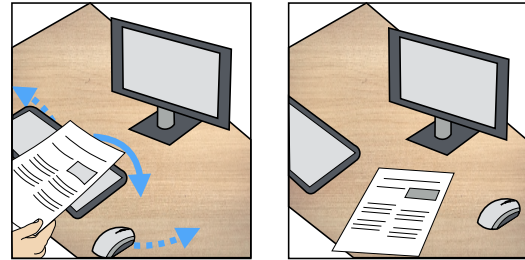
carries an object in her hands (e.g lunch box, printed document, tablet, etc.) and anticipates whether she wants to put it on the desk by moving the devices on the sides. This scenario can be extended to virtual objects when the desk is used as a large output surface (with a tabletop or video-projection) [3]. For instance, the keyboard and the mouse masking important information (e.g. cities) of a virtual map move away to keep information visible.

Devices on demand. The LivingDesktop brings the desired pointing device at hand (or move it away) depending of the current activity. Indeed, some users have several pointing devices, depending of the task they perform, typically one graphic tablet for design tasks and one mouse for other activities (office work, games).

The orientation of the screen can also depends on the current activity: The monitor automatically rotates from the landscape mode to the portray mode when editing a digital portray on Adobe Photoshop or when activating the full screen mode of Adobe Reader with a portray format document in order to make reading more comfortable.

Physicality

A key feature of the Livingdesktop is to reflect digital changes into the physical world through the actuated desktop devices. Actuation has already been used in tangible interfaces to preserve consistency between digital information and physical object [28, 32]. For instance, the position of sliders in a sound mixer can be controlled by the system to be consistent with the current sound parameters. Similarly, the LivingDesktop aims at introducing more physicality in desktop interaction, either to decrease the inconsistency between desktop devices and the manipulated virtual data or to increase immersion by exploiting a larger range of perceptual qualities.
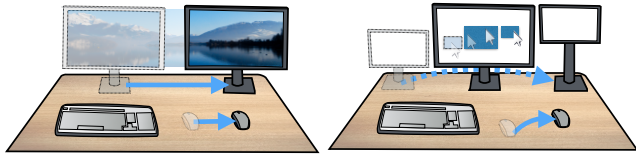
Figure 9. Left. The monitor acts as a *peephole display* over the virtual space. Right. The relative position of the secondary monitor fits the virtual spatial configuration.

The coupling between the physical mouse and the virtual cursor is usually one way: the mouse displacements control the position of the cursor. However, changes in the location of the cursor are not reflected by the mouse. The LivingDesktop allows bidirectional interaction to maintain consistency between digital information and the physical desktop devices (mouse, keyboard and monitor).

Relief. The LivingDesktop can make games or graphical information systems more tangible. For instance, the mouse behavior can simulate the depth on monitors. Depending on the position of the cursor, the system can change the coefficient of friction and constraint trajectories to act as physical gravity wells [27]: the "avatar" can shift along the slip of a ditch or provide resistance when rising a hill. This application illustrates how to reduce inconsistencies between the mouse and the cursor to increase immersion.

This application can be extended to touchscreens: The user touches and feels the relief of a map on the screen which moves on the z axis depending on the position of the finger on the map such as the TouchMover system[44].

Shaking. Applications can also rely on more autonomous behaviors. The mouse and the monitor could shake when explosion or a crash occurs in a game to simulate visual (monitor) and kineasthetic sensations (mouse, keyboard).

Virtual Spaces. LivingDesktop can also be used to navigate in very large documents such as images or maps that cannot be displayed entirely on the screen. When the cursor is approaching the border of screen, the navigation relies on rate-control. However, instead on moving the digital content within the frame of the monitor, the monitor is shifting as a window on the digital content. Thus, the monitor becomes a *peephole display* over the entire virtual space (Figure 9-left), which can theoretically increase spatial recall accuracy over the traditional *panning* approach [19]. We also considered *virtual desktops* which are supported by most recent operating systems. Typically, Mac OS X allows users to organize their applications and windows in virtual desktops arranged in an horizontal line. The LivingDesktop brings this concept into the physical world. It changes the physical position of the monitor depending on the current virtual desktop. For instance moving the monitor to the right when the user switches to the next virtual desktop.

In the same spirit, when users are editing the "Displays Arrangement" preferences, the physical relative position of the monitors is arranged automatically to match the configuration in the virtual space (Figure 9). If the user uses a laptop on his desk, the position of the second monitor can be updated according to the current position of the laptop on the desk.

Implementation

All the above described applications have been implemented for our LivingDesktop prototype. However, functionalities requiring to sense the environment remain limited. For instance, sensing user posture is limited to tracking user's head and hands. Moreover, user is only tracked in the vicinity of the desktop due to the limited field of view of the Microsoft Kinect. Advanced skeleton tracking and using wide-lenses (or raising the kinect when possible) could be used to better track user's activity and postures. Finally, the scenarios only use the available degrees of freedom of our prototype. For instance, the scenario changing the orientation of the monitor from landscape to portrait is incomplete but would be possible with a robotic arm.

SCENARIO EVALUATION

The goal of this study is to both collect feedback about the system and investigate whether the setup could trigger novel usage or applications. To achieve this, we deployed an online survey via mailing lists and social networks for evaluating a subset of 6 applications through videos. We chose a video-based evaluation to reduce the impact of the implementation on participants subjective feedbacks, because our prototype faces miniaturization and autonomy problems and may not be ready for extended use. We focused on applications where motions of devices was easy to perceive on videos, and took care to cover the four classes of applications. Each application was illustrated with a video showing the experimenter interacting with our Living Desktop proof-of-concept. The video was presented in an order that would make sense for an office worker. The scenario was the following:

(1) Bob enters in his office and the monitor rotates to indicate the time of his next meeting. (2) Bob then seats on his working chair. As his posture was not ergonomic, the keyboard and the mouse move away until he adopts a more ergonomic posture. (3) Bob decides to navigate within a large image. He drags the mouse to use his monitor as peephole display. After a break, (4) Bob seats back to his office and put his lunch box and the paper in front of him making the keyboard and the mouse move away to free the desk. When he has finished to read the paper, (5) Bob starts a video skype call with Linda to present his novel idea. When explaining the concept on the whiteboard, the monitor rotates so that the whiteboard is in the field of view of the embedded webcam. The skype call over, (6) Simon wants to help Bob to finalize his talk for this afternoon. Bob rotates the monitor with a dedicated key on the keyboard to share screen content with Simon. At the end of the day, Bob shuts down his computer and his devices move back in place to keep the desk tidy.

After each scenario, we asked (using a 7 item Likert scale) whether the presented scenario was liked, useful and amusing. They could also provide comments. Finally, at the end of the survey, one open question invites participants to suggest novel applications for the LivingDesktop system.
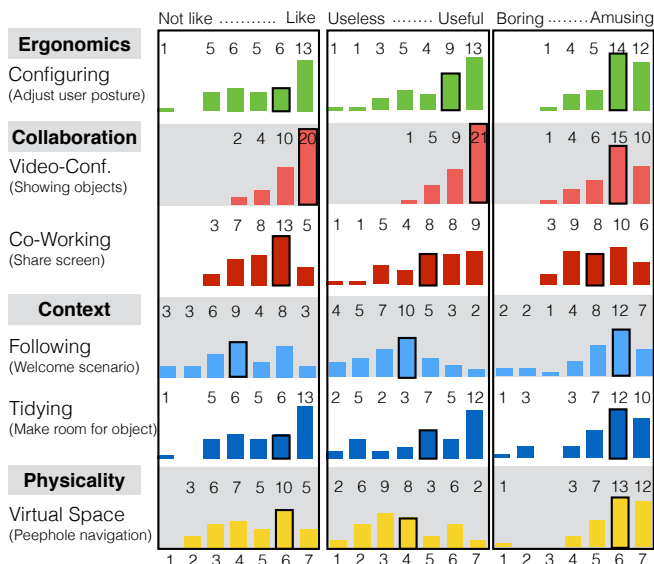
	Not like .... Like	Useless .... Useful	Boring ....Amusing

Figure 10. A summary of participants responses to the 7-point Likert scale questions with the median indicated.

Results

36 participants (11 female) aged 22 to 40 years (mean=28.8, SD=5.0) completed our online survey. Due to the growing concerns regarding null hypothesis significance testing [10], especially in the context of Likert-Scale measures [25, 18], we base our analysis on histogram distributions of ratings and medians (Figure 10). The distributions reveal that participants were particularly enthusiastic regarding three applications: Video-Conferencing (collaboration), Configuring (Ergonomics) and Tidying (context).

Video-conferencing. Video-conferencing received the highest subjective evaluations, especially for its perceived usefulness (median of 7). Participants reported they found it likely to be "*Very useful*", "*Useful in a closed office*"; they also found it was a "*Very good idea because rotating a monitor is every time very cumbersome while video-conferencing*".

Configuring. Participants also reported positive rates for this ergonomics application (median for 6 for all criteria). They mentioned "*I recognize myself and many people in this posture. This could encourage many people to adopt healthier habits*". "*It is a very nice way to improve the posture at work.*", "*This is a very good feature which I personally want to use, the problem is very practical and everyone in the office faces it.*". However, some respondents questioned the applicability of the approach: "*It could be useful, or not. Depending on what we're doing at the moment.*", highlighting the needs of being able to recognize user's posture and activity.

Tidying. Respondents liked the scenario where the devices make room for objects (median of 6) and found it amusing (median of 6). One stated "*I like it a lot. This is really good. I often move my keyboard to eat and I can completely relate to the use case.*". One also mentioned possible limitations when the desk is cluttered of documents: "*This might be difficult to achieve because of the clutter on the desktop*".

Co-Working. This application received strong divergences of opinions and was evaluated as moderately useful (median of 5) and amusing (median of 5) by participants. While some participants reported "*I think it is very useful. It is a very common problem in my job environment*" or "*This problem is finally solved*", others were less enthusiastic either because they "*do not think it would be useful*" or because they find it "*very easy to turn the screen*".

Virtual space. Participants were mixed regarding the usefulness of this application (median of 4), but still liked it (median of 6) because they found it amusing (median of 6). More precisely, they found it "Cool" and "Fun" and one participant said: "*I think this is really nice. If it can move forward and backward, it would be nice as well as that can be the zoom in/out.*". This result highlights the high potential of this application for playful applications and games.

Following. Participants did not like this application (median of 4) and were not enthusiastic about its usefulness (median of 4). They raised several potential privacy issues and were concerned whether it could "*be disturbing for other persons in the workspace*".

Untested techniques

Several participants suggested additional applications described in the paper but not tested in the user study. For instance, the monitor "*moves to not reflect the sun*" or moves back when the user is too close to "*ensure a minimum distance with the eyes and avoid eye fatigue*" (Ergonomic). One participant suggested to "*have one mouse for two seats*" or "*remote teaching scenarios*" (Collaboration). One considered the "Following" application "*useful at home. The screen lights up, rotates with me and provides information*" (Context). Two participants proposed to shake the mouse or the monitor in games (Physicality). Some participants also suggested applications we had not considered:

Accessibility. Two participants (one being a professional working with visually impaired people) reported that the LivingDesktop would be useful for people with disabilities. The *Configuring* application can be useful for people with motor impairments for moving the mouse in the vicinity of the user's hand. It can also be useful for visually impaired people to easily find the location of the input devices or to make the screen content readable by moving it closer.

Social Communication. Two participants suggested social communication applications for co-workers: "*Instead of sending an email to my co-worker, I will temporally show him my screen*" or "*I would attach post-its or other small objects on the mouse and 'order' it to visit my co-worker*". Another application was that when "*you want to speak to your colleague just behind the screen, it could go down a bit*".

Other. One respondent envisioned VR applications: "*When gaming with a VR headset, it can be difficult to grasp the keyboard. It could move towards my hands when I am trying to grab it*". One participant taking yoga video lessons would like the monitor to rotate to follow her postures when practicing. Finally, several participants wanted to actuate other objects such as a lamp or a phone.

DISCUSSION

The participants of our scenario evaluation were particularly enthusiastic with *ergonomics* and *collaborative* scenarios. The system also inspired them as they proposed various additional applications: some that we already considered but did not evaluate, and other novel applications in different domains including accessibility for people with visual or motor impairments or social communications with verbal or non verbal communications.

Our results also highlighted the critical importance of considering the context of interactions. Indeed, participants reported about the Following application that actuated monitor can be obtrusive and disturbing in a workspace. In the opposite, some participants see the LivingDesktop as an opportunity to have "*non-verbal communication between co-workers*". Others mentioned the efficiency of this system at home. Our evaluation was probably bias because the videos were performed in an open spaces with co-workers due to technical constraints. Results could have been different in a closed office or at home. It appears that the location should be seriously considered when deploying this technology.

We also observed strong divergences between participants regarding some applications, often because of different practices and habits between participants. For instance, while some participants found the Co-working application very useful, others found it useless because it can also be done manually. It seems, from the analysis of comments, that the perception of usefulness of this application is correlated to *user practices* and how frequently users perform this operation.

An other critical point highlighted by our scenario evaluation was the importance of not giving "too much" control to the LivingDesktop. This raises one key challenge of future actuated devices: How much should actuated devices be automated/ be controlled by the user? Table 1 shows that our applications cover several *degrees of control*: autonomous, semi-autonomous, semi-manual and manual. However, it appears that several participants were concerned that the system could be unpredictable due to its partial knowledge. We therefore recommend to carefully consider the *degree of control* with the LivingDesktop and to grant users full control of their desktop devices (contrary to adaptative interfaces). For instance, a dedicated key on the keyboard (or on the monitor) could be used to trigger the "Following" mode which can easily be cancelled if a second person enters in the office or if the user is leaving the office. This can for instance reduce the feeling of privacy issues or disturbance for others. However, Mixed initiative [15], which consists of sharing the control over the actuated interfaces between the user and the system, is a promising (but challenging) direction for future work.

A limitation of the LivingDesktop is of course when the desk is cluttered with objects, because the actuated devices are likely to be blocked by or to push objects away. Interestingly, two participants of our scenario evaluation reported that they already knocked objects when they *manually* rotated the monitor. In fact, we see the LivingDesktop as an opportunity to avoid knocking objects with desktop devices. One feature of the LivingDesktop is indeed to sense the presence of objects on the desk (our proof-of-concept using a Microsoft Kinect depth camera). A depth model of the desk and objects located on its surface can be used to prevent actuated monitors (e.g. robotic arms) to move, or make them take a different path in order to not knock objects.

Finally, we believe the results of our scenario evaluation have been strongly influenced by the current technologies used for implementing our proof-of-concept. Indeed, several participants commented that "*The monitor rail takes too much space on the desk*", that "*the keyboard is too high*" or that "*the mouse controller [plotter] could hurt my knees*". Some participants also hoped for smoother and faster motions of the actuated devices. While our prototype has been useful for exploring the potential of actuated desktop devices, we believe an evaluation conducted with better quality and miniaturized implementations would lead to better results. Different implementations could also lead to novel applications, thanks to additional degrees of freedom in our proof-of-concept. Typically, we envision applications where the monitor move front and back and is combined with zoom-based interfaces. Future work should also actuate other equipments and devices that are generally available on a desktop workstation such as a phone or a lamp as suggested by the participants. A promising one is the laptop which is more and more frequently used in workspaces, often combined with other desktop devices.

CONCLUSION

HCI designers just started to explore possible applications of actuated objects [30]. In this exploratory project, we investigated whether actuated devices may be a promising approach for one of most popular interactive environment: Desktop workstations.

We contributed a deeper understanding on how users are arranging their desktop devices. We also provide insights about actuated workstations by describing its main features as well as a set of applications including support for ergonomics, collaboration, context awareness and physicality. Finally, the scenario evaluation provides three main findings: (1) actuated desktop devices appear as a promising approach for applications such as ergonomics and collaboration; (2) Others contexts of application such as accessibility, or social communication could also benefit from actuated devices. Finally, (3) the environment and in particular the location and users practice should seriously be considered when designing actuated interfaces for desktop workstations.

REFERENCES

1. Arai, T., Machii, K., Kuzunuki, S., and Shojima, H. Interactivedesk: A computer-augmented desk which responds to operations on real objects. In *Conference Companion on Human Factors in Computing Systems*, CHI '95, ACM (New York, NY, USA, 1995), 141–142.

2. Bailly, G., Pietrzak, T., Deber, J., and Wigdor, D. J. Métamorphe: Augmenting hotkey usage with actuated keys. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, ACM (New York, NY, USA, 2013), 563–572.

3. Bi, X., Grossman, T., Matejka, J., and Fitzmaurice, G. Magic desk: Bringing multi-touch surfaces into desktop work. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, ACM (New York, NY, USA, 2011), 2511–2520.

4. Block, F., Gellersen, H., and Villar, N. Touch-display keyboards: Transforming keyboards into interactive surfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, ACM (New York, NY, USA, 2010), 1145–1154.

5. Brave, S., Ishii, H., and Dahley, A. Tangible interfaces for remote collaboration and communication. In *Proceedings of the 1998 ACM Conference on Computer Supported Cooperative Work*, CSCW '98, ACM (New York, NY, USA, 1998), 169–178.

6. Breazeal, C., Wang, A., and Picard, R. Experiments with a robotic computer: body, affect and cognition interactions. In *Human-Robot Interaction (HRI), 2007 2nd ACM/IEEE International Conference on*, IEEE (2007), 153–160.

7. Chapuis, O., and Roussel, N. Metisse is not a 3d desktop! In *Proceedings of the 18th Annual ACM Symposium on User Interface Software and Technology*, UIST '05, ACM (New York, NY, USA, 2005), 13–22.

8. Chua, Y., Tee, K. P., Yan, R., Li, L., and Huang, Z. Towards more engaging telepresence by face tracking. In *Proceedings of the Workshop at SIGGRAPH Asia*, WASA '12, ACM (New York, NY, USA, 2012), 137–141.

9. Dietz, P. H., Eidelson, B., Westhues, J., and Bathiche, S. A practical pressure sensitive computer keyboard. In *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology*, UIST '09, ACM (New York, NY, USA, 2009), 55–58.

10. Dragicevic, P., Chevalier, F., and Huot, S. Running an hci experiment in multiple parallel universes. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '14, ACM (New York, NY, USA, 2014), 607–618.

11. Greenberg, S., Marquardt, N., Ballendat, T., Diaz-Marino, R., and Wang, M. Proxemic interactions: the new ubicomp? *interactions 18*, 1 (2011), 42–50.

12. Hall, E. T. The hidden dimension .

13. Healy, G., Lawler, S., Thorp, A., Neuhaus, M., Robson, E., Owen, N., and Dunstan, D. Reducing prolonged sitting in the workplace. *Human Factors and Ergonomics Society* (2012).

14. Hinckley, K., Czerwinski, M., and Sinclair, M. Interaction and modeling techniques for desktop two-handed input. In *Proceedings of the 11th Annual ACM Symposium on User Interface Software and Technology*, UIST '98, ACM (New York, NY, USA, 1998), 49–58.

15. Horvitz, E. Principles of mixed-initiative user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '99, ACM (New York, NY, USA, 1999), 159–166.

16. Ju, W., and Sirkin, D. Animate objects: How physical motion encourages public interaction. In *Proceedings of the 5th International Conference on Persuasive Technology*, PERSUASIVE'10, Springer-Verlag (Berlin, Heidelberg, 2010), 40–51.

17. Kane, S. K., Avrahami, D., Wobbrock, J. O., Harrison, B., Rea, A. D., Philipose, M., and LaMarca, A. Bonfire: A nomadic system for hybrid laptop-tabletop interaction. In *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology*, UIST '09, ACM (New York, NY, USA, 2009), 129–138.

18. Kaptein, M. C., Nass, C., and Markopoulos, P. Powerful and consistent analysis of likert-type ratingscales. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2010), 2391–2394.

19. Kaufmann, B., and Ahlström, D. Studying spatial memory and map navigation performance on projector phones with peephole interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, ACM (New York, NY, USA, 2013), 3173–3176.

20. Kawaguchik, I., Kuzuoka, H., and Suzuki, Y. Study on gaze direction perception of face image displayed on rotatable flat display. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, ACM (New York, NY, USA, 2015), 1729–1737.

21. Kim, S., Kim, H., Lee, B., Nam, T.-J., and Lee, W. Inflatable mouse: Volume-adjustable mouse with air-pressure-sensitive input and haptic feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, ACM (New York, NY, USA, 2008), 211–224.

22. Kudo, H., Suzumori, K., and Kanda, T. Force feedback mouse with differential mechanism for omni-traveling. In *Micro-NanoMechatronics and Human Science, 2007. MHS '07. International Symposium on* (Nov 2007), 430–435.

23. Luff, P., and Heath, C. Mobility in collaboration. In *Proceedings of the 1998 ACM Conference on Computer Supported Cooperative Work*, CSCW '98, ACM (New York, NY, USA, 1998), 305–314.

24. MacKenzie, I. S., Soukoreff, R. W., and Pal, C. A two-ball mouse affords three degrees of freedom. In *CHI '97 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '97, ACM (New York, NY, USA, 1997), 303–304.

25. Marcus-Roberts, H. M., and Roberts, F. S. Meaningless statistics. *Journal of Educational and Behavioral Statistics 12*, 4 (1987), 383–394.

26. Nowacka, D., Ladha, K., Hammerla, N. Y., Jackson, D., Ladha, C., Rukzio, E., and Olivier, P. Touchbugs: Actuated tangibles on multi-touch tables. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, ACM (New York, NY, USA, 2013), 759–762.

27. Oakley, I., McGee, M. R., Brewster, S., and Gray, P. Putting the feel in 'look and feel'. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '00, ACM (New York, NY, USA, 2000), 415–422.

28. Pangaro, G., Maynes-Aminzade, D., and Ishii, H. The actuated workbench: Computer-controlled actuation in tabletop tangible interfaces. In *Proceedings of the 15th Annual ACM Symposium on User Interface Software and Technology*, UIST '02, ACM (New York, NY, USA, 2002), 181–190.

29. Park, W., Park, S., Kim, L., and Shin, S. Haptic mouse interface actuated by an electromagnet. In *Proceedings of the 2011 International Conference on Complex, Intelligent, and Software Intensive Systems*, CISIS '11, IEEE Computer Society (Washington, DC, USA, 2011), 643–646.

30. Parkes, A., Poupyrev, I., and Ishii, H. Designing kinetic interactions for organic user interfaces. *Commun. ACM 51*, 6 (June 2008), 58–65.

31. Patten, J., and Ishii, H. Mechanical constraints as computational constraints in tabletop tangible interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '07, ACM (New York, NY, USA, 2007), 809–818.

32. Pedersen, E. W., and Hornbæk, K. Tangible bots: Interaction with active tangibles in tabletop interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, ACM (New York, NY, USA, 2011), 2975–2984.

33. Perelman, G., Serrano, M., Raynal, M., Picard, C., Derras, M., and Dubois, E. The roly-poly mouse: Designing a rolling input device unifying 2d and 3d interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, ACM (New York, NY, USA, 2015), 327–336.

34. Poupyrev, I., Nashida, T., and Okabe, M. Actuation and tangible user interfaces: The vaucanson duck, robots, and shape displays. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*, TEI '07, ACM (New York, NY, USA, 2007), 205–212.

35. Probst, K., Lindlbauer, D., Greindl, P., Trapp, M., Haller, M., Schwartz, B., and Schrempf, A. Rotating, tilting, bouncing: Using an interactive chair to promote activity in office environments. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '13, ACM (New York, NY, USA, 2013), 79–84.

36. Probst, K., Lindlbauer, D., Haller, M., Schwartz, B., and Schrempf, A. A chair as ubiquitous input device: Exploring semaphoric chair gestures for focused and peripheral interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, ACM (New York, NY, USA, 2014), 4097–4106.

37. Ramstein, C., and Hayward, V. The pantograph: A large workspace haptic device for multimodal human computer interaction. In *Conference Companion on Human Factors in Computing Systems*, CHI '94, ACM (New York, NY, USA, 1994), 57–58.

38. Rasmussen, M. K., Grönvall, E., Kinch, S., and Petersen, M. G. "it's alive, it's magic, it's in love with you": Opportunities, challenges and open questions for actuated interfaces. In *Proceedings of the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration*, OzCHI '13, ACM (New York, NY, USA, 2013), 63–72.

39. Roudaut, A., Rau, A., Sterz, C., Plauth, M., Lopes, P., and Baudisch, P. Gesture output: Eyes-free output using a force feedback touch surface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, ACM (New York, NY, USA, 2013), 2547–2556.

40. Savioz, G., Markovic, M., and Perriard, Y. Towards multi-finger haptic devices: A computer keyboard with adjustable force feedback. In *Electrical Machines and Systems (ICEMS), 2011 International Conference on* (Aug 2011), 1–6.

41. Schmidt, D., Kovacs, R., Mehta, V., Umapathi, U., Köhler, S., Cheng, L.-P., and Baudisch, P. Level-ups: Motorized stilts that simulate stair steps in virtual reality. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, ACM (New York, NY, USA, 2015), 2157–2160.

42. Schneegass, S., Alt, F., Scheible, J., and Schmidt, A. Midair displays: Concept and first experiences with free-floating pervasive displays. In *Proceedings of The International Symposium on Pervasive Displays*, PerDis '14, ACM (New York, NY, USA, 2014), 27:27–27:31.

43. Seifert, J., Boring, S., Winkler, C., Schaub, F., Schwab, F., Herrdum, S., Maier, F., Mayer, D., and Rukzio, E. Hover pad: Interacting with autonomous and self-actuated displays in space. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*, UIST '14, ACM (New York, NY, USA, 2014), 139–147.

44. Sinclair, M., Pahud, M., and Benko, H. Touchmover: Actuated 3d touchscreen with haptic feedback. In *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces*, ITS '13, ACM (New York, NY, USA, 2013), 287–296.

45. Steimle, J., Weibel, N., Olberding, S., Mühlhäuser, M., and Hollan, J. D. Plink: Paper-based links for cross-media information spaces. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '11, ACM (New York, NY, USA, 2011), 1969–1974.

46. Taylor, S., Keskin, C., Hilliges, O., Izadi, S., and Helmes, J. Type-hover-swipe in 96 bytes: A motion sensing mechanical keyboard. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*, CHI '14, ACM (New York, NY, USA, 2014), 1695–1704.

47. Vonach, E., Gerstweiler, G., and Kaufmann, H. Acto: A modular actuated tangible user interface object. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces*, ITS '14, ACM (New York, NY, USA, 2014), 259–268.

48. Weiss, M., Schwarz, F., Jakubowski, S., and Borchers, J. Madgets: Actuating widgets on interactive tabletops. In *Proceedings of the 23Nd Annual ACM Symposium on User Interface Software and Technology*, UIST '10, ACM (New York, NY, USA, 2010), 293–302.

49. Wellner, P. Interacting with paper on the digitaldesk. *Commun. ACM 36*, 7 (July 1993), 87–96.

50. Yang, X.-D., Mak, E., McCallum, D., Irani, P., Cao, X., and Izadi, S. Lensmouse: Augmenting the mouse with an interactive touch display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, ACM (New York, NY, USA, 2010), 2431–2440.

51. Yankelovich, N., Simpson, N., Kaplan, J., and Provino, J. Porta-person: Telepresence for the connected conference room. In *CHI '07 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '07, ACM (New York, NY, USA, 2007), 2789–2794.

52. Zhang, H., and Li, Y. Gestkeyboard: Enabling gesture-based interaction on ordinary physical keyboard. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*, CHI '14, ACM (New York, NY, USA, 2014), 1675–1684.