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Light on horizontal interactive surfaces: input space for tabletop computing.

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In the last 25 years we have witnessed the rise and growth of interactive tabletop research, both in academic and industrial settings. The rising demand for the digital support of human activities motivated the need to bring computational power to table surfaces. In this survey, we review the state of the art of tabletop computing, highlighting core aspects that frame the input space of interactive tabletops: (a) developments in hardware technologies that have caused the proliferation of interactive horizontal surfaces and (b) issues related to new classes of interaction modalities (multi-touch, tangible and touchless). A classification is presented that aims to give a detailed view of the current development of this research area and defining opportunities and challenges for novel touch- and gesture-based interactions between the human and the surrounding computational environment.

Categories and Subject Descriptors: **H.5.2 [Information Interfaces and presentation]**: Input devices and strategies, Interaction Styles.

General Terms: Design, Human factors

Additional Key Words and Phrases: horizontal interactive surfaces, tabletop computing, ubiquitous computing.

1. INTRODUCTION

Twenty years after Weiser's vision [1991] of ubiquitous computing, we are now living in a world where digital information processing is not only limited to desktop computers, but it is more and more integrated into conventional objects. As surfaces prevail in the physical world, the use of touch sensible interactive screen displays (based on rear projection, front projection, liquid crystal or organic light-emitting diodes) has gained interest in Human-Computer Interaction and in a wide range of everyday life settings. For example, as Rekimoto and Matsushita [1997] pointed out: *"It is difficult to imagine offices, museums or homes without walls. Thus it should be worthwhile to research how computer augmented walls will support our daily activities."*

Tables represent one of the most versatile physical surfaces by providing a space where a great variety of habitual activities can occur, from work to leisure activity. They are common horizontal surfaces where objects can be placed and manipulated by individuals or groups. People can use a table as a private space. For example, a person can sit in front of his/her desk and use it as a physical surface for writing on a sheet of paper, for placing the monitor of her desktop computer, folders, pens, a bottle of water, and even a small succulent. Tables, also, naturally support co-located collaborative activities. During a meeting, a table can be used by participants to display and interact with objects as visual and physical aids for the discussion. For instance, during an emergency situation (e.g., an earthquake), people from Civil Defense can convene around a table

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to discuss rescue operations by means of a map laid out on the table. They can specify most damaged areas, define evacuation routes and manage how to displace different rescue teams on the field. Individuals can either draw directly on the map (e.g., highlight damaged areas) or make use of tangible artifacts placed on the map representing these rescue teams.

The rising interest in digitally supported collaborative and personal activities motivated the need to bring computational power to table surfaces. At the very beginning, the technical knowledge and the cost of developing tabletop systems represented a barrier to their distribution. Nevertheless, recent developments in display hardware have caused the widespread proliferation of digital tabletop technologies [Han 2005] together with new interaction possibilities, such as multi-touch and tangible interfaces.

Benko et al. [2009] coined one of the most relevant definitions of interactive tabletop after surveying 58 tabletop computer experts and researchers. The definition states that an interactive tabletop is *"a large surface that affords direct, multi-touch, multi-user interaction."* Although it can be considered a first approximation that highlights pivotal facets of tabletop computing, the definition gives only one perspective. For example, there is no general consensus that the support to multiple users is idiosyncratic for interactive tabletops [Hardy 2012; Wigdor et al. 2007]. Moreover, there is still no clear agreement of whether such research can be referred to as *tabletop computing* or *surface computing*. We think that a definition for a multi-faceted area, such as surface/tabletop computing, is needed. Our proposal consists of shaping this research field by describing different dimensions that represent its boundaries. We have identified five dimensions, as shown in Section 2, to characterize what is an interactive tabletop, and use them to frame the input space for these systems. We adopt the definition of *input space* from Grossman and Wigdor [2007] as *"the physical location where the user can provide input."*

Currently, the desktop computing paradigm still represents the dominant interaction environment between humans and computers. However, this paradigm limits users operating skills. They are forced to interact by means of a 2-Degree-Of-Freedom (DOF) device (the mouse) while they learn to interact with the physical world using a 23-DOF device (the fingers). As touch enabled and tangible interaction techniques suggest, an evolution of interaction paradigms is taking place, which is mainly driven by technological advances. This, in turn, introduces new challenges for the tabletop research community because, together with a paradigm shift, such a big change might affect the way in which interactive processes are perceived. Technological advances have to be followed by new approaches in interactional design and methods for formalizing the interface, without forgetting the lessons learnt from the past. In fact, in the case of new gestural interfaces, which promise natural interaction, Norman and Nielsen [2010] pointed out that the developer community seems to overlook the foundations of HCI research and this *"results in their feeling of empowerment to unleash untested and unproven creative efforts upon the unwitting public."* Radical changes do not take place in a day, but incrementally progress in slow and small steps. First of all, designers need to develop a broader view of technologies and interaction possibilities in order to establish new design guidelines and successively develop the next generation of tabletop-based interactive systems.

While touch sensing has been established as a common technology that allows interactions with a single point of contact, multi-touch allows to employ more than one finger simultaneously, as in chording and bi-manual manipulation [Westerman et al. 2001]. Currently, a large number of multi-touch-based tabletop systems (as well as commercial products) has been developed, investigating both hardware (e.g., sensing mechanisms and display surface configurations) and software aspects (e.g., dedicated widgets and libraries for touch detection and tracking). Approaches for building an interactive tabletop employ electrical or opto-electrical sensors mounted behind, in front, in the periphery or completely integrated into a custom designed surface. Examples of such interactive horizontal surfaces are Circle Twelve's DiamondTouch [Dietz and Leigh 2001] and Microsoft's Surface [Microsoft Corp. 2007]. The interaction with these systems relies on the physical contact between user's hands (fingers) and the surface. Nevertheless, recent efforts also focused on recognizing and incorporating freehand gestures above the surface (e.g., using a combination of projectors and depth cameras [Wilson and Benko 2010]). Additionally, Tangible Interaction is often coupled with multi-touch tabletops. Ishii and Ullmer [1997] first outlined the concept of Tangible Interaction to expound interfaces that assign a physical form to digital bits, by means of physical objects in the surrounding environment. These objects embody mechanisms for interactive control (e.g., reacTable* fiducial markers [Jordá et al. 2007]) and their physical state is strictly related to the digital state of the system. This enriches interaction in a multi-touch environment, where gestural input is used together with manipulation of physical components.

The goal of this survey is to frame the research field of tabletop computing, and in particular, the different input modalities emerging in this area. The wide number of interaction techniques, devices, and display surfaces currently available motivated our work. Presently, given the early stage of tabletop adoption and their relative low availability, the interest of both academia and industry in the emerging use of these devices is increasing the growth of communities of tabletop interaction researchers. This is demonstrated by the creation of conferences such as the ACM Conference on Interactive Tabletops and Surfaces (ITS) or the increasing number of submissions for tabletop-related works in leading Human-Computer Interaction conferences. Just to name a few, the ACM Conference on Human Factors and Computing Systems (CHI), ACM International Conference on Computer Supported Cooperative Work (CSCW), and ACM Symposium on User Interface Software and Technology (UIST). This survey presents to researchers in Ubiquitous Computing and Natural User Interface an overview of the current development of Tabletop Computing, in order to define opportunities and challenges for novel interactions between the human and the surrounding computational environment.

1.1 Outline

This work is structured as follows: in Section 2 a definition of tabletop computing is given, highlighting dimensions and attributes that depict a tabletop computer. In Section 3 the state of the art is presented. We focused on the input space for tabletop computing by reviewing the most influential technologies and identifying their unique contribution to the area. Input technologies for mobile devices and other surfaces, like walls and floors, are also presented that influenced tabletop interaction. In the following three sections, input modalities are reported. Section 4 deals with multi-touch, Section 5 with tangible, and Section 6 with touchless (remote) input. These three kinds of input modalities frame tabletop interaction. In Section 7 a novel organization of tabletop research with respect to the input space is introduced. Section 8 reports on challenges and future works for tabletop research, and lastly, in Section 9 conclusions are drawn.

2. DEFINITION

In this section dimensions and attributes that characterize a tabletop computer (Table I) are introduced.

Table I. Dimensions for the definition of what is a tabletop computer

Dimension	Attributes	Perspective
Display screen	- Front-projected - Rear-projected - Embedded	The display screen is the interactive surface.
Orientation	- Horizontal - Tilted	The horizontal orientation offers a different affordance with respect to vertical orientation. What about tilted surfaces?
Size	- Large	Interactive tabletops are the materialization of board devices [Weiser 1991]: they feature a large, meter-sized display.
Usage	- Co-located - Personal	Tabletop affordances support both co-located groupware and personal usage.
Input modalities	- Touch (Single- and Multi-) - Tangible - Touchless (Remote)	Interactive tabletops are (multi) touch-enabled and support tangible interfaces as well as touchless (remote) input.

Display screen. The etymology of the term *tabletop*, such as for other terms like *desktop* and *laptop*, comes from the place where the computer or, more precisely, the display is positioned [Müller-Tomfelde and Fjeld 2010]. In desktops, it is placed on the user's desk. In laptops, where *lap* stands for *bind*, the display is fully integrated in a single portable computer. In *tabletops*, the display *is* the interactive surface itself. Conversely from desktop and laptop settings, where users need to employ a keyboard and mouse to interact with digital information visualized in a vertical screen; in tabletop computing the horizontal surface embodies the interface the users directly interact with. It is worth mentioning that different hardware setups can be used for the display of the graphical interface. There are examples in the literature of setups that feature (a) a projector mounted on a long support [Dietz and Leigh 2001] or directly placed high on the ceiling [Wellner 1993], (b) a projector placed below the surface [Jordá et al. 2007] or (c) Liquid Cristal Display (LCD) technology that allows integrated solutions [Mazalek et al. 2006].

Orientation. Tabletops are interactive horizontal surfaces [Benko et al. 2009; Müller-Tomfelde and Fjeld 2012]. They share design issues that are similar to large vertical displays, such as information visibility or reachability, but the horizontal orientation of the surface introduces peculiar challenges that have to be taken into account [Shen et al. 2006; Kunz and Fjeld 2010]. First of all, the orientation has a significant influence in users' behavior and interaction. Vertical interactive surfaces implement the metaphor of a whiteboard and are typically designed for disseminating information. Horizontal surfaces offer a completely different interaction environment since the horizontal orientation promotes content elaboration activities. According to Kunz and Fjeld [2010] tabletops are "*used to generate, manipulate, and display digital objects, which are carriers of information and thus the basis of discussion within a team.*" This also highlights how tabletops encourage tangible interaction [Ishii and Ullmer 1997], which cannot be applied to vertical surfaces. A specific affordance of the horizontal orientation, in fact, is that the surface supports any physical object, making interactive tabletops an ideal setting for the seamless integration of tangible interaction. The horizontal orientation also introduces issues in terms of widget visualization [Shen et al. 2003]. For example, considering readability, classical drop-down menus are difficult to read from any position around the table [Wigdor and Wixon 2010]. The touch version of the classical *Midas Touch* problem for eye-gaze interaction [Jacob et al. 1993] is also typical of horizontal orientation [Esenther and Ryall 2006], because users are more prone to leave their hands on the tabletop surface, as opposed to desktop vertical surfaces, thus triggering unintended actions.

Even if research mainly focuses on the dichotomy *horizontal versus vertical*, tilted surfaces up to 30 degrees can be also considered tabletops [Müller-Tomfelde et al. 2008]. Buxton [2009] defined the ActiveDesk (30 degree of tilt) as *"an early version of what has become known as tablet-top or surface computing."* Another example of tilted tabletops is metaDESK (12 degrees) [Ullmer and Ishii 1997]. These systems present a configuration in-between the vertical and horizontal orientation. They still provide affordances similar to the horizontal orientation, such as the possibility to collaborate side-by-side, face-to-face, and to use tangible objects (depending on the slippage of the surface) [Ullmer and Ishii 1997]. They also "*reintroduce directionality, i.e., the notion of top, down, left and right to the display"* [Müller-Tomfelde et al. 2008]. ClearBoard [Ishii and Kobayashi, 1992], with its 45 degrees of tilt, represents a hybrid system, the joining link between tabletops and vertical surfaces. As the authors stated, they explicitly wanted to integrate the two metaphors of (a) talking in front of a whiteboard and (b) talking around a table into the new metaphor of (c) talking through a tilted looking glass. Tilted tabletops cannot only be used for personal work, as demonstrated by the ActiveDesk [Fitzmaurice et al. 1995], but also for co-located collaboration. In particular, Müller-Tomfelde et al. [2008] examined opportunities and challenges of the use of tilted tabletop as a workspace for groupware activities.

Size. Interactive tabletops are the materialization of *board* devices in the original vision of ubiquitous computing [Weiser 1991]. Weiser foresaw the physical environment being pervaded by meter-size interactive display devices (*boards*) that create a physical/digital ecosystem together with wearable centimeter-size *tabs* and handheld decimeter-size *pads*. According to Weiser, *boards* represent medium to large interactive displays fixed in the environment where several people can use them in a shared space at the same time. Müller-Tomfelde and Fjeld [2010] pointed out that a touch-enabled large display space (e.g., more than 40 inches) is a key component for an interactive tabletop setting and the research community agreed that the large form-factor is one of the principal features [Benko et al. 2009; Wigdor et al. 2007]. Findings from the survey of Benko et al. [2009] (involving tabletop computing experts and researchers), reported that large displays of 42 inches diagonal are considered important for co-located groupware activities, but might also be desirable for solo use. Featuring a large surface introduces specific issues for designing tabletop interaction. For example, the size determines what muscle groups are used, how many fingers/hands can be active on the surface, what types of gestures are suited for the device, the display resolution, the visibility, the physical reach, work strategies and social interactions [Buxton 2009]. Moreover, in the case of co-located face-to-face collaborative activities, the size of the group and the size of the surface also affect collaboration around the table [Ryall et al. 2004].

Usage. Tabletop affordances allow several users to interact simultaneously around the board. An extensive corpus of knowledge has been produced regarding the design of interactive tabletop systems for CSCW [Hornecker and Buur 2006; Scott et al. 2003; Shen et. al 2006]. Scott et al. [2003] reviewed tabletop literature up to 2003, co-located collaboration activities, and identified design guidelines for applications to support collaborative behavior. They pointed out that applications developed for interactive tabletops have to be designed considering various aspect of co-located interaction, such as users' arrangements and simultaneous actions. Designers should also contemplate seamless transitions between users' activities, users' personal and shared documents, and interactions between the tabletop and external devices. Tabletop systems are naturally suited to be used in technologically enhanced spaces, in combination with other devices [Coughlan et al. 2012]. Concurrent, co-located, multi-users, collaborative activities raise usability issues such as occlusion, orientation, and readability of digital elements, which have been studied in several research projects [Ringel et al. 2004; Shen et al 2001].

Nevertheless, there are several examples in the literature of tabletops as single-person environments, from early systems such as the DigitalDesk [Wellner 1991] or the ActiveDesk [Fitzmaurice et al. 1995] to more recent developments [Hardy 2012; Wigdor et al. 2007]. For example, Hardy [2012], inspired by the study of Wigdor et al. [2007] on long-term tabletop use in the office environment, developed an interactive desk that was used to collect insights on its use for day-to-day working tasks. Tabletops for personal use take the form of *interactive desks* as firstly defined by Wellner [1991]; these settings are mostly used for working practices. In this case, the horizontal interactive surface is a key part of a digitally augmented office and should fit into the ecology of objects on a user's desk [Hardy 2012], e.g., the display of the desktop computer and standard input devices. To this end, Morris et al. [2008] suggest to make the *"digital surface large enough that users don't mind 'wasting' a portion of the surface by covering it with other devices."* Single-person use is perfect for office life, and encourages hours of continuous work with the interactive tabletop. To this end, longitudinal studies that explore long-term interaction with tabletop systems are needed [Hardy 2012; Wigdor et al. 2007]. Hardy [2012] reported that, after 13 months of working at an interactive desk, *"the combination of mouse and keyboard was the dominant interaction modality"* and *"most of what I interpreted as a benefit of the desk stemmed its affordances as an output device rather than an input device."* These insights are still subjective and resulted from personal reflections. Further studies are required to complement such observations might help to shed light on how tabletop systems are perceived after periods of extended use.

Input modalities. As Kunz and Fjeld [2010] highlighted in their classification of tabletop surfaces, interactions in a digitally augmented table are direct-touch based, though some recent studies began investigating other types of touch-free interactions above and between surfaces [Hilliges et al. 2009; Wilson and Benko 2010] (see Section 6 and Section 7.5). In the classification of Kunz and Fjeld [2010], interaction techniques fall into two classes: (a) *hand-based*, in which users employ their hands to perform simple pointing actions or more complex gestures and, (b) *device-based*, in which an input device has to be used (e.g., a phicon, an object acting as a tangible icon [Ishii and Ullmer 1997]). There is a general agreement that tabletop interaction is essentially touch-based [Benko et al. 2009, Buxton 2009, Müller-Tomfelde and Fjeld 2012]. Early systems made use of a single direct touch method, by means of a stylus-pen (e.g., DigitalDesk [Wellner 1991]) or finger touch (e.g., ActiveDesk [Fitzmaurice et al. 1995]). In the beginning, touch-based devices connected to computer systems essentially replaced mouse-based input [Müller-Tomfelde and Fjeld 2012]. With the development of sensing technologies, multi-touch capabilities have been introduced that allow the recognition and tracking of hand touches and gestures, such as with the DiamondTouch [Dietz and Leigh 2001] (a description of the system is given in the next Section). In particular, Müller-Tomfelde and Fjeld [2012] consider 2001 as the year of the shift from *"single-touch to multitouch and tangibility."* In fact, with systems developed after 2001, the

trend is clearly to combine multi-touch and gesture based interaction with the use of tangible elements (e.g., the reacTable* [Jordá et al. 2007]).
One last point is regarding the use of the keywords *tabletop computing* against *surface computing* to classify research contributions in this area. Even if there is a large group of works that employs the two keywords indiscriminately, a query on Google Scholar[1] database (from year 2001 to year 2012) retrieved 178 results for *tabletop computing* and 1360 for *surface computing*. This is due to the fact that *surface computing* is an umbrella term that embraces research in interactive walls, floors, vertical shared public displays and multi-touch interaction with mobile devices among others. While there are some common aspects between all these interactive surfaces (that are discussed in Section 3.3 and Section 3.4), the physical affordances of each surface define the kind of interactions that can take place and their applications. We therefore consider *tabletop computing* as the correct keyword to categorize this research area, because the term evokes the affordances of a table. *Surface computing* embraces all kind of interactive surface, while *tabletop computing* addresses the design of systems that are shaped by the dimensions presented above. One example to clarify how physical affordances affect interaction on different surfaces is to consider the horizontal orientation typical of tabletops, against the vertical orientation of other surfaces such as walls. Buxton [2008] presented the main difference with a simple and elegant example: *"Well, this is one of those questions perhaps best answered by a child in kindergarten. They will tell you that if you put a glass of water on the vertical one, it will fall to the floor, leading to a bout of sitting in the corner. On the other hand, it is perfectly safe to put things on a table. They will stay there."* This example demonstrates that tables intrinsically support tangible interaction while other surfaces perhaps do not.

3. STATE OF THE ART

The state of the art, from first systems that have influenced the development of the tabletop computing research area, has been reviewed identifying the interaction afforded (input modalities) by these systems and their unique contribution to the field (Table II). The analysis of the interactive capabilities supports the categorization of the input space for tabletop computing presented in Section 7. Most of the relevant works were selected from a comparison of (a) academic publications extracted from the Google Scholar database with the search string *tabletop*, *interactive table*, *interactive desk* or *horizontal surface*[2]; (b) systems analyzed by Buxton [2009] in his compendium of multi-touch technologies; and (c) interactive tabletops presented by Müller-Tomfelde and Fjeld [2010] in their history of tabletop research and technologies. Citations count as a measure of relevance has been contrasted with existing surveys. Moreover, the unique contribution of each system, with respect to the dimensions highlighted in the previous Section, has been taken into account. In this way, we aim to overcome the issues on citations count highlighted by Müller-Tomfelde and Fjeld [2010] such as the fact that they are retrieved from one single database (Google Scholar), they do not reflect the passage of time since the publication and, since a work may contribute to different research areas, the citation may result from more than one field.
As pointed out in the previous Section, input modalities (Table II, fourth column) span from touch-based, to tangible, and to touchless. Early systems made principal use of a single direct touch method, for example using a stylus-pen. Technology developments enabled multi-touch sensing in large surfaces, which can be combined with tangible input [Müller-Tomfelde and Fjeld 2012]. Finally, some systems make use of touchless modalities, like in-air gestures above the surface [Hilliges et al. 2009].
The vision of physical desk empowered with technology as a space where users produce, review and organize information had originated in 1940s by Bush's [1945] memex concept. Even if the physical device has never been implemented, the memex idea deeply influenced the research in digitally augmented physical surfaces. Bush envisioned a desk where a collection of documents can be stored, retrieved and visualized. Inside the desk, some electromechanical mechanisms store

[1] On date 23-01-2013
[2] These keywords cover a broad spectrum of publications including some early ones that do not use the term *tabletop*, such as memex [Bush 1945] or DigitalDesk [Wellner 1991]

information while documents are projected on three touch-based semitransparent screens for reading and annotating.

Table II. A classification of the most influential technologies in tabletop research.
* The most cited article about DigitalDesk is the 1993 publication on ACM Communications [Wellner 1993].
** Relevant research works from Microsoft Research exploited Microsoft Surface as test-bed platform. For example: Wobbrock et al. [2009] (243 cites).

Citation	Year	System	Input modalities	Unique Contribution
5415	1945	memex [Bush 1945]	Touch pointing (Stylus-based)	Envisioned a physical desk empowered with technology.
852	1985	VIDEODESK [Krueger et al. 1985]	Touchless (In-air gestures)	1. Used freehand in-air gestures 2. Introduced the concept of many multi-touch gestures.
281 (1148)*	1991	DigitalDesk [Wellner 1991]	Single-touch (Stylus-based)	The surface embeds the visual display and the interface.
797	1995	ActiveDesk [Fitzmaurice et al. 1995]	Single-Touch (Stylus and finger), Tangible controls	1. Bimanual interaction on a surface. 2. Introduced the concept of graspable interfaces.
810	1997	metaDESK [Ullmer and Ishii 1997]	Tangible	Introduced the concept of Tangible User Interface.
584	1999	Augmented Surfaces [Rekimoto and Saitoh 1999]	Laptop devices, Single-touch (Pen-based, Tangible)	Integration of interactive tabletop with ubiquitous devices.
1080	2001	DiamondTouch [Dietz and Leigh 2001]	Multi-touch	The first multi-user tabletop system.
639	2002	SmartSkin [Rekimoto 2002]	Multi-touch, Touchless	1. Extensible architecture. 2. Interaction on non-flat, flexible surfaces.
903	2005	FTIR [Han 2005]	Multi-touch	Low cost multi-touch surface.
294	2005	reacTable* [Jordá et al. 2007]	Tangible, Multi-touch	1. Tangible interaction through visual markers (reacTIVision framework).
110	2007	Thinsight [Hodges et al. 2007]	Multi-touch	Thin form-factor multi-touch displays.
**	2007	Microsoft Surface [Microsoft 2007]	Multi-touch, Tangible	1. One of the first commercial tabletops. 2. Test-bed platform for research studies on multi-touch input on tabletops.
83	2008	SecondLight [Izadi et al.]	Multi-touch, Tangible (Switchable Diffusers), Touchless (In-air gestures)	Influenced research on interaction above the surface.

The memex system presented unique features that have driven the implementation of modern interactive tabletops such as: (a) the affordances of a physical desk enhanced with digital information processing, (b) the presence of touch-enabled surfaces, (c) the possibility to use external devices to interact, like a keyboard or a pen, (d) tilted surfaces (two of the three screens have a 45 degrees tilt) and, (e) computational mechanisms placed below the surface (e.g., reacTable* [Jordá et al. 2007]). Gesture-based interaction is one aspect that memex did not address and which Krueger et al. [1985] developed later on with VIDEODESK.

The idea of Krueger et al. [1985] was to combine elements from the digital and the real world to eliminate devices, like the keyboard, which he considered a barrier in the human-machine communication. He believed that hand gestures were the most expressive communication form, being able to transmit a higher information bandwidth compared to a set of keystrokes. Therefore, he designed and developed a system made of an illuminated desktop with a display screen and an overhead black and white camera. The camera recognized the hands silhouette (Fig. 1), allowing the user to interact with digital elements directly via basic hand gestures at a distance from the surface.

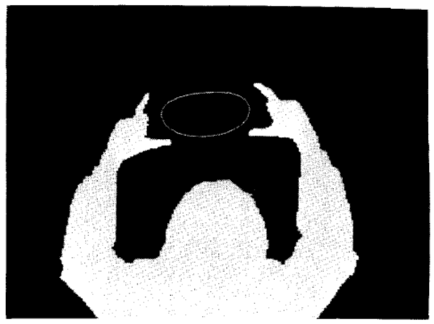

Fig. 1. Gesture silhouette in VIDEODESK. Source [Krueger et al. 1985]. © ACM 1985.

3.1 Modern tabletop systems

Thanks to technological advances, the ideas developed by Bush and Krueger were recently resumed and implemented by Wellner [1991] with the DigitalDesk. Wellner reversed the classical approach of the digital desktop metaphor, proposing not to focus on *"making the workstation like a desk,"* but instead to *"make the real desk more like the workstation*." In DigitalDesk, *"no desktop metaphor is needed because it [the DigitalDesk] is literally a desktop."* The computer display was turned into a desktop by mapping the digital metaphor onto a physical space, by means of a video camera and a projector. Users could interact directly with the surface of the desk employing a LED-based pen and fingers as input devices. By exploiting both a camera and a projector, the communication became bidirectional and the digital space was extended out and merged into the surrounding environment. Wellner also envisioned multi-touch interaction, extending touchless gestures, proposed by Krueger et al. [1985], to touch-enabled video screens. For instance, he presented one of the earliest examples of a two-finger pinching gesture, even if the technology of the time did not allow its actual implementation[3].

Wellner's vision was adopted and further refined by the community, defining a tabletop as an interface where even the computer disappears. The main objective was to generate an environment where users can interact in a more natural manner, utilizing hand-gestures and tangible objects empowered with digital behaviors. Starting from the late 90s, and influenced by the DigitalDesk ideas and design concept, several research laboratories began to develop their own tabletop systems, exploring different hardware settings as well as novel interaction techniques. Particularly, in the last decade, there has been a great interest in interactive tabletops research both in universities and industry, which has resulted in a variety of solutions.

The ActiveDesk [Fitzmaurice et al. 1995] takes the physical form of a drafting table (Fig. 2) and was originally designed to interact with digital objects by means of stylus input. It is a tilted surface (30 degrees) equipped with a rear projected computer screen underneath the interactive board. The objective was to build a digital drawing workbench where users could interact directly with their work. The surface recognizes and tracks input from the stylus, operated with the dominant hand, as well as the position of the non-dominant hand and the pose between the thumb and the index finger. The ActiveDesk was developed as a single-user/single-application workbench. It was employed as a test bed for the development of the first graspable interfaces research studies [Fitzmaurice et al. 1995] emphasizing how the non-dominant hand could manipulate tangible objects (called *bricks*) as input devices on the interface surface. The first *bricks* prototype consisted of two small cubic objects (electronically connected to the system with cables) that were employed as controls in a drawing application. In this way, users could control virtual objects not only by their fingers, but also through physical objects that acted as handles. The interaction with bricks on the ActiveDesk is mainly bimanual, with a brick working as an *anchor* and the other one as an *actuator*. An anchor represents the starting point for interaction while actuators are used to specify *positional values* and work within the *frame of reference* outlined by the anchor. Bricks present a major restriction: they are not intuitive. To overcome this design problem, Ishii and Ullmer [1997] proposed their vision of tangible bits and formalized the

[3] Watch the video http://youtu.be/laApNiNpnvI at minute 3:32 for an example.

early concept of Graspable User Interfaces into Tangible User Interfaces (TUIs). The enhancement proposed by TUIs is that tangible handlers suggest their inherent functionalities by their shape and the physical representation is strongly coupled with the digital state of the system. The main assumption is that by employing shapes familiar to users, for example inspired by objects from everyday life, the interaction with tangibles becomes more intuitive.

Fig. 2. Bill Buxton working on the University of Toronto Active Desk. Image courtesy of William (Bill) Buxton.

Fig. 3. The metaDESK tabletop system. Source [Ullmer and Ishii 1997]. © ACM 1997.

metaDESK [Ullmer and Ishii 1997] is a system developed by the Tangible Media Group at MIT to explore the design of TUIs on a tabletop surface. It integrates multiple 2D and 3D graphic displays with several physical objects (Fig. 3) sensed by different technologies (optical and electromagnetic). In particular, the system converts elements of the classical GUI into tangible elements. For instance, an arm-mounted flat panel display (called the *active lens*) embodies the window metaphor or a digital icon takes the form of a *phicon* (short for physical icon) which is a real object with different level of descriptive abstraction. metaDESK also features a second lens device, the *passive lens*, which respects the physical affordance of a lens and acts as a magnifier for the user interface. Moreover, the device was physically assembled to look like a real magnifier lens (Fig. 3). Interaction on the metaDESK occurs exclusively by means of physical devices. The information visualized on the display screen is managed by phicons, phandlers (physical handlers) and the passive lens. No other touch-enabled interaction (e.g., with fingers or styli) was implemented.

reacTable* [Jordá et al. 2007] (Fig. 4) is another example of a tangible-based tabletop system. The rationale is the same as previous systems. It makes use of tokens, having physical and virtual affordances, to control digital objects and interact with the tabletop surface. reacTable* was conceived as a "*novel multi-user electro-acoustic music instrument with a tabletop tangible user interface"* [Jordá et al. 2007]. It was specifically designed for the casual as well as expert user as to be used in installations, concerts, or to synthesize music via physical pucks.

Fig. 4. reacTable*. Image courtesy of Gunter Geiger, CEO of Reactable Systems.

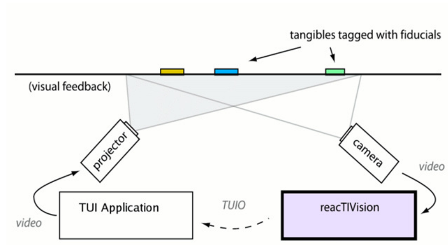

Fig. 5. reacTIVision diagram. Source [Kaltenbrunner and Bencina 2007]. © ACM 2007.

reacTable* implements a visual interaction language where the shapes of the physical pucks determine the syntax. Each puck represents a shape associated to a particular group of functionalities: audio generators, audio filters, controllers, control filters, mixers and global objects. When placed on the table, objects connect to one to another, thus creating a topology that defines the melody that is played. The table has a round form factor, which allows the development of a tabletop interface with no position of advantage or control spot around the table.

Vernier et al. [2002] previously investigated the use of circular tabletop interfaces in their Personal Digital Historian. One of the main contributions of the reacTable* is the opensource and cross-platform computer vision toolkit, called reacTIVision, for the real time detection and tracking of touch inputs and tangible objects [Kaltenbrunner and Bencina 2007]. At that time, researchers favored RFID-based [Patten et al. 2001] or acousting techniques [Mazalek 2001] to enable tangible interfaces on horizontal surfaces. Prior to that, reacTable* and PlayAnywhere [Wilson 2005], demonstrated that computer vision techniques were equally fast and reliable, leading to setups that utilized a camera below (as in the case of reacTable*) or above the surface (as for PlayAnywhere). The reacTIVision toolkit (Fig. **5** shows its logic diagram) is a combination of different elements. Its main component is a software library that allows quick and reliable tracking of fiducial markers by processing the raw data received from a video stream. This library employs a specialized computer-vision algorithm based on a recognition technique for topological markers, first introduced by Costanza and Robinson [2003] for the d-touch system. Learning from the evaluation of d-touch fiducials, Bencina et al. [2005] implemented an upgraded version of the fiducial recognizer to be integrated in the reacTIVision library. Their implementation allows the use of scalable markers in the reacTable* system, whose size may vary depending on the number of tangibles. Along with the main detection and tracking component, the toolkit also provides additional tools like the TUIOSimulator, which allows tabletop applications to be tested on a normal desktop computer during development. reacTIVision is, in fact, the first implementation of Tangible User Interface Objects (TUIO) [Kaltenbrunner et al. 2005]; a cross-platform protocol developed to provide an abstraction of underlying input events and therefore promote interoperability between interactive display devices. As the authors state in the project website[4], the TUIO protocol was conceived for "*encoding the state of tangible objects and multi-touch events from an interactive table surface."* Nowadays there are implementations in almost every known programming language and the majority of software libraries for enabling multi-touch interaction support the TUIO protocol (e.g., CCV[5], MT4J[6] or openFrameworks[7]).
Interactive tabletops can be integrated in ubiquitous scenarios, where different computational devices coexist and communicate in the same environment, as demonstrated by Augmented Surfaces [Rekimoto and Saitoh 1999]. The system was designed following ubiquitous computing principles. Users can exchange digital information by employing laptop computers, tabletops, wall projected displays, and physical objects. Therefore, Augmented Surfaces aims to integrate mobile devices in a digitally augmented collaborative space, consisting of an interactive table and wall, where participants use their laptop computer to interact. A video camera mounted above the table recognizes the device by means of an attached visual marker; as a result of the recognition, the table surface becomes an extended workplace for each laptop computer. For example, Augmented Surfaces implements a technique called *hyperdragging* that allows users to seamlessly drag an object across the boundaries of the computer display. When the cursor moves on the table surface, a line is projected to show a connection between the cursor and the laptop (Fig. **6**).

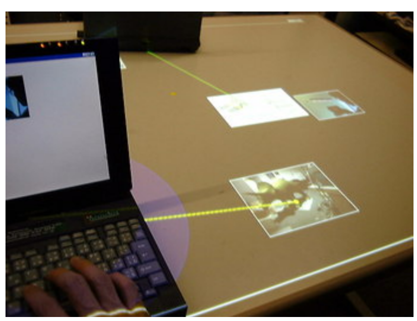

Fig. 6 Augmented Surfaces: hypedragging. Source [Rekimoto and Saitoh 1999]. © ACM 1999.

[4] http://reactivision.sourceforge.net and http://tuio.org
[5] http://ccv.nuigroup.com
[6] http://www.mt4j.org
[7] http://openframeworks.cc

Users can also move data from the table to the wall surface using a laser pointer. Tagged physical objects are employed to create bindings between the real and the virtual world. For instance, users can drag digital pictures to a physical booklet placed on the surface. In this way, the booklet becomes a *real* storage for *virtual* images, which can be retrieved in subsequent interactions. Augmented Surfaces also implement TUIs metaphors such as a mock-up camera used to inspect a 2D scene and change the 3D visualization on the digital wall.

In recent years, the use of imaging touch screens for multi-touch interactive surfaces has been popularized thanks to advances in sensing technologies [Schöning et al. 2008]. These new approaches allow users to compute full touch images instead of a list of discrete points, thus enabling gesture-based manipulations on large interactive surfaces, be they vertical or horizontal [Wilson 2004]. The most used techniques can be categorized into (a) resistive-based, (b) capacitance-based, and (c) optoelectric; each one with its benefits and drawbacks. While it is not the purpose of this survey to present enabling technologies for multi-touch tabletops, an in-depth analysis of sensing hardware can be found in the works of Schöning et al. [2008], NUI Group Authors [2009], Moeller and Kerne [2010; 2012] and Moeller et al. [2011].

The work of Han [2005] highly contributed to the widespread diffusion of modern, low-cost interactive tabletops. The physical principle of Frustrated Total Internal Reflection (FTIR), in fact, is very useful for implementing rear-projection camera-based multi-touch displays. When a user touches the surface, frustrated InfraRed (IR) light exits from a semi-transparent reflective coat, becoming visible to a camera that detects the touch area. The introduction of optical principles (Diffuse Illumination is another well-known technique [Schöning et al. 2008]) promoted the development of Do-It-Yourself (DIY) communities of researchers and practitioners aiming at building tabletop systems at a reduced cost. This is demonstrated by the proliferation of blog posts, forum threads, and documentation produced by groups of people, organized in no-profit open-source initiatives (e.g., the NUI Group[8]). Here the details for the construction of tabletop hardware are discussed, from the essential components (e.g., available semi-transparent coats or IR cameras with the best tradeoff between resolution and speed) to the physical setup (e.g., how to mount the IR emitters in the surface frame).

DiamondTouch [Dietz and Leigh 2001] and SmartSkin [Rekimoto 2002] are two other systems that deeply influenced tabletop research, both of them based on capacitive sensing.

Fig. 7. DiamondTouch. Image courtesy of Richard C. Waters, CEO of Mitsubishi Electrics.

Fig. 8. SmartSkin. Source [Rekimoto 2002]. © ACM 2002.

DiamondTouch (Fig. 7) was developed at MERL (now commercialized by CircleTwelve) as the first multi-touch, multi-user interactive tabletop. Its objective was to support collaborative activities of small groups via an interactive horizontal surface that made it possible to maintain users' eye contact while interacting with digital elements. According to Dietz and Leigh [2001], at that time, *"existing touch technologies were inadequate. Most allow only a single touch and do not identify users. While schemes have been developed where users take turns, we wanted the interaction to be simultaneous and spontaneous."* Therefore, they developed a system that detects multiple simultaneous touches and the user who is touching each point. This allows the tabletop to

[8] http://nuigrop.com

associate touches to a specific user. Recognizing unique user IDs is the most important feature that differentiates DiamondTouch from other tabletops. The system uses the capacitive coupling [Baxter 1997] through the human body and a chair connected to the table to close an electronic circuit. In this way it is possible to detect that a touch is coming from the user seated at a particular chair. This feature makes the DiamondTouch a platform to develop tabletop applications for Computer Supported Cooperative Work (CSCW) scenarios that require simultaneous input from different users [Esenther et al. 2002]. Diamond Touch received the *Lasting Impact Award* at the 2012 UIST conference which demonstrates the impact they encompass in the tabletop computing research community. For instance, Wigdor et al. [2007] employed a DiamondTouch in their longitudinal experiment to study the use of a tabletop computer, over a 13 months period, as a replacement of a classical desktop computer for daily working tasks. As they reported, "*rather than provide authoritative results, our aim is to present insight into potential research directions,"* and the study did succeed in pointing out several aspects of tabletop computing that need further research, like ergonomics factors, bimanual input, or text entry methods.

The main contribution of SmartSkin [Rekimoto 2002] has been a capacitive sensing extensible architecture for building interactive surfaces. First of all, being based on a mesh of receiver/transmitter antennas, SmartSkin can be scaled to very large dimensions, making it easier to build interactive tabletops according to specific collaborative needs [Ryall et al. 2004]. Moreover, while others tabletop sensing techniques work only on flat surfaces, Rekimoto [2002] was the first to introduce multi-touch sensing on virtually any physical surface, even flexible planes. This unique feature of the SmartSkin mesh inspired research on Organic User Interfaces, *"a computer interface that uses a non-planar display as a primary means of output, as well as input"* [Holman and Vertegaal 2008]. The concept of touch enabled interactive systems designed in any shape and form is another step towards computers being seamlessly embedded into the physical world [Weiser 1991]. Smartskin can also sense user's hands at a small distance from the surface, thus enabling in-air gestural interaction in the space above the tabletop, in addition to multi-touch input. One drawback that is common to capacitive sensing surfaces (e.g., the DiamondTouch) is that Smartskin cannot recognize non-tagged objects placed on the surface, thus limiting its adoption for tangible interaction. To overcome this limitation, Rekimoto [2002] developed a tag, made of conductive material, attached at the bottom of an object. When a user grasps the object, the conductive area becomes grounded and the surface interface can recognize it. SmartSkin and DiamondTouch hardware also allow interaction techniques that take into account the shape of the hand on the surface (see the discussion on multi-touch gestures in Section 4). Wu and Balakrishnan [2003] implemented gestural interaction through hand shapes in the RoomPlanner application on the DiamondTouch platform. For example, users can display private information on the table in front of them using a *horizontal hand* gesture that physically impedes others users to view the displayed information.

Microsoft Surface picked up the idea of Augmented Surfaces, considering the interactive tabletop as a computational device fully integrated into the environment. Users utilize hand gestures to manipulate digital objects displayed on the screen. It has also been designed to allow interaction with tagged physical objects. The tags patterns are similar to barcodes visible in the InfraRed (IR) range. The first version of the Surface, commercialized in 2007, implemented the Diffuse Illumination technique [Schöning et al. 2008] with a camera and projector placed under the surface. Its second version (named SUR40), presented at the Consumer Electronic Show (CES) in 2011, replaced the bulky setup of the first version with a thin form factor based on a 40" Samsung LCD screen and the PixelSense[9] technology for touch sensing. The Surface, especially in its version 1.0, has been the test-bed platform in several studies on different aspects of tabletop computing. For example, Wobbrock et al. [2009] used Surface 1.0 in their foundational research on user-generated gestures for tabletop surfaces.

According to Quigley[10], *"PixelSense is the productisation of ThinSight from Microsoft Research in Cambridge."* ThinSight [Hodges et al. 2007] influenced the development of multi-touch surfaces with sensing technologies integrated in the display. It features a grid of retro-reflective

[9] http://www.microsoft.com/en-us/pixelsense/default.aspx
[10] http://qr.ae/1SpeI

optosensors, which are capable to emit IR light and detect incident light at the same time. Therefore, the optosensor is able to detect reflective objects in front of it by capturing the light reflected back. The Pixelsense technology is an enhancement of ThinSight in which the sensing technology is directly integrated into a LC panel instead of being placed behind it. Compared with camera- and projector-based technologies, having sensors embedded in a LC display allows users to deploy slimmer interactive surfaces, with a greater resolution and offers an easier set-up [Motamedi 2008]. The drawback is that an important modification of existing displays is needed in order to embed optoelectric touch sensors, or the production of new displays with the sensing technology inside. ZeroTouch [Moeller and Kerne 2011; 2012] is a multi-touch sensor that addresses this issue by using a frame of IR sensors placed around the surface. The sensors create a mesh of IR light and when the beams are broken the system interprets that as a point of contact. Other examples of optoelectric sensors for enabling multi-touch on LCD surface are HDTouch [Motamedi 2008], with the IR sensor placed on the bezel of the table, and FLATIR [Hofer et al. 2009], which exploits the FTIR technique.

Beside interactions on the surface that are based on the recognition of multiple points of contact and the use of tangible objects, research efforts have pointed in the direction of interactions beyond the surface [Izadi et al. 2008]. For example, recognizing in-air gestures, as proposed by Krueger et al. [1985] in VIDEODESK. SecondLight [Izadi et al. 2008] is a system that integrates concepts from the different dimensions of the tabletop design space, such as: rear projection, computer vision-based recognition of contact points, and support to multi-touch and tangible interaction. It combines, with these, the unique characteristic to track mobile surfaces above the table and project the interface on it by means of switchable diffuser technology. A switchable screen is the key enabler for interactions that overstep the boundaries of the two dimensional surface and exploit the space above or in front of it. In their work Izadi et al. [2008] introduced this novel technology stating that the screen *"can be rapidly switched between two states under electronic control. When it is 'diffuse', projection and imaging on the surface is enabled; when 'clear' projection and imaging through it is possible."* This projection capability allows the implementation of magic lens effects [Bier et al. 1993]. For example, sheets of translucent film can be placed on a particular digital object to reveal its details. It is worth mentioning that magic lenses work even if the sheet is not in contact with the surface. Another important feature of SecondLight is the support to remote input by using physical objects such as the diffuse film or freehand gesturing. Hilliges et al. [2009] further studied touchless interactions exploiting an enhanced version of the SecondLight system and the TouchLight holographic projection screen [Wilson 2004]. See Section 5 for a discussion on touchless interaction.

As a final note, it is not possible in this paper to cover research on three-dimensional (3D) interaction that influenced the context of tabletop computing from various fields such as Augmented and Virtual Reality, Stereoscopic Technologies and Volumetric Displays. For an overview on the impact of these research areas, refer to the work of Grossman and Wigdor [2007].

3.2 Touch-based interaction on mobile devices

Touch-based interaction, as we know it today, has benefited extensively from mobile device touch screens. According to Buxton [2009], *"multi-touch technology has been in existence for decades, and Apple made it famous by using it in its iPhone and iPod Touch devices."* In tabletop computing technology is scaled to large surfaces, enhancing a table's natural affordances with multi-touch sensing. Early attempts to widely implement touch-based interaction on mobile devices are strongly linked to the introduction of Personal Digital Assistants (PDAs). Users became familiar with touchscreens and touch-based interaction via a stylus pen in the early 1990s with Apple Newton, and later on with Palm OS devices and Pocket PCs. The popularity of touchscreens on PDAs brought to the wider public new interaction models based on single-touch technology via a pointing device and handwriting recognition. Successively, the advent of the iPhone, iPad, and Android mobile devices consolidated and expanded the interaction with touch sensitive displays by means of multi-touch techniques. The sensing technologies of this new generation of mobile devices enable a paradigm shift from classical interactions of the desktop computing world, based on the mouse and keyboard, to interactions in pervasive environments that take into account users' mobility. Multi-touch displays provide many advantages for the use of portable devices, such as smartphones and tablets, which should be usable in a wide range of different contexts depending on the user location. The user must be able to share his/her visual, cognitive or auditory attention with the device and the surrounding environment; for instance being able to perform an action with a single touch instead of using a combination of keys [Luk et al. 2006]. In fact, the use of touch-based interaction reduces the user's cognitive load of screen communication and increases the bandwidth of available perceptual interaction with mobile devices and touch screens in general [MacLean and Enriquez 2003]. Even if the tables' larger form factor affords interactions beyond those of mobile devices, we can glimpse the role of interaction styles between small and large surfaces as continuously intertwined and cross inspired. This was envisioned by Weiser [1991] in his categorization of different form factors for ubiquitous interaction. In mobile devices, the small display screen overly affects the interaction. In this context, human constraints such as the *fat finger problem* (precision) [Baudisch and Chu 2009] or occlusion [Bieber et al. 2007] are particularly sensitive. Similar limitations of touch technologies are shared with large surfaces and, therefore, there are many examples in the literature of research works that cope with precision [Benko et al. 2006; Esenther and Ryall 2006] and occlusion [Wigdor et al. 2006] issues for interactive tabletops.

Touch techniques for small displays can be extended to large surfaces—the research on multi-touch interaction for small devices has influenced the development of gesture vocabulary for tabletop surfaces as well as user acceptance of such gestures [Wobbrock et al. 2009]. Tabletop gestures can be bimanual, due to the large size of the surface, but the use of two hands is not mandatory for multi-touch input. There are many examples of single-hand gestures for mobile devices that are used as-is in a tabletop context (e.g., the one hand *pinch-to-zoom* gesture).

The limitation in size and resolution of mobile devices make their use problematic for exploring maps, browsing applications and multimedia contents, but they might be combined with digital surfaces like interactive tabletops to offer a new set of interaction modes. Hardy and Rukzio [2008] demonstrated that *select & pick* and *select & drop* actions might be used to move elements from a mobile phone to an interactive display and vice versa. Steimle and Olberding [2012] extensively studied such kinds of interactions by exploring different dimensions of the *handheld tabletop* design space. They envisioned future mobile devices that can turn into tabletop surfaces by means of rollout displays. In regards to gestural interaction Kray et al. [2010] studied how gesture-based interaction on mobile devices can contribute to perform advanced interactive tasks involving more than one device, as in the interaction between mobile phones and tabletop displays. Tabletops, public vertical displays, mobile terminals and any other kind of input/output devices form part of the same ecology. Therefore, in ubiquitous computing, it is important to explore novel forms of interaction not just between a person and a single device, but also between heterogeneous devices of different form factors and the capabilities that harmonize with the surrounding environment. For instance, research efforts have focused on the use of smartphones as ubiquitous input devices for interactive surfaces [Ballagas et al. 2006].

3.3 Multi-user, multi-surface environments: interactions with tables, walls and floors

Although tabletop affordances are unique to their form factor, interaction techniques do overlap with other surfaces such as walls or floors. Inspired by VIDEOWALL [Krueger 1991], Matsushita and Rekimoto [1997] proposed their vision of *perceptual surfaces*—physical surfaces (such as walls, floors and tables) enriched by sensory perception in such a way that users do not need a control device to interact. They considered surfaces not only as potential large screen displays, but also as something that can be *"aware of the physical environment."* To demonstrate their ideas, they developed the HoloWall prototype and its tabletop version, HoloTable, which are two instances of nearby and proximity-based interactive surfaces that not only recognize touch inputs but also nearby people and objects. The system and the interaction techniques presented by Matsushita and Rekimoto [1997] have influenced the development of tabletop computers, as demonstrated by references in prominent works such as DiamondTouch [Dietz and Leigh 2001], SmartSkin [Rekimoto 2002] and FTIR [Han 2005]. Different interaction modes have been explored for vertical surfaces that have also been implemented on horizontal surfaces (see discussion in Section 7) such as remote interaction with a device [Bolt 1980; Baudel and Beaudouin-Lafon 1993], direct touch [Wilson 2004], indirect touch [Malik and Laszlo 2004] and tangible [Klemmer et al. 2001]. A detailed discussion on touch-less and touch-based techniques and technologies for vertical displays can be found in the work of Banerjee et al. [2012].

Interactions with floors have also been a subject of investigation, especially in the context of embedded and collective interaction [Petersen et al. 2005], as an exploration of ubiquitous computing principles in a large space scale. Interactive floors controlled by co-located people have been integrated in public physical spaces, such as museums, libraries, shopping malls [Petersen and Grønbæk 2004] or in dance floors [Paradiso et al. 1997]. People interact with their footsteps and these prototypes have been developed that recognize users' movements [Paradiso et al. 1997] and their profile via footsteps' pressure [Orr and Abowd 2000]. Additionally, floors have been integrated into smart environments to allow people to distribute digital content within different interconnected interactive surfaces [Petersen and Grønbæk 2004].

Multiple surfaces integrated into multi-user and multi-device spaces are the manifestation of the ubiquitous computing idea of technology-enhanced environments [Weiser 1991]. They are physical spaces where the affordances of physical objects are augmented with digital capabilities, thus creating an ecology of heterogeneous networked devices. An implementation of such a ubiquitous environment is i-LAND [Streitz et al., 1999]. In this project, different interactive surfaces coexist in the same physical space to support collaborative human work: a wall-sized display screen (the DynaWall), an interactive horizontal surface (the InteracTable), and two computer-augmented chairs with a pen-based computer display with laptop docking. The scenario depicted by the i-LAND project establishes a socio-technological system. From the human point of view, digitally augmented surfaces are used to perform collaborative activities and, therefore, it is important to understand how to best design such device ecologies in order to support users needs [Coughlan et al. 2012]. From the machine point of view**,** heterogeneous devices coexist, from digital whiteboards, large projected vertical surfaces, interactive tabletops, tangible I/O objects and personal devices with private display screens. Such devices have to communicate amongst each other and, to make this happen, interoperability is a paramount issue. In order to exchange information from one to another they have to agree on common communication protocols and network architectures. Moreover, being operated with different interaction styles, they also need to share a common definition of the type of data they can process and transmit.

4. MULTI-TOUCH INPUT

The term multi-touch refers to an interaction style that allows users to interact with more than one finger at time, taking into account hand movements as well as gestures. This modality, therefore, allows the recognition of both discrete and continuous input. There are, though, some characteristics that need to be clarified with respect to touch input.

Single-touch and multi-touch. Devices that are capable of detecting touch are often classified colloquially as either *touch* or *multi-touch*, but there are distinctions that help to define the terminology of touch-based interaction. Single-touch devices, such as traditional resistive touch screens, are for discrete input or for emulating a mouse [Potter et al. 1988]. Single-touch means that the detection and control of touch events is made over a single contact point, that is, single-touch systems respond to the movements of only one finger or stylus (e.g., the first PDAs). In multi-touch, two or more touch events can be detected at the same time and movements of contact points are tracked individually. The number of contacts points they can handle is an important feature of multi-touch devices. Two-touch systems are able to recognize and track two contact points and enable gesturing (e.g., two fingers pinch-to-zoom on the Apple iPhone). Multiple contacts (more than two) are required for users to perform multi-touch gestures such as multi-fingered grabbing [Moscovich and Hughes 2006]. Still more contacts must be tracked to enable multiple users to perform multi-touch gestures all at once, as desired for collaborative tabletop interfaces [Dietz and Leigh 2001].

Gestures. The term *gesture*, in a multi-touch environment, is not related to the expressive gestures used in human face-to-face communication, but instead to familiar and conventional hand movements used in some particular task. According to the literature, surface gestures are classified as: (a) multi-touch (or multi-finger) and (b) whole-hand [Wu and Balakrishnan 2003; Freeman et al. 2009]. A description of multi-touch gestures includes attributes such as position, motion velocity, and acceleration of each contact point that the software must use to recognize the gesture and activate the associated interface action. For example, the *de facto* standard, two fingers *pinch-to-zoom* gesture or five fingers pinch (grab) to exit an application on the iPad. Whole hand gestures go beyond handling multiple contact points and require sensing the pose of the hand on the surface as well as its position and dynamics [Wu and Balakrishnan 2003]. The term *surface gestures* [Wobbrock et al. 2009] focuses on the input device in use—the two-dimensional touch display. This classification is useful to distinguish touch gestures from *remote gestures* that do not contemplate contact with a display surface [Baudel and Beaudouin-Lafon 1993] or *motion gestures* that are being used in mobile computing and are performed by exploiting sensors embedded in the mobile device such as accelerometer or gyroscopes [Ruiz et al. 2011]. However, surface gestures discrimination into multi-touch and whole-hand is crucial to understand tabletop computing lexicon [Buxton 2009] and to design rich interactions that induce an effortless and graceful user experience [Wigdor and Wixon 2012]. Isenberg and Hancock [2012] argued that an implicit assumption of the term *gesture* is often employed, which might cloud the understanding and discussion of touch-based interaction. Building upon the work of Baudel and Beaudouin-Lafon [1993], Wu et al. [2006] and Wobbrock et al. [2009], they presented their definition of gesture by differentiating the concept of *gesture* from *posture*. For Isenberg and Hancock [2012] a gesture is *"a way to invoke manipulations in a direct-touch environment that is started by touching the surface in a well def ned initial conf guration and that is continued for some time in a well-defin d motion pattern (incl. the null motion) during which the conf guration may change."* This definition concisely and clearly characterizes 2D surface gestures, according to the concept of *configuration* (e.g., number of fingers, single or bi-manual, shape, etc.) and *dynamic* phase [Baudel and Beaudouin-Lafon 1993; Wobbrock et al. 2009], as well as *registration* and *relaxation* [Wu et al. 2006]. A posture, which is preferred in 3D environments, relaxes the constraint of the *well-defined motion pattern*, thus encouraging direct manipulation of virtual objects. The main difference between gestures and postures, they contend, is that with a gesture the result of the interaction occurs after the gesture terminates and has been recognized, while in postures, manipulations take place while the posture is still active.

Unencumbered gestural interaction in touch surfaces capitalized previous research on touchless gestural interaction. At its very beginning, research focused on camera-based recognition of free-hand gestures [Krueger et al. 1985; Koike et al. 2001], virtual reality environments [Wexelblat 1995], and special input gloves [Baudel and Beaudouin-Lafon 1993; Wexelblat 1995]. This provided a literature of design, empirical, and experimental guidelines. Krueger et al. [1985] were the precursors, implementing rich gestural interaction in different configurations including walls and tables (as described in Section 3 with the VIDEODESK system).

Rekimoto [2002] presented early demonstrations of multi-touch and whole-hand gesture recognition in tabletop surfaces. He explored the recognition of simple hand movements in a capacitance-based architecture known as SmartSkin. For instance, he proposed a mapping of multi-touch gestures to commands, such as two fingers approaching the center of an object to *pick* the object, but also manipulations of virtual objects based on hand shapes or even the entire arms for multi-object selection gestures. Wu and Balakrishnan [2003] went one step further and presented a variety of multi-finger and hand gesture interactions emphasizing the sensing capabilities of the DiamondTouch platform (multiple contact points from several users) [Dietz and Leigh 2001]. They investigated the use of different interaction techniques in the RoomPlanner prototype application: single-touch or two-touch input, single-hand or two-hand techniques, and the sensing the shape of a user's hands. Single finger input works as in the pointing paradigm. Two finger input was employed for rotation and scaling of visual objects. The main idea behind single-hand techniques was to recognize hand positioning over the interactive board (flat, vertical, horizontal and tilted horizontal), and activate the command associated to the respective gesture. Bimanual interaction employed only symmetric gestures with the same idea as for one-hand gestures: the system recognizes the gesture and it executes an action.

The work of Wu et al. [2006] was the first attempt to provide general design principles for the generation of new gestural interfaces for multi-touch-based tabletop applications. They observed that, even though many hand-based interaction techniques were proposed [Rekimoto 2002; Han 2005; Wu and Balakrishnan 2003], the gestures set was defined ad-hoc and no generative framework for its construction was provided. Therefore, they introduced a design framework, based on gesture *registration*, *relaxation* and *reuse*. The main idea was to promote the generation of a complex gesture vocabulary, where each gesture was based on a set of consistent primitives. In this way, gestures with different semantic meaning were generated all from the same initial information. The DiamondTouch tabletop was used as test bed to demonstrate the applicability of the framework principles. The registration phase is the starting point. The user executes a gestural command and the system sets the context for subsequent interactions. Relaxation allows the user to soften a gestural pose. In a setting like a tabletop surface it is important not to be forced to maintain the same gestural pose for a long period of time because of the high variability in users' standing or sitting habits at a table [Wu et al. 2006]. Reuse addresses the definition of primitive gesture to be used for complex gestures. Tse et al. [2006] also investigated the mapping of hand gestures to commands. Like Wu and Balakrishnan [2003] and Wu et al. [2006], they advocated that postures should reflect natural hand gestures as much as possible. Furthermore, they stated that any person interacting at the table should be able to easily understand every hand gesture from other participant.

Multi-user and multi-touch. The tabletop form factor promotes parallelism of actions [Rogers and Lindlay 2004], especially if compared to vertical displays, where users feel awkward standing next to each other [Dietz and Leigh 2001]. To have multiple users simultaneously interacting around a touch surface, the hardware and the software must provide mechanisms to identify which user the touches belong to. Imagine a surface capable of recognizing two simultaneous touch points. It is different if they come from the hands of the one single person or from the hands of two different users. For instance, having the capability of recognizing multiple users, the two touch points would be assigned to two different cursors, that is, if we are interested in emulating the mouse [Esenther et al. 2002]. On the contrary, two touches from different users would be recognized as coming from the same person and processed as one gesture (e.g., pinch-to-zoom). The DiamondTouch enables the recognition of a user who is touching the surface. This feature allowed Wu and Balakrishnan [2003] to envision multi-users gestures, in which one hand *"specif[ies] the frame-of-reference for another hand's action"* and *"one person might specify the context of another person's gesture."* Morris et al. [2004], later on, implemented this idea with the CollabDraw system, which interprets gestures from different users as a single command. For example, if two users were able to touch a digital object at the same time in order to transfer its ownership.

5. TANGIBLE INPUT

Placing an object on a table is the most intuitive method to allow tangible input. Combining tabletop interaction with tangible user interfaces, Tabletop Tangible Interfaces (TTIs) [Ullmer and Ishii 2000] leverages the strengths of both technologies to emerge as a signifi ant research topic in the field of tabletop computing. TTIs enable tangible objects to be manipulated in a dynamic environment augmented by digital representations, offering rich interaction possibilities to users. The idea of coupling digital information with physical objects came from tangible computing, which foundations were laid by Fitzmaurice et al. [1995] and Ishii and Ullmer [1997]. Many systems that rely on the TTI concept have been built during the years. Examples include the already cited Bricks [Fitzmaurice et al. 1995] or metaDESK [Ullmer and Ishii 1997]. In the beginning, research focused on the use of tangible elements to develop planning tools for construction and design such as BUILD-IT [Rautenberg et al. 1998] and Urp [Underkoffler and Ishii 1999]. In particular, Ullmer and Ishii [2000] employed Urp to introduce their conceptual model for tangible interaction, which is based on the ideas of *representation* and *control*. Urp is a tangible interface for urban planning that simulates interactions between buildings (e.g., shadow castings). As Ullmer and Ishii [2000] reported, *"the physical forms (representing specific buildings) of the Urp models, as well as their position and orientation on the workbench of the system, serve central roles in representing and controlling the state of the user interface."* As *representation*, tangible objects specify affordances through their physical form, which is reflected in the digital state of the system. The shape of tangible objects is then used to specify their semantic meaning. Each shape is associated to specific actions in the user's interface (e.g., phicons in metaDESK or pucks in reacTable* [Jordá et al. 2007]). As *controls*, the objects are used as input devices, as in the case of activeDesk or metaDESK. Ullmer and Ishii [2000] formalized these concepts into the MCRpd model that organizes a unique frame for digital information (Model), the interaction (Control), the physical objects (Rp), and their coupled digital representation (Rd). They also presented instances of tangible interfaces listed in a four-dimensional space. TTIs contribution in the *spatial* category is that—*"they interpret the spatial position and orientation of multiple physical artifacts within common frames of reference"* (the table surface). Fishkin [2004] introduced a taxonomy for tangible input according to, among other dimensions, the level of embodiment (full, nearby, environment, and distant). This demonstrates how tangible input spans over different input possibilities, which include direct contact with an interactive surface and also remote interaction. In this survey, the input space for tabletop interaction is also categorized according to the embodiment (see Table **III** in Section 7).

Tangible interfaces meet in interactive horizontal surfaces as a natural environment. Their intended benefits include spatial multiplexing and bimanualism [Fitzmaurice and Buxton 1997], and natural affordances of tangible objects [Fitzmaurice et al. 1995]. Fitzmaurice and Buxton [1997] conducted the first formal study, comparing the mouse with tangible input in a f xed-duration target-tracking task. Their finding revealed that while the mouse is a general-purpose device, tangible input is considered to be more specific. The mouse can perform well but in limited areas, like learning domains (e.g., molecular biology or chemistry) [Marshall 2007] or, as already pointed out, architecture or urban planning [Underkoffler and Ishii 1999]. One important challenge is, therefore, to understand in which situations tangible input can offer significant advantages. Researchers need to figure out the tradeoffs involved in using a TTI, whether multi-touch, or in which cases a combination of the two can result in a better user experience. There is still some literature analyzing tangible interaction opportunities and problems in a multi-touch tabletop environment. A study by Marshall et al. [2009] analyzed how human-to-human interaction is mediated by tangible technologies in a co-located setting. However, their conclusions were biased and cannot be generalized because they conducted an experiment with an extremely focused user group, such as children. Terrenghi et al. [2007] also depicted implications of coupling physical and digital manipulation. They found that a simple digital representation of the physical space and the use of multi-touch input might not be enough in order to offer a natural physical world interaction. Nevertheless, they only considered multi-touch interactions in a WIMP-like environment and this limited the overall validity of their findings. To our knowledge, Tuddenham et al. [2010] is the only work that tried to generate a deep understanding of tangible input for interactive tabletops. They demonstrated real advantages of tangible controls over other inputs for manipulation and acquisition tasks. They also observed one important drawback of multi-touch interaction that they labeled the *exit problem*, which was partially observed previously by Forlines et al. [2007] and Wu et al. [2006]. The problem refers to the difficulties experienced by the users to disengage from a touched digital object without generating some extra movements. Although their work represents a first step in the comprehension of TTIs, their results are still somewhat limited. For instance, they did not consider complex gestural interaction [Wu et al. 2006].

In general, TTIs make use of passive objects that a user can easily manipulate to change the coupled digital model. However, the physical model does not reflect such changes, causing inconsistencies between the physical and digital worlds [Jordá et al. 2007]. To alleviate this inconsistency, some researchers have attempted to create active TTIs, thus providing bidirectional physical interfaces. Active TTIs, in fact, are capable of moving or changing their physical status to reflect changes in the digital model [Pedersen and Hornbæk 2011]. Active and actuated objects are one of the trends that guide the future development of tangible interfaces [Shaer and Hornecker 2010].

6. TOUCHLESS (REMOTE) INPUT

Recent approaches have also demonstrated the utility of differentiating in-air hand postures, as opposed to those that occur while in contact with a device [Hilliges et al. 2009; Wilson and Benko 2010]. The SecondLight system can see through the display, and can both project light and sense interactions in the volume above the display itself. Hilliges et al. [2009] used cameras to detect simple postures both in the air and when in contact with the display, exploiting the moment of contact as a transitional state to delimit interactions. This enables both the user and the system to agree on, and differentiate between, hand gestures that occur in contact with the display, as opposed to incidental movements of hands in the air. Wilson and Benko [2010] further explore interaction in the space around the surface, using multiple depth cameras and projectors. Touchless interaction not only considers hand-gestures or the manipulation of physical objects, but it also exploits motion sensing, as in proxemics interactions, which takes into account users position relative to the display [Annett et al. 2011]. Remote interaction demonstrates how direct input is more than touch alone. The motions of users' hands above the display [Tang et al. 2010], and the posture of the hand as it comes into contact with the displays [Holz and Baudisch 2010], are also forms of direct input that can extend and enrich user interfaces. What is critical to note about these examples is that they do not attempt to use in-air gesturing to replace the mouse, simulate text entry on a virtual keyboard, or replace established touch gestures. Rather they leverage the distinct properties of spatial sensing to provide new capabilities that are well differentiated from direct touch and other inputs.

While remote pointing has been extensively analyzed for vertical large displays [Guiard et al. 2004], very few works focused on horizontal interactive surfaces. One example is TractorBeam [Parker et al. 2005], a remote pointing system that allows users to interact with distant objects on tabletop surfaces. In their work, Parker et al. [2005] compared remote pointing with stylus touch and demonstrated that task completion is faster for remote pointing with large targets and slower for small targets. In all other cases, no significant difference was found. They also reported that people preferred remote pointing interaction than stylus touch.

7. INPUT SPACE FOR TABLETOP INTERACTION

In a tabletop system, the interactive surface embodies a double function. It is (a) the display, where user interface elements are visualized, and (b) the input device at the same time [Shen et al. 2006] (see the definition in Section 2). Therefore, since a tabletop merges both concepts of providing a visual output and allowing input on the same surface, major idiosyncrasies of direct input devices need to be taken into account [Hinckley and Wigdor 2012]. Moreover, Kunz and Fjeld [2010] highlighted in their classification of tabletop surfaces that interactions in digitally augmented tables are direct-touch based, though some recent works have started investigating other types of touch-free interactions above [Hilliges et al. 2009] and between surfaces [Wilson and Benko 2010]. According to the classification of Kunz and Fjeld [2010], the types of interaction fall into two classes: (a) hand-based, in which users employ their hands to perform simple pointing actions or more complex gestures, and (b) device-based, in which an input device has to be used (e.g., a tangible icon [Ishii and Ullmer 1997]). Nevertheless, Kunz and Fjeld [2010] did not articulate how their classification can be used to compare and contrast different approaches, nor the rationale behind it. As demonstrated by the review of the state of the art, tabletop systems adopt a wide range of input technologies, not only based on direct touch. *"The two main reasons for the wide disparity in choice of input devices are the variety of tasks that can be performed using a tabletop display, and the inherent strengths and weaknesses of the input devices. In addition, there is a lack of understanding concerning users' interactions with the tabletop display and various input strategies"* [Ha et al. 2006]. A classification based on the presence or absence of input devices falls short in understanding benefits and shortcomings of different input modalities. Additionally, Kunz and Fjeld [2010] did not take into account the combination of input modalities. For instance, they did not consider pen+touch bimanual interaction. Focusing only on the comparison of individual modalities might lead to the ill-posed question: is device A better than device B? The perspective here should not focus on which device, input modality, interaction or sensing technique is the best, as Buxton [2009] declares that *"everything, including touch, is best for something and worst for something else"*; but on how they can cooperate in the same ecosystem [Hinckley and Wigdor 2012]. To this end, conversely from Kunz and Fjeld [2010], we adopted a classification of the input space based on the interaction afforded by tabletop systems. For the sake of clarity we repeat that, in this work, the definition of input space is *"the physical location where the user can provide input"* [Grossman and Wigdor 2007]. The first dimension is the *directness* of the input: *direct* or *indirect*. In direct input, as reported at the beginning of this Section, the input and the display spaces are the same (e.g. IR styli and users' fingers on a touch screen. In direct interaction there is no intermediary and users' movements are directly mapped into system input. Indirect devices, on the opposite, translate some action of the human body into data for the machine (e.g., mouse); the output is provided in a space that is not unified with the input space. The second dimension is related to the *embodiment* expressed through physical contact with the surface: *explicit contact, contrived contact and contact-less*. Explicit contact includes direct touch input like a stylus or users' hands, or a combination of both device-based and finger touches. Contrived contact occurs when the user interacts with the tabletop system by interacting with a different surface; for example, the display screen of a personal mobile device. Contact-less describes an input that is originated without any physical contact with the surface; for instance through motion gestures, manipulating tangible objects at a distance, in-air gestures or proximity. Each of the three attributes of the embodiment dimension, in turn, can be direct or indirect. This distinction will hopefully become clearer in the discussion ahead. In the rest of this Section, input modalities for tabletop interaction (multi-touch, tangible and touchless) are discussed within the frame of the six categories (the combination of direct/indirect with explicit contact/contrived contact/contact-less). The organization in Table III is intended to be a starting point for framing the input space of tabletop systems and defining shared attributes that may be usefully compared amongst each another. At the end of this Section, two other characteristics that span over the input space are described: bimanual interaction and text-entry.

Table III. Organization of tabletop technologies according to the input space.

		EMBODIMENT		
		Explicit Contact	**Contrived Contact**	**Contact-less**
DIRECTNESS	**Direct**	ActiveDesk [Fitzmaurice et al. 1995], DiamondTouch [Dietz and Leigh 2001], reacTable [Jordá et al. 2007], metaDESK [Ullmer and Ishii 1997], DigitalDesk [Wellner 1991], SmartSkin [Rekimoto 2002], FTIR [Han 2005], Microsoft Surface [Microsoft 2007], SecondLight [Izadi et al. 2008], Augmented Surfaces [Rekimoto and Saitoh 1999] and InteractTable [Streitz et al. 1999]	Beyond [Lee and Ishii 2010] and SLAP widgets [Weiss et al. 2009], ResponsiveWorkbench [Cutler et al. 1997] and Virtual Workbench [Poston and Serra 1996]	SecondLight [Izadi et al. 2008], in-air gestures [Hilliges et al. 2009], VIDEODESK [Krueger et al. 1985], SmartSkin [Rekimoto2002], Responsive Workbench [Cutler et al. 1997] and Virtual Workbench [Poston and Serra 1996]
	Indirect	Superflick [Reetz et al. 2006]	CommChair [Streitz et al. 1999], normal mouse [Forlines et al. 2007], multi-touch mouse [Villar et al. 2009] and Augmented Surfaces [Rekimoto and Saitoh 1999]	Medusa [Annett et al. 2011]

7.1 Direct

Direct manipulation interfaces refer to a system that provides a continuous representation of digital objects being manipulated and immediate visual feedback of reversible operations that affect the objects [Shneiderman, 1982]. Moreover, they foster recognition versus recall, physical actions on graphical interfaces instead of textual commands with complex syntaxes. The direct manipulation of virtual objects on a screen surface via a pointing device was firstly facilitated by Sketchpad [Sutherland 1964]. Although Sketchpad is not an example of a tabletop system, it is worth mentioning here for it has redefined the way the user interacts with computers. By means of an input device like a light-pen, in fact, it was possible to provide a direct mapping between user actions (e.g., the manipulation of digital objects) and the state of the system, as displayed on the screen. The works of Bolt [1980], Krueger [1991], and Baudel and Beaudouin-Lafon [1993] introduced direct manipulation through gestural touchless interaction with large surfaces.

In their paper on direct manipulation interfaces, Hutchins et al. [1985] identified two phenomena that can describe the sensation of directness: (1) the reduction of the information processing distance between users' intentions and the interface offered by the computer, and (2) the representation of objects as themselves (e.g., a folder icon representing a folder). Interactive tabletops offer an even more advanced sense of directness since the user is able to manipulate digital representations of objects or even physical objects as in case of tangible interaction. Tabletops give birth to a whole new set of user interfaces extensively employing direct manipulation interaction styles. In fact, according to Shen et al. [2006], "*tables provide a large and natural interface for supporting direct manipulation of visual content for human-to-human interactions.*" For instance, Beaudouin-Lafon [2000] introduced the concept of *Instrumental Interaction* to go beyond the classical WIMP interfaces [Van Dam 1997], which included both classic direct manipulations, gestural, and touch-based input combined with augmented reality. The principle was based on interaction instruments (resembling real world tools) mediating between the user and application domains. We rarely finger-paint because we rather use a pen or a stylus as a mediator for writing on a surface, in the same way many users, prefer to interact with a stylus instead of fingers for certain tasks on interactive tablet surfaces like the iPad.

7.2 Indirect

An indirect input device does not provide input in the same reference space as the output. Indirect devices eliminate occlusion of the screen by the user's hand and fingers. However, typically they require more explicit feedback and representation of the input device itself (e.g., a cursor), the intended target on the screen (e.g., highlighting icons when the cursor hovers over them), and the current state of the device (e.g., whether a button is held or not). While indirect input devices such mice and track pads, may feel antiquated in the context of modern ubiquitous computing; combinations of indirect input devices are still suitable for many applications and remain important to understand for interaction designers. This is particularly true in scenarios where an interactive tabletop is integrated into the same environment with heterogeneous devices. For instance, Ha et al. [2006] investigated how the choice of direct or indirect devices affects various aspects of tabletop interaction, such as co-located collaboration, territoriality, and awareness. Findings from their three experiments made it possible to define benefits, drawbacks and design considerations for direct and indirect input. In particular, indirect input addresses: (a) reaching problems which allow items on the far side of the table to be easily accessed, and (b) occlusion, because a small pointer does not obscure elements on display. On the contrary, lesser support for awareness of intention and action may impede coordination and collaboration. Moreover, the visualization of multiple cursors may be distracting or confusing. One important consideration is that, in case of indirect input with a device, additional space must be arranged for the device, on or around the table.

7.3 Explicit contact

Explicit contact refers to an input that is originated by a physical contact with the tabletop surface, by means of any input device such as optical styli, tangible objects, users' fingers and hand gestures.

Direct. As Table **III** shows, direct interaction by explicit contact is used the most in tabletop environments, because it is directly supported by physical affordances of the table form factor. Direct interaction via explicit contact is supported by almost any tabletop system in the form of stylus input, bimanual pen+stylus [Hinckley et al. 2010], multi-touch, and tangible interfaces. By employing different technologies (see [Schöning et al. 2008] for a detailed description), current tabletops recognize and track multiple points of contact on the surfaces to implement different interaction styles. Touch input can be used for mouse emulation. For example, a user can displace the mouse cursor by moving the finger (one contact point) on the surface, and mouse right click can be emulated by touching the surface with two fingers (two contact points). Multi-touch has been used to develop shape-based object manipulation, as described by Rekimoto [2002] in the Smartskin infrastructure. For example, arm gestures can be implemented to move a group of objects (e.g., brush off the table surface with one arm).

Although many multi-touch systems only make use of multi-finger techniques, the most interesting capability of multi-touch interactive surfaces is the recognition of hand gestures.

Tabletop systems such as DiamondTouch [Dietz and Leigh 2001] have made it possible to recognize and track complex hand shapes from multiple users simultaneously.

In reacTable* [Jordá et al. 2007], computer-vision algorithms are employed both for recognizing tangible objects and finger contact points on the surface. Thus, this architecture allows the combination of tangible and multi-touch interfaces. Direct, explicit contact of tangible interfaces uses real world objects as input devices [Fitzmaurice et al. 1995; Jordá et al. 2007].

Indirect. Due to the natural affordance of the table, the notion of indirect explicit contact is not very representative of tabletop interactions. Still there are some cases where indirect interactions based on explicit contact would be helpful to cope with reaching problems [Ha et al. 2006]. Reaching problems result directly from the table form factor, being most of the time the tabletop surface wider than a user's arm. There may be cases in which a user wants to interact with an interface element outside his/her action area. Findings from the study of Ha et al. [2006] revealed that indirect techniques *"allow items on the far side of table to be easily accessed."* For instance, the Superflick [Reetz et al. 2006] system utilizes a virtual overview of the whole tabletop display that can be operated via stylus input. Interacting with the overview allows the user to reach physically distant objects on the main interface.

7.4 Contrived Contact

In this category we group interactions that take place by touching, but the input involves another surface that is different from the tabletop.

Direct. Novel tangible interfaces that change their shape due to users' interaction are an example. In this case the tangible object is not used as a direct input device as in the case of direct, explicit contact (e.g., a physical prop which its movement causes a visual representation to move on the display), but instead the user manipulates the physical object that is in contact with the surface in a way that changes its physical characteristics that produce a direct input to the digital surface. Beyond [Lee and Ishii 2010] is a collapsible tangible device in the form of a stylus for direct 3D manipulations. When pressed against the surface, the device *collapses* in the physical world and it extends into the digital, so that the user can have the illusion that they are inserting the tool into the virtual space. SLAP Widgets [Weiss et al. 2009] are transparent physical widgets made from flexible silicone and acrylic. As input devices, they combine the advantages of physical and virtual on-screen widgets. They provide a haptic operation experience with tactile feedback, supporting fluid and eyes-free operation. At the same time, thanks to their transparency, they support dynamic software-controlled labeling using the rear projection of the interactive table they rest on.

Manipulation of tangible elements that are not in contact with the tabletop surface can also be exploited to enable this kind of input. As demonstrated by Hinckley et al. [1994], physical manipulations of real-world props have been used to specify spatial relations with interface elements in neurosurgical applications. However, the system works with a vertical display and, to our knowledge, there are no tabletop systems that follow the same design rationale.

Indirect. Mouse input is the most diffused example of this category. Müller-Tomfelde and Schremmer [2008] focused on differences and commonalities between mouse and touch input in collaborative tabletop scenarios. In their experiments, teams of two users were given the freedom to choose between mouse or direct-touch inputs to accomplish puzzle solution tasks. Findings from their experiments cannot demonstrate if one input technique is better than the other for this kind of task. Users uniformly chose between touch and mouse as preferred input, and similar collaboration patterns were observed in all trials. Moreover, completion and manipulation time did not statistically differ.

Many research works focused on mouse input as a way to solve the intrinsic limitations of touch technologies: precision (which is known in literature as the *fat finger problem*) [Benko et al. 2006; Esenther and Ryall 2006], and occlusion [Wigdor et al. 2006]. Aiming at improving the usability of mouse-based applications on tabletop environments, Esenther and Ryall [2006] developed the Fluid DTMouse system. They pulled from the interactive capabilities of the DiamondTouch surface and implemented a touch-based emulation of a mouse to cope with two main challenges of touch-enabled surfaces. Those being (a) interpreting a single touch when used as a replacement for mouse input and (b) the lack of input precision when using a single finger as the mouse cursor. Benko et al. [2006] focused on the lack of sensing precision together with the size of human

fingers. In their work, they proposed five techniques (*Dual Finger Selections*) to help users select very small targets in touch-enabled surfaces, including both vertical and horizontal display solutions.
A less addressed problem of direct touch interfaces is the feedback ambiguity, caused by the elimination of a digital pointer and physical feedbacks provided by an external device, like a mouse. The work of Wigdor et al. [2009] demonstrates actual research efforts to face this problem. They developed a mechanism (*Ripples*) that works by displaying visual feedback only around contact points on the surface. Such feedback guides the users during the interaction, notifying successes and errors.
Overall, it has been already demonstrated how tabletop surfaces support direct touch hand gestures for input. This allows users to perceive actions from other users concurrently interacting with the tabletop. Furthermore, as gesture vocabularies become more natural, they will enable rich interactions among users, having each user understand other users' objectives by simply viewing their gestural interaction with the system. From another point of view, indirect input devices present other advantages. For example, by using indirect remote devices it is possible to solve both the reaching and the occlusion problems [Ha et al. 2006]. Designers should take advantage of the intrinsic characteristics of direct touch techniques and indirect devices when designing the interaction for tabletop applications. A closer examination should be carried out for integrating standard input devices in a multi-touch context. This would provide users with richer input possibilities to be used for different tasks.
Indirect, contrived contact-based input is also used in multi-surface environments. For instance, in i-LAND [Streitz et al. 1997] and Wespace [Wigdor et al. 2009], users operate the tabletop interface by a portable device. In this case, interactions in a surface, like the one provided by a tablet or a smartphone, are reflected in the tabletop interface. Another example can be the multi-touch mouse developed by Villar et al. [2009] in which multi-touch gestures are performed on the mouse surface instead of directly on the tabletop surface. These kinds of indirect interactions are worthy of investigation because of the growing need to support multi-device interaction in technology-enhanced environments [Coughlan et al. 2012].

7.5 Contact-less

Contact-less or remote refers to an input that is not originated by any physical contact with a surface, in contrast with touch interactions that suggests the presence of an input device that touches the surface, like a stylus or users' hands.
Direct. Instances of direct, contact-less input come from touchless gestural interaction research. VIDEODESK [Krueger et al. 1985] was one of the first inspirational examples. Hilliges et al. [2009] expounded the space above the surface in combination with the tabletop display to implement rich in-air gestures that allow more intuitive manipulations of virtual elements.
Direct touchless manipulation research, applied to tabletop computing, crosses the boundaries of Virtual Reality, as in the Responsive WorkBench [Kruger et al. 1995] which is a VR tabletop device that features a stereoscopic display for the visualization of 3D virtual elements. The system exploits hardware devices such as gloves and stylus' for the remote manipulation of digital elements. Moreover, it provides a logical abstraction of input devices through manipulators (e.g., right and left gloves are encapsulated into a two-handed manipulator), and tools that allow users to perform specific tasks (e.g., panning, zoom, free rotation, etc.). The Virtual Workbench [Poston and Serra 1996] also permits remote direct manipulations. It makes use of physical tools with attached digital behaviors to interact with medical images. For instance, users can explore magnetic resonance images of the brain by holding a device for grabbing in their left hand, while moving and rotating the image with a stylus in their right hand to perform sensitive work. SecondLight [Izadi et al. 2008] is another example of contact-less interaction via input devices in 2D tabletops. In this system switchable diffuser surfaces in the space above the surface are employed as magic lenses. As demonstrated by the presented systems, direct contact-less interaction is particularly suited for 3D and Augmented Reality tabletops where the users can directly reach virtual objects and grab them or manipulate virtual representations through hand-free movements.

Indirect. Contact-less input can be also indirect. Even if there are less examples of this approach in the history of tabletop computing, recent developments in spatial sensing are enabling proximity-based interactions, which exploit the positions of users relative to the display [Annett 2011; Marquardt et al. 2011a]. Medusa [Annett 2011] is a clear example. It is a tabletop system that adapts the user interface according to the user's presence, his/her distance, and the body and arm locations. Even with this much reduced class of the input space, we foresee future systems using more and more environmental sensing technology in order to interact with the surrounding physical/digital world, as was demonstrated by research efforts towards the development of software libraries for proxemic interactions [Marquardt et al 2011a].

7.6 Other elements of the input space

We report here on two other features that span the whole input space, specifically (a) bimanual interactions and (b) text-entry. Due to their importance and extension, they need to be addressed separately.

Bimanual interactions. Two classes of bimanual techniques can be identified: (a) *asymmetric* input, in which hands are labeled as dominant and non-dominant and, (b) *symmetric* input, in which the same role is assigned to each hand [Balakrishnan and Hinckley 1999]. Bimanual techniques find their theoretical foundations in the *Kinematic Chain* framework by Guiard [1987] and have been the subject of several research projects and empirical studies. The works of Buxton and Myers [1986] Latulipe et al. [2005] and Balakrishnan and Hinckley [1999] are particularly relevant in the HCI field. Buxton and Myers [1986] highlighted that using bimanual input increases the speed of performing tasks with GUI elements. However, that is only true for tasks with high levels of parallelism. Latulipe et al. [2005] focused on the use of two mice for bimanual input. Findings from their experiments stressed that in the majority of the proposed tasks, performances of symmetric bimanual input (two mice) are strongly better than asymmetric bimanual input that, in turn, are better than single mouse interaction. Therefore, they suggested that designers should take into account symmetric interactions and not automatically take for granted that all two-handed interactions are asymmetric. The contribution of Balakrishnan and Hinckley [1999] has shed some light on the role of proprioception in asymmetric bimanual interaction. In their experiment they used two pucks on a horizontal tablet in front of a vertical display to perform a *connect-the-dots* task in a 1:1 mapping of the input space to the display space. They found that the *visual* is the dominant feedback channel over the *kinesthetic,* and when the visual feedback is absent, users benefit from absolute reference frames (e.g., the tablet space).

Prior research typically centered on (a) direct bimanual input in large vertical displays [Balakrshinan et al. 1999], (b) indirect input with classical desktop displays [Kurtenbach et al. 1997] and, (c) the benefits of bimanual over unimanual interaction for specific tasks [Balakrishnan and Hinckley 1999; Buxton and Myers 1986; Latulipe et al. 2005]. Over the years many works have focused on different aspects of bimanual interaction in tabletop settings: (a) two-fingers and two-handed multi-touch [Benko et al. 2006; Rekimoto et al. 2002], (b) direct and indirect interaction [Forlines et al. 2007; Kin et al. 2009], (c) pen plus touch [Brandl et al. 2008; Hinckley et al. 2010], (d) direct manipulation of virtual 3D elements [Cutler et al. 1997] and, (d) tangible interfaces [Fitzmaurice and Buxton 1997; Fitzmaurice et al. 1995; Ullmer and Ishii 1997].

Multi-touch does not necessarily mean two-hand (see Section 3.2 on touch input for mobile devices), but the tabletop's large form factor enables two-hand gestures. For instance, Rekimoto [2002] developed two-handed gestures for the direct manipulation of digital objects in the SmartSkin architecture, and Benko et al. [2006] presented multi-fingers techniques for the activation of graphical widgets, tools and menus. Krueger et al. [1985], with the VIDEODESK system, previously explored by freehand, discovered bimanual interaction that does not require further explicit input devices. His work led to the definition of several in-air gestures that inspired the development of many multi-touch gestures for tabletop computing.

Forlines et al. [2007] analyzed quantitative and subjective performances for both single and bimanual interactions with touch and mouse input. They also wanted to study the peculiarity of bimanual interaction in the case of direct (touch and pens) or indirect (mouse or trackballs) input. Results from their study indicated that direct-touch interaction is most suited for co-located tasks requiring bimanual interaction. Moreover, their insights raised doubts on the real benefits of a direct-touch interface for a single user tasks requiring single-point interaction. Mouse (indirect interaction) is better for tasks requiring unimanual input, whilst fingers (direct touch) are better for bimanual input. Nevertheless, these findings have to be considered with care. Even if, considering speed and accuracy, indirect input might be the best choice for one-handed tasks, there are several other aspects to be considered. In terms of fatigue, spatial memory, and awareness of other's actions in a multi-user setting, single-finger touch input might perform better that single-mouse input. For this reason, Forlines et al. [2007] reported that further studies are needed to improve the design of unimanual and bimanual interactions on tabletop surfaces. One attempt to fill this gap is the work of Kin et al. [2009] that proposed design guidelines for multi-target selection tasks, based on the results of an experiment with direct/indirect and unimanual/bimanual input: one mouse, one finger, two fingers and multiple fingers techniques. Brandl et al. [2008] investigated the combination of different devices for bimanual, single-finger input. In their work, they proposed a set of principles for the design of two-handed input techniques. In particular they focused their research on the use of pen and touch for interaction with a horizontal display surfaces. During their experiments they compared three different combinations (symmetric and asymmetric) of bimanual interaction for a tabletop system: *touch and touch*, *pen and pen,* and *pen and touch*. Users preferred the combination of pen and touch to accomplish selection, drawing, color picking, and cut/copy tasks. This technique performed better than the others in terms of speed and accuracy. Additionally, Hinckley et al. [2010] focused on pen and touch input. While research works commonly argue that one technique is better than another and present studies to demonstrate their claims, Hinckley et al. [2010] followed a different philosophy. Since there is no modality that is best for any task, we should then not ask, *"what is the best?"* We should instead change the framework to a cooperative perspective and ask, *"[W]hat is the logic of the division of labor between pen and touch in UI design?"* Hinckley and Wigdor [2012] further extended the question to the whole set of input modalities and form factors for device ecologies, including motion and postural sensing, and proximal and spatial interactions. Following that vision, they articulated their work in interactions where users manipulate the interface through touch, writing with the stylus, and pen+touch, thus they produced new tools that exploit the combination of both touch and stylus interaction primitives.

Bimanualism is one of the claimed benefits of tangible interfaces [Fitzmaurice and Buxton 1997]. For instance, ActiveDesk [Fitzmaurice et al. 1995] supports asymmetric bimanual input through anchors and actuators as described in Section 3 and metaDESK [Ullmer and Ishii 1997] exploits phicons as physical handlers to perform bimanual manipulations such as: (a) scaling, which is moving two objects closer or farther, and (b) rotating, which is moving the two objects together in parallel. However, while research works argument that tangibility encourages bimanualism over unimanualism, Tuddenham et al. [2010] found that more complex patterns arise. Together with classical bimanualism (two hands operating one object, like the *rotation-constraint instrument* in metaDESK), they identified two further patterns. This were (a) *concurrent unimanualism*, when each hand operates a different object, and (b) *lateral sequential unimanualism,* where each hand operates in a different area of the display (commonly the left hand on the left side and the right hand on the right side).

Cutler et al. [1997], exploiting the Responsive Workbench tabletop, provided design guidelines for bimanual symmetric and asymmetric input for the manipulation of VR objects. They also gave insight and raised questions for bimanual interaction research applied to interactive surfaces. For instance, one area for further research could be to have the system automatically recognize when two hands are used together, what is the dominant hand in non-symmetric interactions, and the transitions between one- to two-handed modes.

Text-entry. Text-entry is a critical issue to address tabletop environments suitable for general-purpose computing. Questions include: *Is there a valid alternative to physical keyboards for typing? Can multi-touch support efficient virtual text entry modes on a table surface?* In their long-term study, Wigdor et al. [2007] reported that software keyboards do not negatively impact on the composition of emails. Even if this finding suggests the widespread adoption of tabletop computers for day-to-day tasks, replacing classical desktops, still proper text-entry solutions need to be developed.

The application of text-entry methods to tabletop computing has been influenced by mobile computing research. The first PDAs introduced handwriting and gestural alphabets such as Graffiti [MacKenzie and Zhang 1997] or Unistroke [Goldberg and Richardson 1993]. During the evolution of mobile devices to modern smartphones and tablets, several other methods have been introduced. Both off-screen (or external) methods such as physical mobile keyboards (mobile devices that embed small buttons for typing [Silfverberg et al. 2000]), and on-screen, such as stylus-based soft [MacKenzie et al. 1999] and gesture keyboards [Perlin 1998]. Software keyboards implement direct, software mappings from typing on a physical keyboard while the introduction of gestures enables the interface to connect letters with a continuous movement, without lifting the stylus.

The study of Benko et al. [2009] highlighted that expert users miss an efficient text-entry alternative to keyboards for tabletops, because current software approaches do not work properly. Hinrichs et al. [2007] carefully revised existing text-entry methods and examined their viability on tabletop displays. They identified several factors related to (a) the visual arrangement of the characters and their layout, (b) performances (efficiency and ease to learn of the text-entry method) and, (c) the physicality of the table form factor, such as large space and rotatability. They used these criteria to evaluate existing methods and to provide insights on text-entry modalities depending on the task. The use of a digital keyboard seems to win big. Nevertheless, Shen et al. [2006] are clear that, when it comes to tabletops, *"bare fingers are insufficient for text input. Our experiences with the tabletops have shown that text input is particularly challenging. Providing virtual keyboards on the tabletop has proved a feasible, but tedious, solution."* Further studies are then required to explore other input devices or different layouts and modalities for soft keyboards.

Findlater and Wobbrock [2012] designed and evaluated personalized touchscreen keyboards by observing the differences in typing from one user to another. They found out that personalized input models improve typing on software keyboards. The capability to adapt to users' typing idiosyncrasies is a key factor to explore in the future, because it precludes to the lack of haptic feedback, which makes virtual keyboards less precise and subject to errors [Rabin and Gordon 2004]. For instance, Edelmann et al. [2012] proposed an approach to generate user's typing models they called the *Keyboard of Oz*—inspired on the Wizard of Oz technique [Kelley 1983]. The method simulates a perfect classifier for data acquisition while typing a predetermined text. This allows the gathering of real typing data without having to previously define any model and, thus making the user-centered process to build and evaluate adaptive input strategies more agile.

Text-entry is an active research area that touches upon different context and devices in addition to tabletops: mobile terminals [Zhai et al. 2005], vertical surfaces [Olsen and Nielsen 2001], and wearable devices [Lyons et al. 2004]. Kristensson et al. [2012] recognized that there is a need to build a community of text-entry researchers because possible text-entry environments are heterogeneous and different research fields are involved. These include human computer interaction, experimental psychology, human factors, natural language processing, and pattern recognition to cite a few. Kristensson et al. [2012], therefore, organized a workshop at 2012 CHI conference with the objective of gathering together text-entry researchers and establishing past, present and future directions of the field. Main topics that will drive future research are: (a) defining standards for text-entry evaluations, (b) developing novel text-entry methods that leverage on new technologies and, (c) identifying what contexts and environments require better text-entry solutions, as in the case of tabletop surfaces [Hinrichs et al. 2007].

8. ENVISIONING THE FUTURE

In this Section, we present major challenges that guide research in tabletop computing. While the first three challenges (1 to 3) address unsolved problems that researchers are familiar with, the last four (4 to 7) envision the future of tabletop computing: enabling seamless interactions that are not only based on direct touch and confined by a physical two-dimensional surface. The vision is to have interactive surfaces merging with the environment so to blur the boundaries between the physical and the digital world. With the evolution of sensing technologies, the interaction is ready to go out of the surface. Many sensors are available at a very low cost (e.g., depth sensing cameras like the Microsoft Kinect), which enables rich interactions. However, our actions with digital surfaces are still based on a point model, legacy of the mouse paradigm. For instance, as mentioned in Section 4, although many interactive surfaces are able to recognize whole-hand gestures and retrieve data about orientation, and shape and pressure of the hand, this information has been usually discarded [Han 2005], condensed into a rectangular region [Dietz and Leigh 2001] or simply used for the registration of discrete gestures [Wu and Balakrishnan 2003]. In order to make the most of the rich interactive space that is all around the user, enabling technologies are needed, such as organic interfaces, non-flat surfaces, and infrastructures for device ecologies, together with a change in the interaction model to encompass higher degrees of freedom. An attempt to realize this vision has been made by Wilson et al. [2008], who proposed physics-based interaction techniques, inspired by our real world experience, to manipulate virtual objects. They implemented interaction techniques based on the direct mapping of users' touches with contact forces. This, in turn, enables multi-touch, whole-hand gestures and tangible input, enhancing tabletop interactive experience with real-world dynamics.

Challenge 1: Active and passive contact. The correct recognition of intentional and unintentional contact points (*Midas touch* [Esenther and Ryall 2006]) is a problem that is inherent to the use of multi-touch sensing. For example, when people write on a sheet of paper they usually use their free hand (the one that does not hold the pen) to hold the paper. When simulating the act of writing in a digital document, a digital stylus can be used as the input device and the system should ignore finger contacts on the document. However, when the user raises the stylus from the surface, the system should begin detecting fingers contacts, since the user may want to move the digital document with his/her hand. A stylus can also be used as a pointing device; therefore the system should be able to detect, depending on contextual information, if the user is employing the stylus for writing on a document, or simply for selecting it. Moreover, there can be objects on a table that can be used as inputs for interaction (e.g. physical objects for tangible interaction) but, at the same time, users can place on the board other types of non-interactive physical objects (e.g. a cup of coffee).

The capability of recognizing unintended touches will require both hardware and software solutions. Sensor processor and software should be able to track many simultaneous touches and assign a context to each one with respect to the current interaction. With this contextual information together with a formal specification of interaction, it would be possible to filter out and ignore unexpected touches.

Challenge 2: Recognizing user identity. Given the current development of tabletop computing, it is foreseeable that multi-touch interactive surfaces will be more and more present and integrated into everyday environments. In such cases, user identification is an important aspect to take into account in order to provide personalization of the interaction [Zhang et al. 2011], personalization of the interface [Ryall et al. 2005], and secure access of data in shared interfaces [Schmidt 2010]. Currently, there is no widely accepted and developed technique that allows user identification for surface interactions. DiamondTouch [Dietz and Leigh 2001] can associate touch to users, thus enabling user differentiation, but it cannot reveal any information about a user's identity. In this architecture touches occurr by means of capacitive coupling and, therefore, the system can only recognize that someone seated on a particular chair is touching the surface. Some attempts has been made to identify the user, such as using biometric approaches based on hand contours or employing personal devices (e.g., smartphones) to act as users' virtual identity [Schmidt 2010]. Marquardt et al. [2011b] proposed the use of fiduciary tagged gloves, but this was for more as a toolkit to investigate and highlight possible benefits of users and hand parts identification, than a real solution.

Challenge 3: Understanding the real benefit of multi-touch interaction in horizontal surfaces. Schöning [2009] pointed out that, while the user has developed sophisticated skills for sensing and manipulating objects in the physical environment, these behaviors do not reflect the way in which they interact with multi-touch enabled surfaces. For example, while interacting with applications enabled for multi-touch input, users do not exploit the full potentialities of multi-touch and hand gesture, limiting their interaction mostly to the touching and pointing paradigm. Open research questions are: *What are the real benefits of multi-touch, gestural interfaces over single-touch interactions? What are the best suited application contexts for multi-touch input? What are the interaction possibilities offered by gestural input?*

Possible advantages and inconveniences of combining touch input with other touch or touchless devices such as mouse or styli are still not clear. *What effect do direct and indirect input devices have on collaborative interactions? What are the tradeoffs between choosing one input device over another?* [Ha et al. 2006]. First of all, it is important to identify applications and the tasks users will perform on the tabletop, in order to select suitable interaction techniques. It is still unclear why stylus inputs are not popular and if direct and indirect input can be successfully combined. Although touch input seems to be the most important feature of a tabletop system [Benko et al. 2009], it is necessary to further investigate the mix of different input modalities that could be helpful in mitigating some touch input limitations, like the lack of precision or object obstruction.

Challenge 4: Redesigning the user interface for natural interaction. This challenge is somehow related to gestural input. We are witnessing the paradigm shift from desktop to ubiquitous computing, but as devices change from desktop computers to mobile terminals, the same is not happening for interaction styles and metaphors. In particular, metaphors from the desktop world are adapted, when not simply transposed, to ubiquitous interaction, thus generating a sort of hybrid-WIMP environment. Designers will have to completely rethink interaction, instead of reusing existing elements from the WIMP paradigm, because a change in input devices alone (from indirect devices such as the mouse to direct touch devices) does not always provide a better user experience. Before designing natural interfaces for interactive touch-enabled surfaces, researchers should try and answer these questions, *Are these interfaces more natural only in the sense they offer a higher degree of freedom and expression power, when compared with a mouse-and-keyboard interface? Or, are we really aiming at empowering users with a means to communicate with computer systems so that they can access information in a seamless way?* The final objective should be to create an interface in which a user can act and feel natural and that makes the most of users' innate and acquired (learned) skills [Wigdor and Wixon 2011].

One strategy for developing natural interaction is to use participatory design techniques, thus involving users in the design of gestural languages [Wobbrock et al. 2009]. While this approach allows to select gestures with the higher consensus (users' preferred gestures) and, therefore, bring tabletop computers closer to real users, O'Hara et al. [2012] argued that *"naturalness is not something that lies purely within the interface itself and is not something that can be treated simply as a representational concern through which intuitiveness ease of use and learnability can be achieved."* One of the challenges is therefore to understand how natural interaction is achieved through embodied interactions that take into account not only the system but also the social context. Interaction designers should not only focus on the best way to achieve an efficient human-computer communication, but how social and technological elements can be combined for a meaningful and natural user experience.

Challenge 5: Infrastructures and interaction design for device ecologies. Currently, an entire ecosystem of digital surfaces (wall displays, tablets, tabletops, etc.) is surrounding us in our everyday interactions with digital technologies. Such ecology of different form-sized interactive surfaces offers an environment where users might expect a seamless integration of systems and infrastructures supporting a wide range of inputs/outputs, affordances, multi-user and, multi-views applications.

Interactive tabletops form part of technology-enhanced environments as demonstrated by projects such as i-LAND [Streitz et al., 1999] and WeSpace [Wigdor et al. 2009]. Weiser [1991] argued that the real power of ubiquitous computing does not come from single devices but from the seamless and fluid integration of each device into an ecology of interactions. To fulfill this vision, in the last few years, there has been an increasing amount of research on intertwined interactions among different digital surfaces. For instance, Kray et al. [2010] studied gesture-based interaction involving different surfaces, as in the interaction between smart phones and tabletop displays. Spatial awareness and proxemic interactions [Marquardt et al. 2011a] have also been investigated, leading to the development of novel toolkits that support the development of reactive environments. Nevertheless, the subject is still fragmented among various heterogeneous research areas. There are many relevant challenges involved in modeling infrastructures and designing applications among these different digital surfaces giving birth to a wide set of distributed interfaces. More specifically for tabletop research, we might ask, "*[W]hich elements of the* *distributed interface/interaction best fit tabletops? What are the implications of interacting between public (e.g. tabletops in shared environments) and private settings (e.g. smart phones)? Is there any effective strategy to manage interface migration and distribution among such ecosystems?"* And, *"[H]ow to configure the varied properties of devices into a holistically-designed system, with desirable characteristics in terms of the assemblage of people, artifacts and technologies, and the transitions that occur between them?"* [Coughlan et al. 2012].

Challenge 6: Organic Interfaces. Researchers at Queen's University, Canada, developed Papertab, which is an interactive touch-sensitive 10.7-inch sheet of plastic able to display documents, images, videos, and the like [Alexander et al. 2013]. The so called Organic User Interfaces [Holman and Vertegaal 2008] will take advantage of the object's physical shape to control it, and in particular the form factor of a sheet of paper, currently available, might change the way in which digital surfaces interact with tabletops. For instance, sheets might act as physical windows, each one including a specific application, while the tabletop might be used to orchestrate the interaction among different Papertabs. Steimle and Olberding [2012] proposed the concept of mobile devices that can turn into tabletops through rollout displays. Exploiting recent advances in flexible display technologies is thus possible to create hybrid devices that combine the benefits of mobile interaction with the possibility to support co-located collaboration with shared surfaces.

Actuated tabletop surfaces that can change their shape, providing 3D haptic feedback [Leithinger and Ishii 2010] is an emerging topic. These novel surfaces that react to users input by changing their physical configuration allow new kinds of manipulations and visualizations on the physical surface that extend human expressiveness, otherwise relegated in a two dimensional space. *"We intuitively use gestures to express intent and desire, and if the surfaces around us could better understand such notions then digital design could be a more transparent and seamless experience"* [Blackshaw et al. 2011].

Challenge 7: Beyond two-dimensional surfaces and interaction. Interactive tabletops enhance physical affordances of a real table surface with digital computation capabilities. Users can manipulate virtual objects with their hands and fingers by direct touch. Additionally, many systems exploit tangible objects as input, with the physical behavior coupled with digital actions and representations. However, in the majority of cases, the interactive surface is two dimensional, rigid, and confined in a rectangular shape. In contrast, Steimle et al. [2012] argue that, *"[M]ost physical objects are 3D shaped, curved, and/or deformable. What if the interactive surface itself incorporates these characteristics rather than just providing a scene for such tangible objects?"* According to this vision, researchers are exploring how novel physical forms for the surface can enable new applications and interactions. Benko [2009] explored non-flat surfaces, identifying the need of an interaction that is not bounded by rectangular surfaces, but that involve people's physical movements and the objects that surround the surface. Non-flat surfaces include spherical (where the concept of borders disappear), curved, and bended shapes that facilitate their integration into the ecosystem of computational devices. Moreover, these surfaces are equipped with novel sensing technologies, such as depth cameras, that enable interactions that go beyond the physical display as demonstrated by the work of Benko [2009] and Wilson and Benko [2010]. Benko [2009] foresees that integrating interactive surfaces of different shapes in our real environment will make natural interaction come true, where *"the only experience the user needs to start interacting is their real life experience."*

9. CONCLUSION

Research in interactive surfaces is more than 25 years old [Buxton 2009] and the film industry has portrayed potential uses of such technology in movies like *Tron*[11]; where a multi-touch tabletop interface was used to communicate with the *Master Control Program*. The dedicated conference, ACM ITS, and the rising number of contributions in leading HCI conferences, such as CHI, CSCW and UIST, gives an indication on the increasing development of tabletop computing research and are a valuable source to understand past trends and shed light on future directions.

[11] http://www.imdb.com/title/tt0084827/

In this survey the literature of horizontal interactive surfaces has been reviewed, focusing on the input space. The support to multi-touch input is a key factor for the development of this research area. By enabling recognition and tracking of multiple contact points on the surface, a more fluid interaction can occur, which do not necessarily have to be based on the mouse *point model*. Thanks to a table's natural affordances, interaction can be enriched by the use of tangible objects that can be coupled with digital information. The introduction of novel interaction styles, if compared with the classical desktop environment, brings challenges for interaction designers. For example, it is still not clear what are the real benefits of multi-touch, gestural, and tangible interfaces. As demonstrated by a few studies [Wigdor et al. 2007; Schöning 2009], users tend to interact by touching the surface with only one finger at time, following the classical pointing style they learnt in a desktop environment. Only after experimenters told them they could use more complex gestures, they started to explore these new interactive possibilities.

Each input mode presents distinctive benefits and drawbacks that have been framed, in this work, within a classification of the input space that takes into account: (a) directness of input (direct or indirect), and (b) embodiment (explicit contact, contrived contact, and contact-less). The use of direct touch devices, for instance, suffers from occlusion [Shen et al. 2006]. Indirect devices solve this problem but they do not provide a direct mapping of users' intentions and system actions. *"The wide disparity in choice of input devices, […] the variety of tasks that can be performed using a tabletop display,"* and *"the inherent strengths and weaknesses of the input devices"* [Ha et al. 2006] originate a scenario in which interaction modes should be considered together with application contexts and tasks, trying to understand how they can cooperate in the same ecosystem.

By (1) reviewing technological achievements, (2) framing the input space of tabletop computers, and (3) highlighting challenges that will guide future research, we aim to support the vision of Müller-Tomfelde and Fjeld [2010]. As they forecasted, in the next decade, tabletop development can reach the same stability as other inventions like the GUI or the Internet. But this will be possible only with a clear understanding of the problems to be addressed. In conclusion, the objective is to materialize the idea of ubiquitous computing [Weiser 1991]: ecologies of interconnected, heterogeneous devices that interact between each other and with users in a way that the interface becomes invisible.

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